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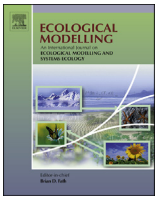

Cycling emergy: computing emergy in trophic networks

Lucía Zarbá*, Mark T. Brown

Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, FL, USA

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ABSTRACT

While cycles are a very important phenomena of ecosystems, they represent a methodological challenge in emergy accounting. The relevance of feedbacks is acknowledged in emergy evaluations, however they are not considered by the emergy algebra. In this paper, we present supporting arguments in favor of an update in the emergy accounting methodology. We argue that including the contribution of feedback emergy is essential to understand a system's internal functioning, thus studies interested in better capturing these features should consider emergy cycling. Feedbacks represent emergy that entered the system in the past (therefore it is not double counting), and they enable additional organization and work above that supported by input emergy alone.

To evaluate the effect upon system properties of including feedbacks, we compared two different methods for calculating transformities using trophic networks as case studies. One method followed the classic emergy rules where feedbacks were not included, and the other included the feedbacks (we refer to them as static and network method, respectively). The comparison between the resulting transformities and system emergy patterns showed that (1) transformities and system emergy were significantly higher with the network method, and (2) this increase affected the network compartments unevenly, altering their position in the emergy hierarchy. Estimating relative importance of the system's components or their true emergy requirements are only possible by evaluating the total emergy that flows through them.

1. Introduction

Ecosystems cycle energy and material through an intricate network of interactions between their components. The processes that result from these interactions are unique and define the conditions that support the ecosystem's biotic community and drive change. Although cycles are considered among the most important features of ecosystems they are often disregarded in the analysis due to methodological limitations (Allesina, 2009). Emergy theory is not an exception. Despite the recognition of cycles as an important system property, they represent a challenge for the mathematical basis of the accounting methodology.

In defining the emergy rules, Odum stated that feedbacks carry energy but not emergy (Odum, 1996) mainly to prevent double counting and avoid other technical difficulties. However this assumption has further implications for other system's properties. The fact that feedbacks have null influence over the transformity of the elements they flow into weakens the power of these flows in relation to the rest, altering the internal relationships, and masking the overall effect that cycles have upon the system.

These issues may or may not be of relevance depending on the type of question the researcher is trying to address. If the study attempts to estimate how much emergy a system needs to import in order to produce a product or service, then traditional emergy accounting is a good approach. But if the researcher aims to make inferences about the system's internal emergy dynamics, elucidate the brut emergy requirements of its different components, or understand the value of the system's structural configuration, then ignoring the cycles could lead to wrong conclusions. Several studies have already raised the issue that the emergy algebra does not allow a proper comprehension of the emergy dynamics of systems with recycling flows (Tilley, 1999, 2011a; Cohen, 2003; Cavalett and Ortega, 2007; Winfrey and Tilley, 2013).

In this paper we argue that cycling is a controversial point for Emergy theory that needs to be discussed and the limitations overcome. Especially if there are intentions to articulate Emergy with other systems ecology theories, for whom the underestimation of network cycling is a point that conflicts fundamentally with their approach (e.g. Ecological Network Analysis).

1.1. *Relevance of cycles for network ecology*

Below we introduce several cycling-dependent network analysis and ecological principles with the purpose of illustrating how

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* Corresponding author at: 100 Phelps Lab, P.O. Box 116350, Gainesville, FL 32611, USA. Tel.: +1 352 293 2429.
E-mail address: luciazarba@gmail.com (L. Zarbá).

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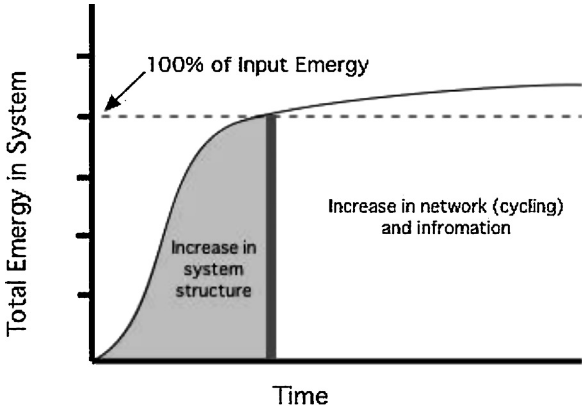

Fig. 1. Ecosystem growth and development (after Jørgensen et al., 2000). When the uptake of input emergy through primary production reaches its maximum (dashed line), the ecosystem can still grow by developing new network connections and recycling.

much cycles contribute to the study of ecological networks. Our intention is to provide supporting arguments in favor of an update of the emergy methodology to include the contribution of feedbacks.

Cycles are ultimately connections between components within the system, and as with all the other links, they carry not only energy (or the particular currency used in the model), but also information. Information arises from both the existence of the link itself, and the amount transferred. Measurements of network information are used by many interesting indices. One classic example, Ascendency (Ulanowicz, 1997) and the family of indices that derive from that concept, has been proposed by the author as one of the foundations of a central theory in ecology (Ulanowicz, 2003).

Cycling is a mechanism for expanding the available energy (and materials) supporting the system (Jørgensen et al., 2000; Fath et al., 2004). In early phases of development, ecosystems experience growth by increasing primary production, and then can continue to develop through an increase in network connections and cycling (Fig. 1). This is stated in the 9th and 10th principles proposed by Jørgensen (2009) as the basis for development of Fundamental Laws in Ecology. While some authors suggest that very different factors can induce an increase in cycling (e.g. disturbances, Baird and Ulanowicz, 1993), the ability of recycling to amplify ecosystem growth has not been questioned.

Indirect effects depend strongly on structural connectivity, and play an integral role in defining overall system functions (Fath and Patten, 1999; Fath and Halnes, 2007; Baird et al., 2009; Salas and Borrett, 2011). A metastudy conducted on 50 published trophic networks (Salas and Borrett, 2011) found that in 74% of them, indirect effects were higher than direct effects. Community-level relations that derive from indirect effects, such as mutualism (the preponderance of positive over negative or neutral relations) and amplification (when a same particle enters a component more than once), are therefore affected by the network recycling as well (Fath and Patten, 1999).

1.2. *Why static emergy algebra does not account for feedback emergy?*

There is no doubt that cycles and cybernetic influences were recognized by Odum and Emergy theory as major phenomena in ecological systems. However in terms of the emergy accounting rules (Odum, 1996; Brown and Herendeen, 1996; here referred as "static" emergy algebra), feedbacks are disregarded to avoid double counting. They do not contribute any emergy to the elements they are flowing into. We can think of four reasons that have led to the formulation of the emergy algebra in this way.

The first is the nature of the systems studied with distinct boundaries in both space and time, which resulted in a static computation of transformities. Complex systems were at first dissected into individual processes with distinct boundaries, under the assumption of steady state with no acknowledgment of dynamic properties of feedbacks (i.e. delays). Thus all flows in studied systems were simultaneous.

The second one is the result of the first, the issue of double counting. Steady-state simultaneity resulted in the problem of feedbacks adding emergy that was already accounted for.

The third one is amplification of the systems' emergy. Cycling recognizes the possibility of emergy circulating through the network circuits at a given time to be greater than the emergy entering the system, which is not coherent with the static emergy principles.

The last one refers to the nature of the formulation of the question. The question of "what is the external emergy driving a system?" is different from "what is the emergy moving through its circuits?". The former is focused on the imports and products (the overall contribution of the external drivers to the performance of the system given a particular structural configuration), internal cycling does not affect the answer, thus there is no need to unravel the emergy required by each component of the system.

1.3. *Including feedbacks does not contradict emergy theory*

Several authors have suggested that cycling should be computed in emergy accounting and very insightful ideas and arguments can be found in their work (Tilley, 1999, 2011b; Cohen, 2003; Brown, 2005; Cavalett and Ortega, 2007; Bastianoni et al., 2011; Winfrey and Tilley, 2013). In addition, recent advances in emergy theory and methodological tools are providing rich contributions that merit amending the emergy accounting rules. Development of the methodology for dynamic emergy accounting (DEA) and the principles that accompany it (Odum, 1996; Tilley, 2011b) have constructed a solid base to sustain the discussion about feedback emergy. It has also been demonstrated that including feedback emergy does not incur double counting (Bastianoni et al., 2011) and that cycling can coexist with the idea of hierarchy (Higashi et al., 1991). Further, it has been observed that the emergy flowing through a system can exceed the emergy crossing the boundaries at a given time (Cohen, 2003; Tilley, 2011a). Brown (2005) and Tilley (2011b) have proposed that emergy can be decomposed into partial emergies (emergy of the energy, the materials, and the information) with different attributes. Finally, new methods for calculating transformities have made it possible to compute them integrating the feedbacks in the process (Patterson, 1983; Odum and Collins, 2003; Bardi et al., 2005; Li et al., 2010).

According to the set theory perspective, there is no double counting by including the feedback's emergy contribution to a process (Bastianoni et al., 2011). The set of emergy that enters a system in one time step does not overlap with the set that enters the same system one time step later (or before). Furthermore, the same approach proposed for evaluating nested territorial systems (Morandi et al., 2013) could be applied in this case for the temporal dimension. In an appropriate (longer) time scale we can synthesize the emergy embodied in the structure and the emergy required for its function in a unified emergy budget, but in the shorter time scale they represent temporally independent emergy sources. In this sense it is a property of the system to be able to keep circulating energy that entered the system in the past, and do more work with it.

Hierarchy definition is challenged by the occurrence of cycles, but these concepts are not necessarily incompatible in theory. As was stated by Patten (1995) the ideas of Higashi et al. (1991) of