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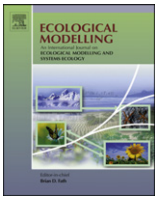

Ecosystem services as a counterpart of emergy flows to ecosystems

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ABSTRACT

A generic input–state–output scheme has been used to represent ecosystem dynamics. Systemic approaches to ecosystems use functions that are based either on inputs, state or outputs of the system. Some examples of approaches that use a combination of functions have been recently proposed. For example the use of eco-exergy to emergy flow can be seen as a mixed input–state approach; more recently, to connect the state to the output of the ecosystem, the relation of eco-exergy and ecosystems services has been proposed. This paper studies the link between the useful output of an ecosystems and its input through the relation between ecosystem services and emergy flow, in a kind of grey/black box scheme (i.e., without considering the state and the structure of the ecosystem). No direct connection between the two concepts can be determined, but identifying and quantifying the emergy flows feeding an ecosystem and the services to humans coming from them facilitate the sustainable conservation of Nature and its functions. Furthermore, this input–output relation can be established in general by calculating the ratio of the value of the ecosystem services to the emergy flow that supports the system. In particular, the ratio of the world ecosystem services to the emergy flow supporting the entire biosphere has been calculated showing that, at least at the global level, Nature is more efficacious in producing "money" (in form of ecosystem services) than economic systems (e.g., national economies and their GDP).

1. Introduction

Ecological systems are thermodynamically open, hierarchical, self-organized, and self-regulating. Self-organization is when systems (composed of many parts) organize, achieving a configuration, which defines its state. These systems can only maintain themselves by having inflows and outflows of energy (see for example Lotka, 1922; Morowitz, 1968; Odum, 1971; Jørgensen et al., 2007; Salomon, 2008; Swannack and Grant, 2008).

An ecosystem, as a bounded system, is defined by the functioning of the system and exchange of energy with an external source-sink system (Fath, 2008). The qualitative and quantitative nature of the inputs received feeds the internal organization of the system, which develops and produces various outputs. The definition of the system boundaries is crucial to distinguishing between what is "input" to the system, what is "output" from the system, and what is part of the internal dynamics and cycles of the system functioning.

Systems are usually characterized as having components (state variables or stocks), interactions between them (flows of matter, energy, or information) and, in open systems, fluxes in and out of the system boundaries (inputs and outputs) (Limburg et al., 2002).

A "State" of an ecological system is a particular configuration of the abiotic–biotic system components. It is characterized by specific relationships between living organisms and non-living surroundings. To give a measure of the State of a system also means to quantitatively describe its components and the relationships among them. Structural complexity and biodiversity influence the possible evolutions of the system toward another (more or less) stable state.

The "Inputs" to an ecosystem are all flows of energy and matter entering the system from the environment (defined as all that is not the system). The "Outputs" of an ecosystem are all flows of energy and matter moving from the system to the environment. Ecosystems utilize energy sources from the environment, and thereby are a part of the global energy balance (Kleidon, 2008).

1.1. An input–state–output representation of ecosystem functioning

Starting from thermodynamic laws and energy flows in ecosystems, we can present an ecosystem in a very schematic way, as in Fig. 1. A number of holistic methods exist to interpret the level of organization, complexity and/or health of ecosystems. Since the

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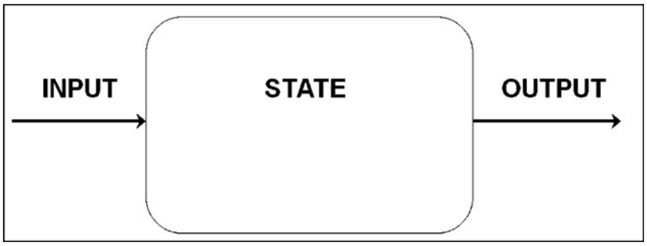

Fig. 1. Input, state and output representation of a system.

beginning of thermodynamic approaches to ecosystems (e.g., Lotka, 1922) much attention has been paid toward the cause/effect relations that link inputs, states and outputs.

Both Lotka (systems which maximize their flow of energy survive in competition; in: Gilliland, 1978) and Boltzmann (1905) ("systems which maximize their flow of free energy available for doing work, are successful systems in the struggle for life"; see also Tiezzi, 2006) identify the quantity and quality of inputs as the key to developing a system. The approaches to the analysis of ecosystems that are based on the consideration of inputs are called "donor-side" approaches. Among these, emergy evaluation is probably the most used.

Emergy is a tool that is able to evaluate the convergence of matter and energy (several inputs) to a system on a common basis. Odum et al. (2000) defined it as "the availability of energy of one kind that is used up in transformations directly and indirectly to make a product or service". It represents the work done by nature to provide a flow or a service calculated on the basis of the solar energy processed (and memorized) in space and time. In fact it is expressed in solar emergy Joules (seJ) (Odum, 1996, 2000; Odum et al., 2000). The ecosystem can be represented by the quantity and quality of the energy and matter converging in the same system, measured in terms of emergy. Therefore, emergy enables us to identify, quantify and weight the inputs that feed the system.

Several approaches attempt to characterize the state of the system. These approaches are based on the description of the internal network organization of the system, of the system's complexity, and/or on the study of how system cycles energy and matter in its dynamic evolution. In these approaches classical ecological concepts such as biodiversity, trophic levels structures, ecological successions and so on are included. One of the functions able to describe the state of a system is the eco-exergy. It is a state-based descriptor of a system's structure (and functions, networks, interactions) based on how usable energy is organized in storages. Genetic information and biomass are the basic components of eco-exergy (Jørgensen and Mejer, 1979, 1981; Jørgensen, 2006, 2008). It measures the distance from thermodynamic equilibrium and is given by the formula:

$$\text{Eco-Ex} = \Sigma\beta_i \cdot c_i$$

where c_i is the concentration of the ith component of the ecosystem and β_i the weighting factor that accounts for the genetic information that the component carries (for a list of β-values, see Jørgensen et al., 2005). Eco-exergy is a measure of how much information an organism contains, and can also be used as an ecosystem health indicator (Jørgensen, 2006).

More recently, approaches have been developed that describe ecological systems considering the useful outputs generated by them. In this view it is crucial to define which subjects receive the outputs from the ecosystems. In other words, in a "user-side" approach, it is crucial to define the user, mainly to identify which outputs to consider and the criteria that guide this consideration. Different users can uptake different outputs, and their analysis describes the same system in a different manner. The ecosystem-services approach is a user-side approach that has recently been developed and is now increasingly applied (Costanza et al., 1997; MA, 2005; TEEB, 2010). It derives from a re-conceptualization of ecosystem functioning from an anthropocentric viewpoint (De Groot et al., 2002). In the case of ecosystems services, the output of the system is, in fact, related to the ecosystem functions, which provide services to be used by humans: this anthropocentric view of the utility of the ecosystems implies that the quantification of their values is made by means of environmental economic methodologies. Ecosystem services are defined as processes or functions of value to humans (Fisher et al., 2008). They include ecosystems organization (structure), operation (process), and outflows, if they are consumed or utilized by humans either directly or indirectly (Boyd and Banzhaf, 2007).

This paper aims at connecting a donor-side approach (the emergy evaluation of ecosystems) with a user-side approach (the ecosystem services evaluation) to better understand the role of resources availability for natural systems as a counterpart of benefits valuable in a socio-economic context. This approach identifies possible connections between ecosystem services and ecosystem functions. We will define, in this way, a comparable measure of ecosystems and anthropic systems in the context of services provided. This is not an alternative method to the Ecosystem Services Evaluation, but rather a complementary and systemic approach to highlight the mechanisms of services production by different systems.

1.2. *The joint use of orientors and ecosystem services evaluation*

According to Jørgensen et al. (2007), "It is important to try to understand the many different ecosystem theories in relation to each other and examine if they are contradictory or form a pattern that can be used to give a better understanding of the nature of ecosystems". Fath et al. (2001) support the use of a plurality of "goal functions", "because it is probably their complementarity and interdependency that has made the identification of a single universal extremal principle difficult". In this plurality, some relationships have been acknowledged by different authors.

The ratio of eco-exergy to emergy flow was used to represent the level of organization of an ecosystem (as eco-exergy) per unit input (as emergy flow) (see Bastianoni and Marchettini, 1997; Bastianoni et al., 2006).[1] The eco-exergy/emergy flow ratio can be regarded as a measure of efficiency of an ecosystem: a higher value means that an ecosystem is more able to convert the available inputs in structural organization, i.e., if the ratio tends to increase it means that natural selection is making the system follow a thermodynamic path that will bring the system to a higher organizational level. Eco-exergy/emergy flow ratio can be applied to assess ecosystem health: in natural systems, where selection has acted undisturbed for a long time, the ratio of eco-exergy to emergy flow is higher, and decreases with the progressive introduction of artificial inputs and stress factors that make the emergy flow higher and that lower the eco-exergy content of the ecosystem (Bastianoni, 1998; Pulselli et al., 2010). The eco-exergy/emergy flow ratio combines a donor-side approach (emergy flow) with a state-centered approach

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[1] Bastianoni and Marchettini (1997) first introduced this relation as the ratio of emergy (flow) to eco-exergy. This choice was made in order to maintain coherence with the definition of transformity and to point out the differences: transformity is the emergy that contributes to a production system divided by the energy content of a product (or empower divided by power). The emergy flow to eco-exergy ratio, instead, represents an empower converging to a certain system divided by the eco-exergy of the whole system. Afterwards, the inverse seemed more comprehensible, where the effect (eco-exergy) is the numerator and the requirement is the denominator, as in any efficiency indicator.

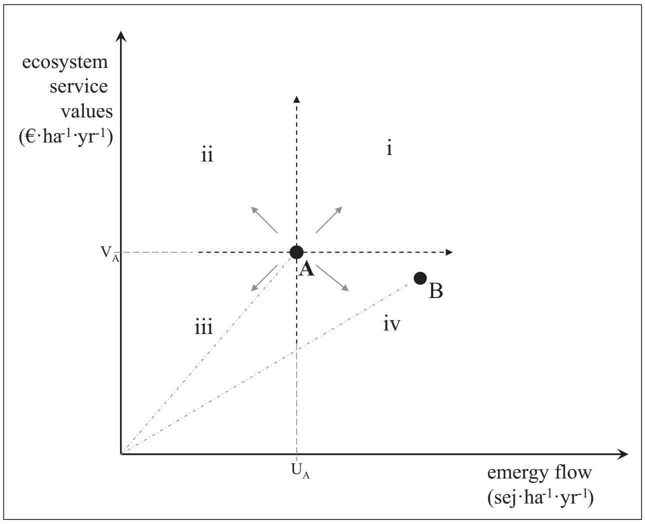

Fig. 2. Ecosystem dynamics represented by change in emergy flow and ecosystem services value.

(eco-exergy), as an example of the complementarity of two orientors.

Jørgensen (2010) has performed a first attempt to correlate ecosystem services with eco-exergy. This approach connects a system's structure and organization descriptor (eco-exergy) to a user-side approach (or an output-based analysis, namely the value of ecosystem services), highlighting a relation between a biophysical and an economic evaluation of the environment. In fact, establishing a connection between "quantitative changes in ecosystems and changes in human welfare" seems necessary (Kontogianni et al., 2010), because pure environmental economic procedures used to evaluate ecosystem services are not able to embody the intrinsic and objective value of Nature. The anthropocentric viewpoint of the evaluator risks to cause a distorted comprehension of the ecosystem-side of socio-ecological systems (SESs), as defined in Berkes and Folke (1998) (see also Petrosillo et al., 2010). Jørgensen's study is therefore very important because it provides a physical basis to the classical ecosystem services theory and related applications.

Other theoretical studies have tried to integrate "ecosystem services" with ecological-thermodynamic concepts. Peterson et al. (2009) introduced the concept of the "ecosystem worker" as the "organisms that produce services in an ecosystem service marketplace", to highlight the work done by ecosystems (to humans) and the public understanding of biodiversity; Kremen (2005) identified "the species, or other entities, that have a key role in the provision of services" and introduced the "ecosystem service provider" concept; Luck et al. (2003) presented the "service-providing unit", referring to a population that provides a recognized ecosystem service at some temporal or spatial scale. See also Kontogianni et al. (2010) and Luck et al. (2009) for a joint use of some of these concepts.

2. A relation of inputs and outputs

As in many models of system representations, we can avoid describing the state of the system in detail, and concentrate only on the role of inputs and outputs. In this grey/black box vision we can, for example, study the relation between the emergy flow that feeds the ecosystem and the services it provides. To better understand this relation, in quantitative terms as well, the diagram in Fig. 2 can be of help. It summarizes the characteristics of an ecosystem, quantifying the inflows of resources by means of the common basis of solar emergy, on the x axis, and useful services for humans, valuable in economic terms, on the y axis. The point A at time t tells us that the ecosystem is supported by a flow of emergy equal to U_A seJ ha^{-1} yr^{-1}, and provides services with a value of V_A € ha^{-1} yr^{-1}. The slope of the segment connecting the origin with point A (=ecosystem services/emergy flow) quantifies how much money of ecosystem services is produced by a system fed by a unit emergy flow. Two (similar) systems give a different ratio of ES to EM according to how each system reacts to available inputs and to what the systems are able to provide to human utilizers. In Fig. 2, the ecosystem identified by point A (at a certain time t) is more efficient in transforming the available inputs into ecosystem services than the ecosystem represented by point B.

Note that ecosystems do not only provide services for humans. The emergy flow supports the ecosystems, their functioning, dynamics, their role in global equilibrium and their services supporting other species. This means that the anthropocentric relationship between emergy flow and ecosystems services (for humans) can be rather weak, even though emergy represents the necessary physical counterpart of the ecosystem services, since it represents the importance of the environmental work for human actions and welfare.

The ecosystem represented by point A in Fig. 2, following its evolutionary patterns, can move, at time $t+1$, in one of the four quadrants of the sub-diagram in which A is the origin of the axes. If the change brings the ecosystem in quadrant *i*, we will have an increase in emergy flow corresponding to an increase in the value of ecosystem services. In the case of *ii*, the ecosystem will be able to provide more services using a decreasing emergy flow. In *iii* less emergy will correspond to less services. Finally, if the ecosystem moves toward *iv*, then it will provide less services (in terms of the value they represent) despite a larger emergy flow supporting it.

The conditions of *i* and *iii* are rather intuitive: more (less) resources available to be used by the ecosystem may lead it to provide more (less) services. Re-forestation, cultivation in arid areas, restoration of riparian zones, are examples of *i*; the lack of human care of fragile or quasi-natural ecosystems (threatened species, reduction of irrigation in conditions of draught, as well as neglected archaeological sites) that may result in a progressive degradation of them, is an example of *iii*. Cases in *ii* and *iv* present a dichotomy between the inflow of energy and matter and the value of ecosystem services. In these cases, respectively, a decrease in resource flow corresponds to an enrichment of the ecosystem and its capacity to provide services (as in case *ii*), and, conversely, the resources processed by the ecosystem are translated into a loss of utility for humans (as in case *iv*). Pollutant source removal or crop rotation with portions of land set aside are examples of *ii*; pollution, human intensive exploitation of the system (like monoculture or intensive farming), oversized infrastructures (like dams) are examples of *iv*. Especially in the last two cases, it becomes crucial to know the nature of the emergy flow that seems to have negative effects (if added) as well as the role played by anthropic activity in managing and using ecosystems and related services.

Since the concept of ecosystem services (and related economic values) is anthropocentric, we suppose that the ecosystem under study moves from point A by virtue of human activity as well. In other terms, the concept of ecosystem services exists only because there is a final user of them, who, in turn, influences ecosystem dynamics through its activity of withdrawal, use, enjoyment, fruition, etc., of those services. These activities can be crucial for ecosystem capacity of providing services and resources. In general, it has been shown that progressive human intervention in natural dynamics of ecosystems (agriculture, silviculture and forestry, aquaculture, territorial and urban management and planning, etc., in different forms) may imply a decrease in ecosystem services, independent of the fact that human activity often results in an increase in the use of resources (increase in emergy flow) (see for example, Balmford et al., 2002).

Monitoring ecosystem dynamics, including human activity, may therefore foster a better management of nature, taking into account its usefulness for our species as well.

3. The ratio of ecosystem service value to emergy flow

Emergy flow and ecosystem service values can be independent from each other, according to the scheme presented in Fig. 2. In fact, an ecosystem works independently of the "economic" fruition of it made by humans. On one hand, ecosystem work can be represented by the emergy flows that support it, but emergy is more a measure of a potential than of actual complexity or organization; on the other hand, the value of ecosystem services represents "the benefits human populations derive from ecosystem functions" (Costanza et al., 1997). Therefore the former depends on natural dynamics; the latter on the utility humans (decide to) draw from nature, which may vary from case to case. Therefore, a direct quantitative relation between the two does not seem appropriate. As stated by Sagoff (2011), "a conceptual distance divides microeconomic efficiency and macro-ecological stability with respect to ecological services".

However, an indirect use of the relation between emergy and ecosystem service evaluation is possible by putting into relation the two entities, at least at the global level. Campbell (2000) proposed a global emergy budget, as the emergy supporting the cyclical activity of the entire biosphere, equal to 9.26×10^{24} seJ/yr.[2] Costanza et al. (1997) found that the global value of services yearly provided by terrestrial ecosystems was between 1.82 and 6.15×10^{13} €/yr.[3] Dividing the world ecosystem service value by the emergy flow to the biosphere, we obtain the amount of money that is, in average, produced by one seJ of solar emergy. Formally:

$$\frac{\text{world ecosystem service value (in €/yr)}}{\text{emergy flow in the biosphere (in seJ/yr)}}$$
$$= \text{ecosystem service per unit emergy (in €/seJ)},$$

This ratio combines an amount of money that is not really circulating in the global economy and the flow of all renewable resources that feed the planet (sunlight, geothermal heat, rain, wind, etc.). It can be considered as a potential efficiency of the entire biosphere in providing a kind of economic wealth for humans (since at least a portion of it can be converted into real economic utility/benefit) based only on its natural functioning.

In emergy theory, a combination of emergy and economic value, called "emergy-to-money ratio" (EMR), is often used. It is traditionally calculated as the ratio of the emergy flow to a nation to its GDP, expressed in seJ/€, and represents how much emergy corresponds, on average, to one unit of money produced by the national economy. The reciprocal of the ratio of the world ecosystem service value to the emergy flow in the biosphere can be seen as an "environmental" EMR (in seJ/€), since only natural components are involved: humans are only the final users of the services. The value of the "environmental" EMR is between 5.09×10^{11} seJ/€ and 1.51×10^{11} seJ/€ (depending on the minimum and maximum values calculated by Costanza et al., 1997). Both maximum and minimum values are lower than traditional EMRs calculated for national economies: the order of magnitude of the latter is in general 10^{12} or more (for an overview of national EMRs, see Sweeney et al., 2007). This means that the global ecosystem uses, on average, less emergy than a national economy per unit money provided to humans. Nature is thus more efficient in producing economic value than any economic system that is designed to do just that. This result corroborates the conclusion of Costanza et al. (1997), who found that the value of the world ecosystem services is 1.8 times larger than the global economic product. Moreover, since Costanza et al. (1997) provided only a "minimum value" of ecosystem services, the "environmental" EMR should be even lower.

This calculation made at the biosphere level could also, in principle, be performed at a smaller scale, that of the single ecosystem. At the first level of observation, we have the value of ecosystem services of the 16 biomes estimated by Costanza et al. (1997) at our disposal; on the other hand, emergy flows to many ecosystems have been calculated by a number of analysts. However, especially for emergy flows, we have found very heterogeneous results even for the same kind of biome. For instance, regarding results for temperate/boreal forest, there are results differing by two orders of magnitude: 3.60×10^{14} seJ ha^{-1} yr^{-1} (Brown and Bardi, 2001); 1.11×10^{15} seJ ha^{-1} yr^{-1} (Campbell, 2009); 1.12×10^{16} seJ ha^{-1} yr^{-1} (Juan and Chang, 2005). Coscieme et al. (2011) presented a list of average emergy flows for the 16 biomes, obtained through combining a large number of data from literature. It is striking that a difference of up to 5 orders of magnitude can be found between terrestrial and marine ecosystems.

The ecosystem services analysis at the smaller scale may also assume very different values. This variety may depend on physical/ecological conditions, on the role played by users, as well as on the hypotheses and methods utilized. For instance, the same ecosystem can provide different levels of services according to the fact that the potential user is the population of a city, or a farmer: for instance, Turner et al. (1988) calculated different values for the same ecosystem.

4. Conclusions

Emergy evaluation increases our knowledge about functioning and production of services by ecosystems. Emergy is in fact valuable both for natural and anthropic systems. This wide applicability is probably the principal advantage of using this method.

However the total emergy input that supports a system is not necessarily converted into ecosystem services, even if the system exists and maintains itself only capturing this energetic input. We have shown that, in the input–output representation of ecosystems, the resources supporting an ecosystem and the services it provides that are useful for humans are rather independent from each other. It depends on the intrinsic characteristics of ecosystems, on their usefulness for humans, and on the method used to calculate results. Therefore, it might not be correct to perform an evaluation of ES purely based on emergy.

Anyhow, emergy evaluation is an important step if we want to understand the reasons why an ecosystem, which must be open, survives and offers benefit to human society. We have shown that emergy can represent this thermodynamic openness by taking into account the flows of energy and matter that support ecosystem functioning. The emergy based evaluation is thus a substantial, but also conceptual, basis to determine the intrinsic value of nature and its role as a source of benefits. In this context, the two methods (emergy and ecosystem service evaluation) have been put into relation with the aim of highlighting the role of the physical basis of human use of ecosystems. At the global level, we have found that Nature contributes to humans not only more (as Costanza et al., 1997), but in a more efficient way, than all the world economic infrastructures. For single biomes, problems of standardization in

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[2] At the moment, this value and related calculation procedure are under debate by emergy analysts. Odum (1996) calculated a global budget of 9.44×10^{24} seJ/yr; in Odum (2000) this value is 15.83×10^{24} seJ/yr; Brown and Ulgiati (2010) proposed $15.2\ (\pm 0.3) \times 10^{24}$ seJ/yr.

[3] The values calculated by Costanza et al. (1997) were 16×10^{12} \$/yr and 54×10^{12} \$/yr (\$ value of 1994). They have been translated into € 2010 value.

emergy synthesis and extreme simplification in ecosystem service evaluations still exist.

Efforts are necessary to study these relationships in depth: more accurate and consistent emergy evaluations, advances in ecosystem service assessments, and the integration of state descriptors in this purely input–output (grey-black box) representation would be of great help in improving the scheme.

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