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The free energy of an ecosystem: towards a measure of its inner value

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Abstract

Based on a free energy approach, we propose the estimation of an ecosystem's Inner Value, which is both non-instrumental and objective, reflecting the ecosystem's value for itself as a natural entity, abstracted from any human valuation. The ecosystem services approach has become the dominant criterion for studying human and natural relationships, but this and similar approaches concentrate on the human advantage giving little or no regard for the well-being of the ecosystem. Although there is concern about preserving and recuperating damaged ecosystems, we seldom consider how much the ecosystem values itself. Then, we propose that Inner Value could be a tool to evaluate and model ecosystems' health before any anthropic disturbance, allowing comparison with the impact these disturbances may have in the future. We also suggest that it should be a requirement for any Environmental Impact Assessment.

Keywords Ecosystem inner value, Ecological networks, Ecosystem services, Free energy

1 Introduction

The value of nature has been (and still is) the object of a profound debate that involves philosophical, moral, and ethical discussions (Rowlands 2000). Each value category is derived from a different cognitive framework that reflects a given relationship with nature (Muradian and Pascual 2018). There is a consensus that the biosphere has value per se but, what kind of value? related to what? or even for whom? (Azqueta Oyarzún 1994) are still questions extensively debated.

One of the most significant and widespread research fields aimed at studying the relationship between humans and nature is the Ecosystem Services Science (Armsworth et al. 2007), which mainly focuses on defining, classifying (de Groot et al. 2002; Pereira et al. 2005; Fisher and Turner 2008), and estimating the value of the services they provide (McCauley 2006; Hein et al. 2006; Costanza et al. 2014) as well as to define and assess the risks they are facing (Zhang et al. 2011; Richardson et al. 2015; Munns et al. 2016). Risks are generally due to changing global, regional, and local conditions and anthropic activities as well, while valuation depends primarily on the notion of value adopted. This notion also includes the decision of preserving or not an ecosystem or converting it to human use (Barbier et al. 2008).

Although there is a significant advance considering the relationship between ecosystem services and societal concerns, particularly in marine and coastal environments (Elliott 2023), the results are still anthropocentric conceptually. Of course, there is plenty of concern about the preservation and even recuperation of damaged or fragmented ecosystems, but with a psychological sensation (e.g., culpability?) that humans are a species that

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tends to destroy the planet for its benefit, regardless of the consequences. Seldom, if ever, do we think from the ecosystem point of view? Do we inquire about what the ecosystem needs or wants for itself or, more importantly, what is the value of an ecosystem regardless of the benefits it provides to humans?

In this context, we propose a new paradigm by defining a mechanism of valorization of the ecosystem using a completely different approach and unit of measure than those used by the specific literature hitherto. Therefore, we define the Inner Value of an ecological network as a normalized amount of the free energy concept (Gottwald and Braun 2020). Our objective is to find a measure of the value of an ecosystem, both non-instrumental and objective, which reflects the value that the ecosystem has for itself as a natural entity, abstracted from any human valuation (and, consequently, stripped of the subjectivity inherent to the valuation process). To achieve this, we provide results based on estuarine ecosystems.

2 Value and valuation of nature

The instrumental value is perhaps the more explored and discussed value of ecosystems: nature has value because it plays a role in supporting and furthering human interests or, in other words, the value of nature consists in what it can do for us (Rowlands 2000). Instrumental covers a variety of values: *use-value* (consumptive and non-consumptive, direct or indirect); *option values* (option value proper and quasi-option value); and *non-use values*. Among the latter, which reflects the willingness to pay to preserve the environment for the benefit of other people, intra and intergenerationally (Chee 2004), the more studied is the existence value motivated by altruism, heritage, symbolism, or the belief in the right to the existence of other forms of life: a position congruent with the different variants of non-anthropocentric ethics (Azqueta Oyarzún 1994).

Except for the value related to the last two reasons, all instrumental values can be considered extrinsic because what is valued is something other than the specific good for our own well-being or for the well-being of others. On the contrary, intrinsic values refer to an essential type of value, given by the contribution of an object or action to maintain the health and integrity of an ecosystem or species per se, no matter any human satisfaction (Farber et al. 2002). Then, intrinsic value tries to capture the value attached to the environment and life forms for their own sake (Chee 2004), beyond their ability to fulfill human needs.

Despite this apparent simplicity, the notion of intrinsic value is still confused and widely debated in the literature (O'Neill 1992; Callicott 1995; Chan et al. 2016; Zimmerman and Bradley 2019). The discussion about instrumental and intrinsic value has also generated new developments, mainly aimed at improving environmental policy. Thus, the *relational value* concept (Chan et al. 2016) emerges as a third kind of value, which is not present in things but reflects the relationships and responsibilities to them. For instance, Rowlands (2000) identified three different interpretations of intrinsic value: the value that an object possesses in virtue of its intrinsic properties or features; the value understood as non-instrumental value; and the value that objects have irrespective of whether sentient creatures value them or not. Davidson (2013) defines *warm glow* value and *existence* value as the satisfaction that people derive from altruism towards nature and the mere knowledge that nature exists, respectively, and differentiates such values from intrinsic value, reflecting the value that nature has for itself.

This definition implies that intrinsic value lies outside of the ecosystem services framework. Nevertheless, such exclusion does not necessarily imply that ecosystem services are an anthropocentric approach in the moral sense since it does not deny that nature has value for itself. Instead, the intrinsic value lies outside because it does not reflect nature's value from a human perspective (or, in Rowlands' terms, its instrumental use for all sentient creatures).

Intrinsic and Instrumental values reflect different aspects of what nature does for itself or us, respectively. Nevertheless, in both cases, the perspective from which an environmental good or service is valued is purely and exclusively anthropocentric. It is impossible to dissociate the value from the activity of valuation made by individuals.

The ecosystem services framework, undoubtedly the dominant paradigm for describing the relationship between humans and nature in our times, considers that ecosystem functions become services only if they satisfy people's needs and increase their welfare. Then, the ecosystem services provision depends on the degree of dependence on those services by certain groups and the relationship of such a service with other ecosystem services. In the equation, there is little or no focus on the conditions or potentialities of the ecosystem other than that required to maintain the ecosystem as a service provider for satisfying human needs, which means that instrumental value prevails all over other types of values. Then nature has no value besides human valuation.

Logically, valuation is always a subjective issue. Consequently, there is no unique value for each ecosystem service, which generates a wide range of interpretations when judging the potential of, for instance, ecosystem preservation or extraction of products (either tangible or intangible). The valuation may also vary as a time function (Chaudhary et al. 2015; Rau et al. 2020). The rate of variation of the ecosystem value depends on the relative scarcity of the service, the need that the service satisfies, and the use it will have rather than the actual value that the service has per se. Also, the ecosystem's valuation is based on the services it can provide depending on whether it has some particular value in the past, present, or future. These values clearly vary with time, even if they are essential, considering the market estimation of the service, and even can vary for different cultural or regional approaches.

The lack of consensus about how an ecosystem (whatever its nature) must be assessed has created a deep void among most economists. They are trying to evaluate the services in monetary terms, and ecologists are concerned about the system's past, present, and future status. To abstract from such extreme positions and avoid the usual anthropogenic logic underlying the valuation of nature, we propose the notion of Inner Value derived from both the idea of an ecological network (in the present case, coastal ecosystems) and the need to find a non-instrumental and objective measure of the value of a system, which is also independent of any monetary criteria.

3 Ecological networks

Ecosystems, even those we may consider simple ones, are characterized by a complex spatial heterogeneity of their features and services (de Groot et al. 2002). To develop their complete life cycle, individual elements of an ecosystem require several interactions with the other (but not necessarily all) members of the ecosystem. The energy transfer can describe those interactions from one individual taxon to another (Ulanowicz 1972, 2004) and their relationship with the surrounding structure (i.e., geomorphology, nutrient input/output) and external input/output (i.e., solar radiation, gas exchange).

Although we do recognize the importance of the exchange with the exterior, for the sake of our analysis, we consider the ecosystem as a closed system receiving only solar radiation and nutrient input from the sediment surrounding the system. Our idea is to track and evaluate how the interaction of the taxa based on the ecological trophic transfers provides an estimation of the Inner Value of the whole ecosystem at a specific time, as well as how we can use the Inner Value as a tool to analyze the ecosystem self-evolution over time.

An ecosystem is integrated by several biological organisms aggregated in taxa and the surrounding physical (abiotic) conditions as a physical environmental structure. Organisms interact among them, and the various factors continually influence their behavior and evolution continuously. Although we are discussing natural ecosystems, any economic system can also be regarded as an ecosystem where the agents interact among themselves, but some of them must have relationships with external influencers (i.e., buyers, providers, competition, etc.).

Another way to see an ecosystem is like an ecological network where the interaction between taxa and the surrounding environment is based on a transfer of energy, and this transfer can be either in one direction or bidirectional. The fact that the same external factors may interact with different taxa at different rates and the various interaction mechanisms that the biotic organisms have among themselves demonstrate that ecological networks are rather complex but also variable at different times of ecosystem life. In other words, the same exchange between two particular taxa may be different depending on the degree of maturity of the ecosystem and may change if the mass of one taxon has different values at different stages of, for instance, a seasonal cycle. Furthermore, some taxa may interact with another under some circumstances, but if the appropriate conditions are not met, the interaction may have a different magnitude or even be null.

Since we assume the ecosystem is closed, we are not considering any influence of climatic variables and water input from rivers, sea or groundwater. We intend to evaluate the energy exchange among the various ecosystem components towards obtaining its inner value. We then define the Inner Value *as a measure of how the elements of the ecosystem determine the significance of the ecosystem by itself before any exchange with the external world.*

Basically, we look to separate the ecosystem from its external factors to maximize the inner value. Then, once the system is open to the exterior, we could evaluate how the input/output may affect this inner value and its evolution. Furthermore, the inner value could also be employed to measure the internal efficiency of the system's organization and, by continuously maximizing it, developing tools for mitigation or resilience.

4 Inner value from free energy

Complex systems can either fail or succeed based on how they resist internal and external tendencies toward their disintegration. This is the case with ecological networks, which are self-organizing systems. That is, systems in which their internal dynamics contribute to preserving their structure and behavior. The lack of thermodynamical equilibrium with its environment clearly indicates live activity.

All ecosystem processes are irreversible (Jorgensen and Fath 2004). At each process, energy is lost in the form of heat that contributes to entropy production (Morowitz 1968), implying that processes involving energy flux are associated with the disorder (Ulanowicz and Hannon 1987). There are two primary types of incoming energy (Fig. 1): (i) solar energy that enters the ecosystem via

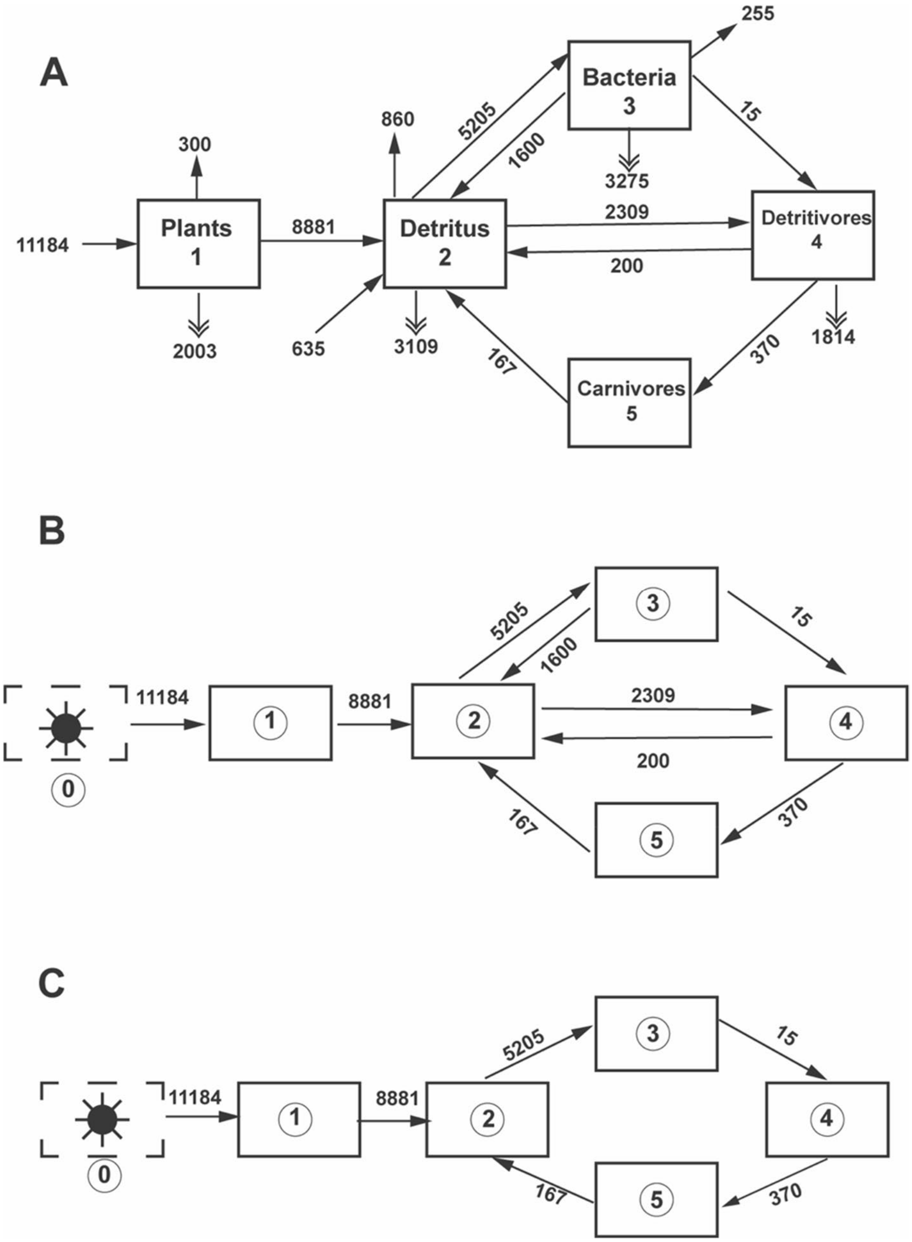

Fig. 1 **A** Example of the Cone Spring closed ecosystem as proposed by Ulanowicz (1972). **B** Simplified version of A considered in the estimation of the IV(t). **C** Simplified version of B but in this case the flows between taxa 5 and 3 have been removed as well as the flows between taxa 2 and 5, and 3 and 2. The energy for each taxon was estimated from the standing crop proposed by Tilly (1968). Data and calculations are in Table S1 (Perillo 2023)

photosynthesis and (ii) the energy bound in chemical components which flows through the boundaries of ecosystems via inorganic or organic nutrients pools (Saint Béat et al. 2015).

The free energy principle states that any self-organizing system is in a non-equilibrium steady state with its environment and must optimize its (variational) free energy. In these terms, we intend to define the notion of the Inner Value of an ecological network as a normalized amount of "free energy". We do know that there is extensive and controversial literature going back to the 80's regarding the use of thermodynamic approaches to analyze the interactions within an ecosystem (i.e., Odum 1968; Bosserman 1983; O'Connor 1991; Brown and Herendeen 1996; Kaberger and Mansson 2001; Fisk 2011). However, when considering an ecosystem, the only interactions that exist are via the transfer of mass or energy. From our point of view, there is no better way to calculate an ecosystem's conditions and evolution. Therefore, even though there are valid concerns, we consider that they are not strong enough to preclude the use of concepts like free energy or entropy (which are within the realm of the thermodynamic processes) to evaluate these interactions.

To make this discussion concrete, let us consider a relatively simple ecosystem structure as depicted in Fig. 1. We use the notation drawn from Ulanowicz (2004) and Scotti (2008). In a system with n taxa, we have:

$$X_i + \sum_{j=1}^{n} T_{ji} = \sum_{k=1}^{n} T_{ik} + E_i + R_i$$

where X is the rate of solar radiation flow (for simplicity, we assume the existence of a single outside source of energy that affects a single taxon in the ecosystem and comes from a fictitious "taxon" 0); E_i is the rate of loss to the medium of taxon i to the outside world; R_i is the rate of dissipation of taxon i; T_{ij} is the rate of transfer from taxon i to taxon j, E_i and R_i, for i = 1,…,n are left unspecified at this step. Then, the free energy principle could be expressed as (Gottwald and Braun 2020)

$$\text{“}\mathit{free\ energy}\text{''} = \text{energy} \pm \text{constant} \times \text{entropy}$$

where energy is the expected value of some quantity of interest; entropy refers to a quantity measuring disorder, uncertainty, or complexity, and the constant translates between units of entropy and energy.

We interpret these magnitudes in the context of an ecological network N as follows:

- Energy (Total System Throughput): $TST_N = \sum_{i=0}^{n}\sum_{j=1}^{n} T_{ij}$
- Constant: the external input: $T_0 = \sum_i T_{0i}$
- Entropy: $H_N = -\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{T_{ij}}{TST} log\left(\frac{T_{ij}}{TST}\right)$

Then, the free energy is

$$F_N = TST_N - T_0 H_N$$

Notice that this expression is closely related to the notion of exergy, the goal function of ecosystems promoted by Bendoricchio and Jorgensen (1997).

According to the free energy principle and, given the physical constraints on the taxa and their interactions, the actual F_N of any given ecological network N at a steady state must be assumed optimal. Evolutionary forces use the free energy of the network to change its configuration by interacting with its environment. A network N is in a steady state when the system reaches a minimum value for F_N.

By the definition of F_N, we have that (since $H_N \geq 0$) for any possible network N in the environment:

$$T_0 \leq TST_N \leq F_N$$

Notice that we assume that T_0 is the same for all possible networks on the same class of taxa. Then, we have that $\frac{T_0}{F_N} \leq 1$. This allows us to propose a relative measure of the free energy of N as the Inner Value (IV) of the network:

$$IV_N = \frac{T_0}{F_N} \in [0, 1]$$

The rationale for this IV definition is that a system tends toward a configuration in which free energy is minimal and, thus, IV is maximal. However, this is a non-equilibrium state in which sudden changes in the environment may make it unstable, forcing a reconfiguration, at which the free energy is no longer minimal. One possibility is the unraveling or extinction of the system. This measure, unlike free energy, is invariant to constant changes in the values of the flows T_{ij}, with i,j = 0,…,n.

Considering a simple closed ecosystem (Fig. 1a) like the one proposed by Ulanowicz (2004) for Cone Spring, we estimate, employing the scheme in Fig. 1b, TST_N, H_N, and F_N, resulting in $IV_N = 0.15$ (Table 1). The Inner Value can change if some flows disappear, yielding a network as defined in Fig. 1c. In this case all variables are now giving $IV_N = 0.18$ (Table 1). This indicates that the disappearance of some flows may increase the inner value of the ecosystem. Another example is Chesapeake Bay network (Tilly 1968) flow model (Fig. 2) from which we estimated the same variables giving $IV_N = 0.12$ (Table 1). All data for these calculations are in Tables S1 and S2 (Perillo 2023).

Since we seek to assess the inner value of the system based on F_N, we consider that IV can be an adequate variable to assess the time evolution of the ecosystem. Nevertheless, we do not provide, at this stage, a criterion about what is the actual health of the ecosystem based on the

Table 1 Estimation of the inner value for the examples in Figs. 1 and 2

Ecosystem (Figure)	TST_N	H_N	T_0	F_N	IV_N
Cone Spring (Fig. 1B)	30191	0.67	4891.4	33477.8	0.15
Cone Spring (Fig. 1C)	26082	0.36	4891.4	27548.6	0.18
Chesapeake Bay (Fig. 2)	4812042	1.41	695371.3	5790986.7	0.12

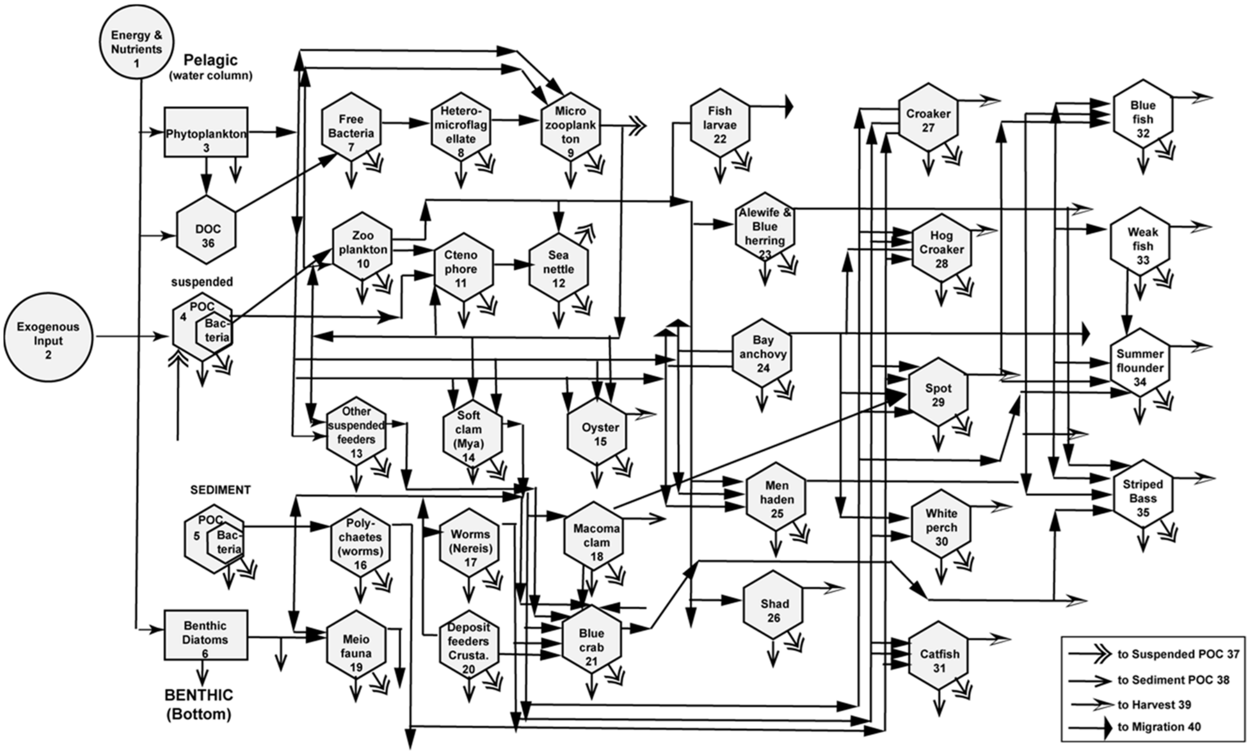

Fig. 2 Diagram of the carbon flows of mid-Chesapeake Bay ecosystem modified from Ulanowicz (2016). All values are in Table S2 (Perillo 2023)

IV. That will require the development of a model to be tested against ecosystems in different health stages.

However, we propose an ideal evolution (Fig. 3) in which the network starts to grow from an initial configuration. It increases its size and complexity until it reaches a final period t_e of expansion or a particular threshold is crossed that further growth is impossible. It then achieves a metastable state while still being subject

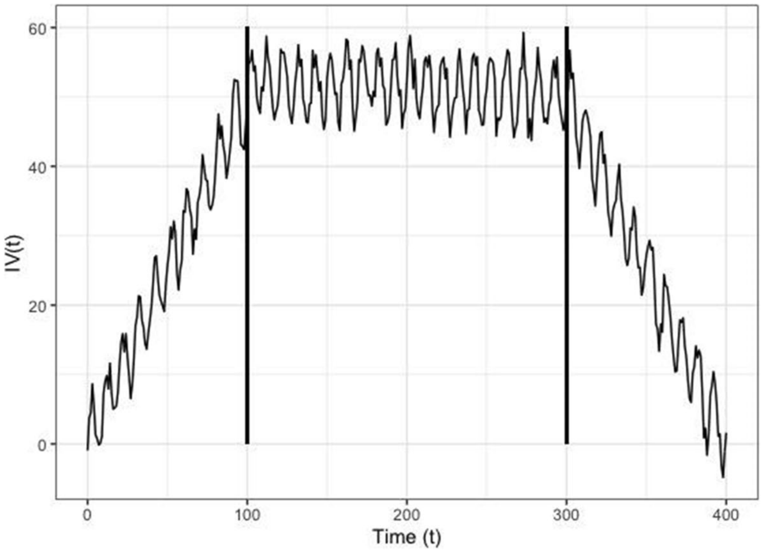

Fig. 3 Schematic, time evolution of a closed ecosystem having three stages: grow, meta stable and declining until disappearance, with both periodic and random variabilities. Each stage is constrained by a threshold value (t_e, t_d). Although this is an ideal complete evolution, an ecosystem may have different behaviours (i.e., never reaching t_d; continuous growth, etc.). The IV is well suited to monitor such evolution

to both seasonal (i.e., regular) and random fluctuations. At that stage, it remains at a plateau until, at some time t_d the internal interactions make it susceptible to destabilizing forces that lead to its decay and eventual disappearance. Its inner value changes accordingly. This behavior is usual in open systems, whose internal states minimize free energy (Friston 2012). Although for this ideal example, we considered a continuous evolution, we further assume that eliminating or adding taxa may produce jumps on the curve.

The notion of the Inner Value of an ecological network presented here is not the only measure that can be defined purely in terms of the internal flows of the network. For instance, Ulanowicz (2004) summarizes a line of research into this topic based on Information Theory, presenting the concept of Ascendency.

Ascendency gauges the performance of the ecological system in processing its inputs. Its formal expression is

$$A_N = \frac{AMI_N}{TST_N}$$

where AMI_N is the average mutual information of the system, relating the sources and the targets of flows, it measures how orderly and coherently the network flows are connected. The similarity between A_N and IV_N resides in the fact that both the former and F_N (the free energy of the network) yield a proportion of TST_N. Ecosystems tend to increase both magnitudes (Ulanowicz 2004).

However, perhaps more relevant are the differences between A_N and IV_N. The first one is that AMI_N is just the contribution to H_N arising from local interactions, disregarding the chain connections among different taxa along the network. On the other hand, while A_N yields an absolute measure, IV_N is defined in relative terms, facilitating the comparison among different systems.

Exergy (Bendoricchio and Jorgensen 1997) is an alternative that can be defined as

$$Ex_N = T_0(H_0 - H_N)$$

where H_0 measures the entropy of the ecosystem's environment; thus, Ex_N gauges how far the ecosystem is from achieving equilibrium. Then, in comparison with IV_N, it has some disadvantages. The first one is defining the organization of factors external to the ecosystem. Another drawback is that different networks can be compared only in terms of how far they are from their equilibrium states but not their capacity to do practical work.

5 Discussion and conclusions

Ecosystems have an efficient organizational structure in which every member (taxon) has a clear, definite role. To maintain an efficient structure, every taxon has an adequate amount of free energy balanced throughout the ecosystem. Changes, either periodic (i.e., blooms) or eventual, in a specific taxon rapidly trigger the response of dependent taxa in the trophic chain to keep the internal balance or move to a new equilibrium state. Valuing ecosystems services must be consider in, at least, a four-dimensional coordinate system: time, space (i.e., location, cultural), use, scarcity (Fig. 4). However, specialy use and scarcity, are variables that have a strong subjectivity related to who is (going) to use and in what moment the scarcity of the service is evaluated. Therefore, the concept of ecosystem service is difficult to employ due to the

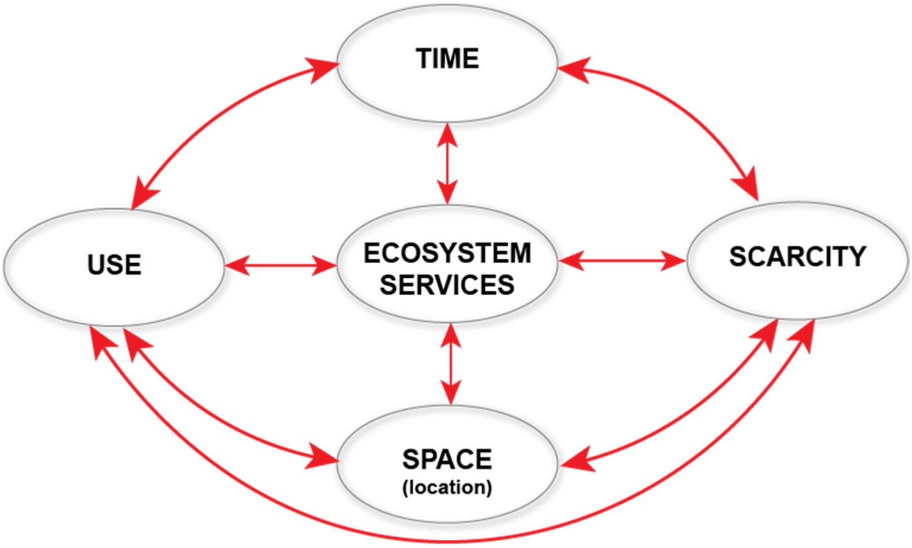

Fig. 4 The value of the services an ecosystem can provide depends on the relationships of a least four variables. Furthermore, the variables USE and SCARCITY are also function of time

different approaches that can be applied to the same ecosystem. The only thing they have in common is the use of a monetary number to define its value.

We then introduce a novel approach, different from those proposed previously, by applying the free energy concept to estimate the inner value. In this sense, we cover the whole energy spectra by considering both the total energy and its entropy. Maximizing the latter ensures that the ecosystem is in its most stable condition, whereas the total energy provides an integral estimation of the system's state.

When we analyze the ecosystem rationale, the system does not look for profit or benefit to humans but for its own survival and expansion. In the process, it tends to develop services that can help external actors to achieve their goals, which are picked up by traditional valuation methods imbued with subjective elements. Also, ecosystems tend to be inherently and internally efficient and, thus, achieve the maximum output towards sustainability and growth. Inefficient branches in ecosystems are eliminated, and the rest of the ecosystem absorbs their mass/energy. Inefficient branches receive more energy than the one they return, generating an unbalance in the energy exchange and accumulating more internal energy in the node. The lack of frequent inner evaluation of the whole system may preserve these inoperative branches that consume energy that is necessarily extracted from nodes that generate an energy surplus. Therefore, estimating its inner value allows for defining the status of the ecosystem. This rationale could contribute to prioritizing measures of biodiversity policy, promoting the formulation of initiatives aimed to discourage the protection of inefficient branches and enhancing those addressed to keep the balance in the energy exchange of the system. In terms of our approach, this implies giving priority to conservation to those ecosystems with a higher IV, fostering the development of the more efficient nodes.

On the other hand, if the Inner Value could be normalized and assessed across many different ecosystems, it may be possible to identify the status of the ecosystem in comparison with others similar. By analyzing its evolution through time (i.e., Fig. 3), this value may indicate the system's health and potential for growth or survival. Furthermore, the IV evolution could also indicate how the ecosystem behaves under some external stress. Establishing new metrics to evaluate the health of a particular system in a particular time and space will require the development of a model to be tested on ecosystems in different health stages, which constitutes a future line of research derived from this work.

The inner Value of an ecosystem could also be a necessary requirement for any Environmental Impact Assessment (EIA). By modeling the changes in the inner value by the impact of any disturbance on a specific taxon (or factor, in the EIA terminology) or even the whole ecosystem, one can appreciate the degree of resilience the ecosystem may have, and one could define the maximum level of disturbance the ecosystem can support and his capacity of response to such a disturbance. In this case, using the IV would allow to minimize or avoid the bias in the selection of EIA methodology, strongly impregnated with the analyst's subjectivity hitherto.

Modeling the inner value is also a factor when analyzing the services the ecosystem can provide and how much it can be extracted from it without crossing a threshold that may irreparably affect the ecosystem itself but also the service proper. As in many polluted or disappearing ecosystems, the previous modeling could have prevented exceeding the damage and saved the economic loss due to the lack of the service(s). Once again, this contribution could improve the accuracy of EIA methods, increasing the fine tuning in determining pollution thresholds disregarding subjectivity in the valuation process, which is extremely relevant (mainly) in the treatment of irreversible impacts.

Ecosystem services are a human-centered concept in which humanity receives some product (either cultural or commercial), or indirectly benefits from the ecosystem's regulatory functions. In pursuit of extracting the most benefits from the ecosystems, humans have directly exploited almost all ecosystems on our planet or even modified them to increase profits. As we propose measuring the inner value of an ecosystem, we pretend to contribute to elucidating the key question Armsworth et al. (2007) introduced: will we achieve greater conservation success by protecting nature for its own sake or for our own sake?

In the present study, we propose estimating the inner value of an ecosystem as a tool to be applied at different stages and specific conditions to evaluate its health. Before any exploitation or anthropic disturbance bound to affect the ecosystem. Estimating the initial value before any action is made provides the basal level upon which to compare the impact of the disturbances in the future, which is the core of the EIA. Furthermore, it can also be employed to model how different impacts, individually or acting simultaneously or sequentially, may have on the ecosystem. This could provide a clue to better allocate biodiversity policy resources, addressing the efforts to make those ecosystems more efficient regarding energy exchange.

Of course, while discussing natural ecosystems, any economic system (i.e., a company, industry, or business) can also be regarded as an ecosystem where the agents interact. Some of them must also have relationships with external influencers (i.e., buyers, providers, and competition). Doors inside, understanding the firm ecosystem in this frame, could maximize the efficiency in the flows of materials, human resources, and information, optimizing the exchanges among the wide variety of actors involved in the firm's operation and logistics. At the market level, competition could also be analyzed with the IV if each competitor is considered as a different node in a particular ecosystem. This application could contribute to analyzing the potential behavior of firms in more concentrated or more atomized markets, assessing possible responses and market strategies. The measure of Inner Value can also be applied to establish an economic system's efficiency level when disconnected from external influences.

The limitations of our proposal are the proper of a novel approach. While the IV is formulated for a closed system, including external influence could eventually become their calculation more complex. Moreover, the use of the IV as a measure of the health of an ecosystem still requires a deeper analysis at different stages of its life cycle, which remains out of the scope of this work.

In spite of this, the possibility to measure the value of an ecosystem (whatever it was) through the Inner Value opens the door to multiple applications in a wide range of ecological, environmental and even economic systems that certainly require an objective metric to assess its richness disregarding the value that humans could confer them. Adapting this framework to each particular case constitute an ongoing challenge in the study of the value of nature.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44218-024-00036-y.

Additional file 1.

Additional file 2.

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Authors' contributions

GMEP proposed the idea of the Inner Value and ecosystem analysis and co-wrote and reviewed the manuscript, MZ discussed the original idea, co-wrote and reviewed the manuscript, FT developed the formal definitions, co-wrote and reviewed the manuscript, MCP reviewed and contributed to the discussion and co-wrote the manuscript.

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Availability of data and materials

Data are already published and publicly available, with those items properly cited in this submission. It can be accessed at Perillo (2023) https://data.mendeley.com/datasets/3fxwnsf5xx/1 DOI: 10.17632/3fxwnsf5xx.2.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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