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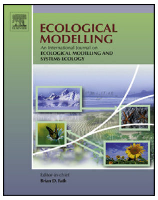

Cycling emergy. Computing emergy in trophic networks

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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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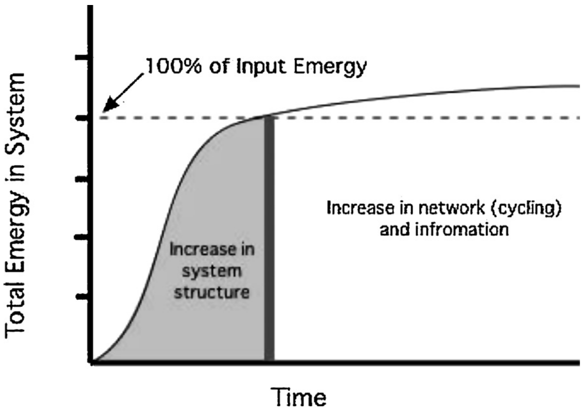

Fig. 1. Ecosystem growth and development (after Jørgensen et al., 2000). When the uptake of input emergy through primary production reaches its maximum (dashed line), the ecosystem can still grow by developing new network connections and recycling.

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

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representing intricate trophic networks as a sequence of transfer steps demonstrates how the hierarchical organization proposed by Odum has a solid mathematical support, even in networks with conspicuous cycling. Higashi's method compresses networks' elements to fit into a linear sequence without breaking their circular connections. Anticipating an answer to a frequent concern: the losses through dissipation and exports ensure the material does not keep looping indefinitely and the system eventually reaches steady state. The resulting trophic positions are analogous to transformity relationships. Although it may be impractical (almost impossible) to compute them by hand, it can easily be performed by methods for calculating transformities based on matrices or fully connected equations.

1.4. *What is the emergy of a recycling flow?*

Dynamic simulation methods employed by Cohen (2003) and Tilley (2011a) involve a distinction between different types of outflows with different attributes. Either called dispersal flow by Cohen (2003) or recyclable materials by Tilley (2011a), both suggest that while this feedback flow should carry emergy, it has different properties from the main process' outflow (called yield or product, by respective authors). In both cases the recycling flow was arbitrarily assigned the same transformity of the storage it was flowing into. Along the same lines, Brown (2005) proposed that the material being recycled in a process should carry the emergy it contributed in the first place. This raises an important question... Should the transformity of recycling flows be constrained to equal some predetermined quantity or should it be determined in some manner by the systems' cycling process? Answering this question exceeds the scope of this paper, but we strongly emphasize the need of continuing the discussion opened by these authors. Further development of the topic can be found in the discussion section.

In this study we analyzed the effects that acknowledging the emergy of feedback flows within the equation for calculating transformities have upon transformity values and empower of the different system components. We used two ecological systems taken from the literature as examples. In each of them we computed the transformities using two methods for comparison: a static accounting method and what we term a "network method". The static accounting method is more or less standard practice in computing emergy and transformities of products and processes, while the network method uses a matrix of flows to solve simultaneously the transformities of all flows, including feedbacks.

2. Methods

2.1. *Preparation of the data*

Two data sets taken from the literature were used to evaluate differences in emergy and transformities with and without feedback dynamics. The two systems were the trophic network of the estuary of Crystal River, Florida, adapted from Odum et al. (1977); and the trophic network of the freshwater graminoid marshes of the Everglades National Park (Ulanowicz et al., 2000; Heymans et al., 2002) available at http://www.cbl.umces.edu/~atlss/data_files/ (we used an average annual matrix computed as the arithmetic mean between the wet and dry season matrices). Hereafter the Crystal River and Everglades are called CR and EV respectively. Both are trophic networks, meaning that the links connecting the components represent feeding relationships, and they are all splits (there are no co-products in these examples). A system diagram of CR is shown in Fig. 2. We do not include a diagram of EV due to the size of the network. However, simplified versions of both systems are shown in Fig. 3. The units, originally expressed in biomass (milligrams of organic matter in CR, and grams of organic carbon in the EV), were converted into joules per square meter per year.

The external emergy sources were computed in CR as the summation of the emergy of sunlight (4.01E9 $\mathrm{seJ/m^2/yr}$), the Crystal River discharge (3.5E10 $\mathrm{seJ/m^2/yr}$), earth cycle/heat flow (2.19E9 $\mathrm{seJ/m^2/yr}$), and tides' kinetic emergy (4.0E10 $\mathrm{seJ/m^2/yr}$). In addition imports from the nearby marsh contributed detritus material equivalent to 4.39E10 $\mathrm{seJ/m^2/yr}$. In EV the driving emergy was estimated as the summation of rain chemical potential (3.42E10 $\mathrm{seJ/m^2/yr}$), run-in chemical potential (5.72E9 $\mathrm{seJ/m^2/yr}$), and the ground water inflow (1.35E9 $\mathrm{seJ/m^2/yr}$).

2.2. *Protocol followed*

For each system we calculated the transformities based on the static emergy algebra (static transformities) and the transformities including feedbacks (network transformities). Then we compared the differences in (1) the transformity values obtained with each method, and (2) the resultant empower distribution based on them.

2.2.1. *Static method*

The static transformities were calculated according to the classic emergy algebra procedure (Odum, 1996; Brown and Herendeen, 1996). The static transformity of a compartment *i* was computed as the sum of the emergy of all input flows (excluding feedbacks) multiplied by the storage turnover time divided by the energy of the storage:

$$\sum_{i}^{n} Em_{(u_i)} * TT_{(Q_i)} = Em_{(Q_i)} \tag{1}$$

and

$$Tr_{(Q_i)} = \frac{Em_{(Q_i)}}{En_{(Q_i)}} \tag{2}$$

where:

$Em_{(u_i)}$ = Emergy of input i

$TT_{(Q_i)}$ = Turnover time of storage Qi, computed as the storage energy divided by the sum of all input and output energy divided by 2.

$Em_{(Q_i)}$ = Emergy of storage Qi

$Tr_{(Q_i)}$ = Transformity of storage Qi

En_{Q_i} = Energy of storage Qi

To be disregarded, the links that represent a feedback first need to be identified. In CR the only cycle was the detritus recycle loop. The feedback links were identified by simple observation of the diagram. Due to the size of the EV network (66 compartments and 792 connections between them), identifying the feedbacks was not straightforward, especially considering on one hand that not every flow to detritus is precisely a feedback, and on the other hand, that there are feedbacks that don't involve detritus. The cycles were identified using an algorithm developed for that purpose through the software R (R Core Team, 2013). 120 links were removed, corresponding to those flowing toward a non-living compartment or, if not possible, the smallest link in the loop.

2.2.2. *The network method*

The network method follows the same procedure for calculating the transformity of Qi described for the static method (Eqs. (1) and (2)), with the only difference that the emergy input $Em_{(u_i)}$ includes the emergy of feedbacks. For this purpose, the network method

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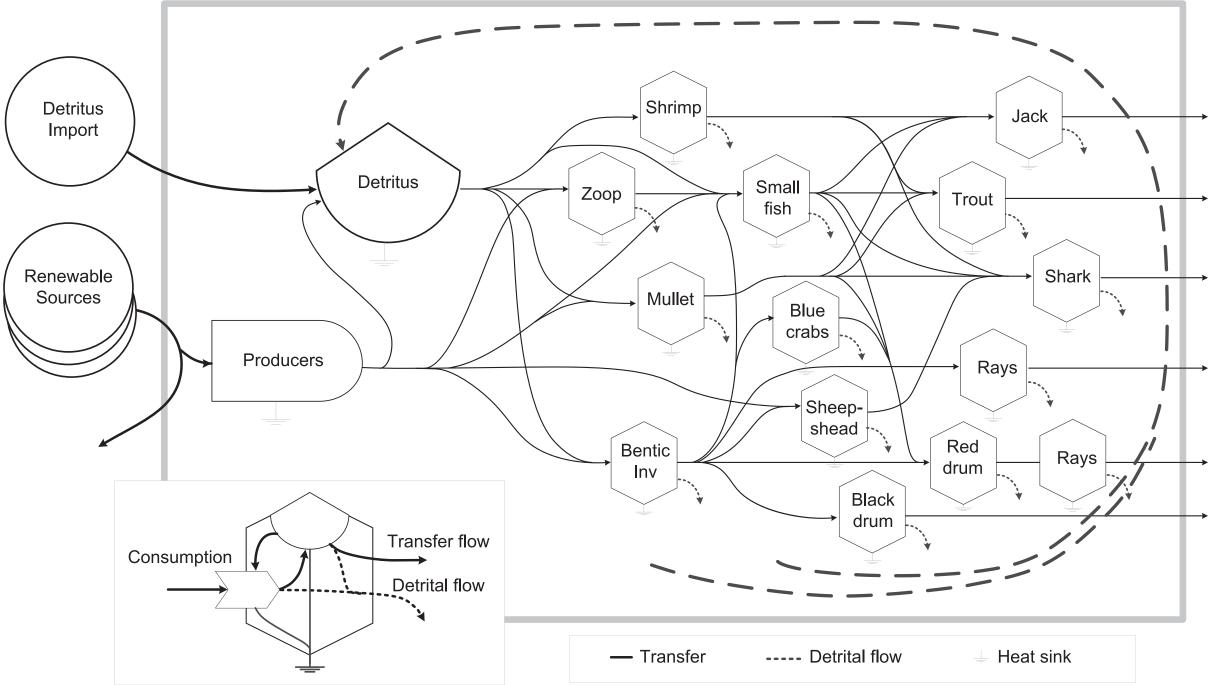

Fig. 2. System diagram of the trophic network of the estuary of Crystal River, Florida (after Odum et al., 1977). To avoid confusion, the detrital flows from each compartment are shown as short doted line. They actually are connected to the heavy detrital recycle pathway. Inset shows the details of input and outputs for each of the compartments.

incorporates an extra step at the beginning: calculating the equilibrium transformity of all flows in the diagram. For simplicity and network consistency purposes, no a priori assumptions were made about the transformity of the feedback flows. Their transformity was computed, as for all other flows in the network, based on the information in the diagram.

To compute the transformities of flows, we organized the data in a square matrix where the value in the cells represented the

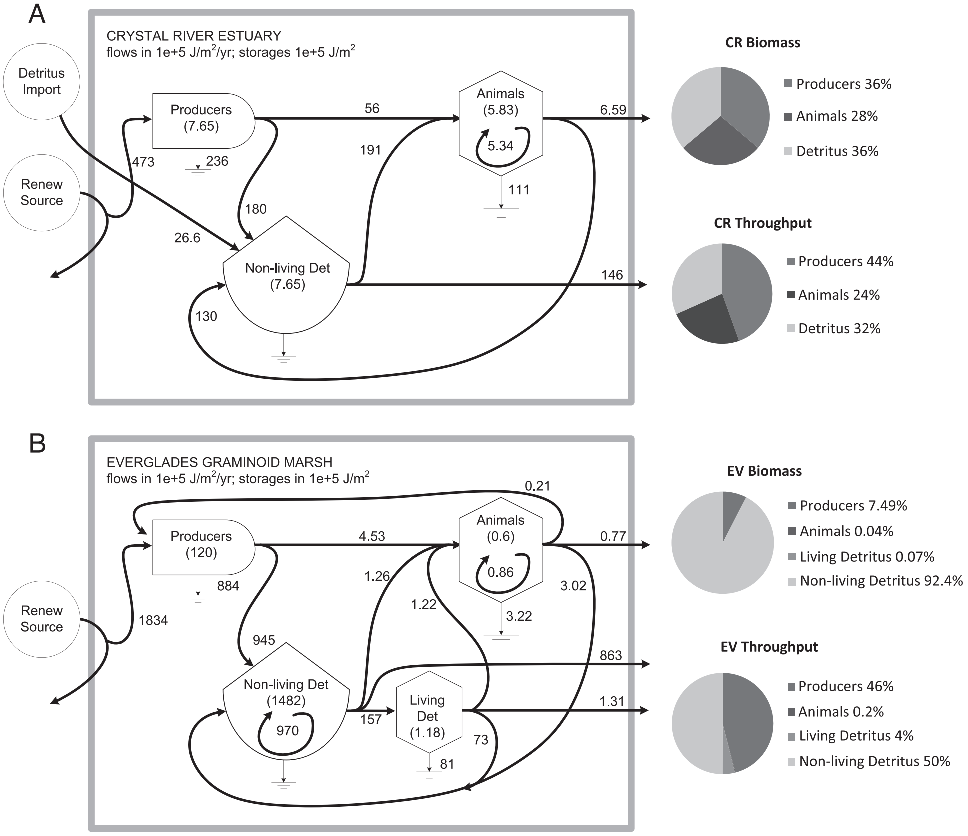

Fig. 3. Synthetic diagrams. Simplified versions of the system diagrams of CR (A) and EV (B) showing the major groups' biomass (number in brackets) and flows. The proportions of the major groups' biomasses and throughput within each system are shown in the pie charts on the right (CR top, EV bottom).

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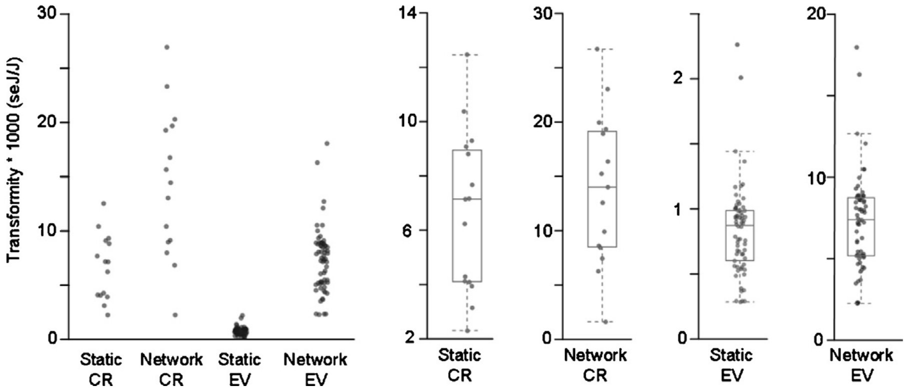

Fig. 4. Transformity values. Transformity values obtained through the network and static methods for EV and CR were plotted together (left graph) and separated fitting a more appropriate scale (right).

flow from the element in the column to the element in the row. The matrices also included the driving emergy sources. Then we computed the transformities following the minimum eigenvector method (Odum and Collins, 2003) performed in the software R, and the Microsoft Excel method (Bardi et al., 2005). The network-based methodology considers all the information in the matrix simultaneously, in an integral fashion. Since there is no fixed sequential order for solving the equations, the occurrence of feedbacks does not prejudice the performance of the operation, allowing feedback emergy flows to be accounted as inputs in the energy transformation equations. Although this method assumes steady state conditions, by adding the feedback information into the matrix, the temporal adjustments of the transformity values are “included” in the computational process. The logic of this procedure is in line with the principles of the Dynamic Emergy Accounting defined by Tilley (2011b).

Please note that the network transformities calculated in this way represent the transformity of the flowing material, which in some cases can be different from the transformity of the storages they come from (Odum and Collins, 2003). These transformities were multiplied by the energy of the respective flows, obtaining an “empower map”, used in turn, to calculate the transformity of storages following Eqs. (1) and (2). For comparison purposes, the transformities presented in the results section correspond to the storage transformities Tr_{Q_i}.

2.3. Considerations about the two systems

The assumptions and protocols followed during the data collection of each system are probably different since they were conducted by different researchers and for different projects. It is well known that the results of systems analysis are highly dependent on how the network is constructed (Baird et al., 2009). The level of aggregation is quite different between the two networks: EV is composed of 66 compartments (63 living and three non-living compartments) whereas the CR has 15 compartments (one of them is detritus, and the other 14 are living elements). The results of the analyses performed here should not be used to derive conclusions about the differences between the two ecosystems. The intention of this paper is to compare the methodologies for calculating transformities.

Either due to ecological properties or the protocol followed, there are some important differences between the two systems that are worth highlighting in order to contextualize the discussion of the effects that the network and static methods had on them. The relative distribution of biomass and flows between major functional groups are quite different between the two networks (Fig. 3). In terms of biomass, the EV network is highly dominated by detritus (more than 90% of the biomass was in the form of non-living detritus), although the amount of energy moving through it is roughly equal to the energy moving through the producers (49.9% and 46%, respectively). As a result of the dominance of the detritus, the 57 compartments of animals (all added together) represented a relatively minor percentage of total biomass in the Everglades network. The CR network shows a more even distribution. From the perspective of energy per m^2, the EV system supports almost 9 times more living biomass and has a higher through flow (3.76 times bigger) than CR. However, analyzing the same variables per compartment instead of area, compartments in CR have less biomass (17.51 times smaller mean biomass per compartment) but a higher through flow (7.08e + 6 $J/m^2/yr$ in CR, and 6.05e + 6 $J/m^2/yr$ in EV).

In addition to the size, the level of complexity is different between the two systems. With more than four times more compartments, the possible combinations of links between them are much greater in EV than in CR system. The pathways of flows through the EV are longer and less straightforward, they diverge and merge again several times and, perhaps the most relevant in this case, they develop more circular connections.

3. Results

3.1. Changes in transformity values

The two network-based procedures (i.e. the minimum eigenvector and the Microsoft Excel methods) returned the same transformity values, therefore we refer to them simply as the network transformities. The values obtained through the network method were higher than the values obtained through the static method (Fig. 4). The network mean transformity was 4.67 times bigger than the static mean in CR (1.43E + 04 and 3.06E + 03, respectively), and 8.67 times in the EV (7.30E + 03 and 8.42E + 02). The statistic analysis performed indicated that the differences between both methods were statistical significant (Student's paired T test for CR data: $t(14) = -7.65$, $p < 0.001$; Wilcoxon rank sum test for EV data: $V = 0$, $p < 0.001$).

The relationship between network and static values fit a linear model in both systems (CR: $r = 0.989$, $p < 0.001$, EV: $r = 0.990$, $p < 0.001$), indicating that the changes were proportional along the compartments of the network (Fig. 5a). Although looking at the differences, compartments of higher static transformities tended to experience a higher absolute increment (Fig. 5b). In addition, the EV data suggested a slight tendency for elements of higher static transformity to experience smaller percent changes (Fig. 5c). This pattern was supported also by the cumulative distributions of the transformity values (Fig. 5d), where the deviation of the

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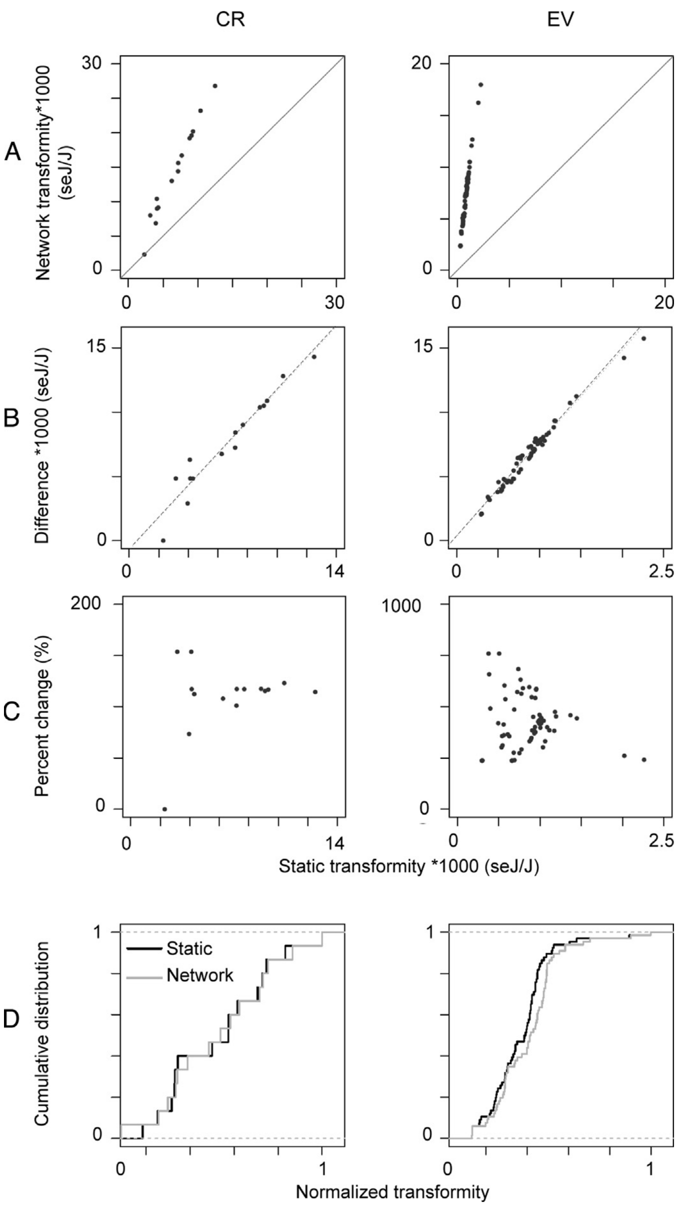

Fig. 5. Comparison of changes in transformity values. The left column corresponds to CR and the right column to EV. The rows from top to bottom are (a) correlation between the static and network methods, (b) absolute changes in transformity in relation to its static transformity value, (c) percent change in transformity in relation to its static transformity, and (d) a standardized cumulative distribution of the transformities.

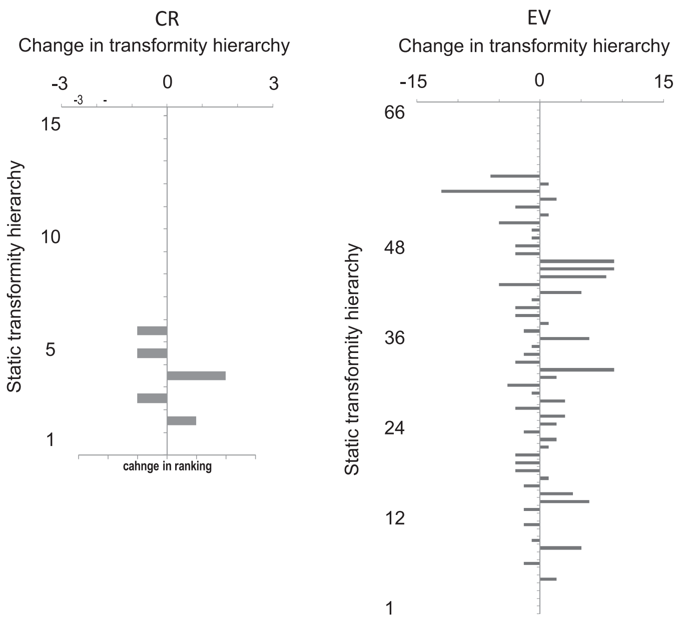

Fig. 6. Changes in hierarchy positions of components in CR (left) and EV (right) ecosystems. The *y* axis represent the hierarchical position based on static transformity (higher number indicates higher transformity). The bars represent the difference in number of position between the network compared to the static hierarchy.

network transformity distribution line toward the side of higher transformity (compared to the static distribution line) indicates that compartments with smaller transformities increased more in relation to the increase experienced by those of higher transformities. Although this difference is small in magnitude, it is in line with the idea that changes are not necessarily equivalent for all compartments, especially in systems of greater complexity. On the other hand, the percent changes and cumulative distribution of transformity values of CR show that the changes in that system were proportional, which is consistent with the simplicity of its structure.

The relative hierarchical position (as measured by transformity) of compartments in each of the ecosystems exhibited shifts (Fig. 6), even considering the changes in transformity were fairly proportional (as shown in Fig. 5). Shifts in hierarchical position in CR involved five compartments (33% of the total number of elements) moving one or two positions. Changes in EV involved 49 compartments (74% of the network), and while the majority of the elements moved less than five positions, others moved as much as 13. Compartments with highest static transformities did not experience shifts in their hierarchical positions, neither in EV or CR.

3.2. Changes in empower

The total system empower (summation of all the emergy flows exiting all compartments of the system) and the emergy of biomass per m^2 were almost double with the network method compared to the static method in CR, and were more than eight times bigger in EV (Table 1). However, not all compartments experienced equivalent increases. Comparison of the changes in emergy of the living compartments (all grouped together) versus the non-living compartments in both systems revealed that the non-living compartments experienced greater increments. For instance, in CR the emergy of living biomass increased by 68% as compared to an increase of 154% in the non-living detritus biomass. In EV the non-living compartments increased 9 fold while the living increased about 7 fold. Regarding the available emergy to support living compartments, the contribution of recycle generated a two fold increase in the emergy budget of both CR (static = 1.26E11 seJ/m^2/yr, network = 2.34E11 seJ/m^2/yr) and EV (static = 4.13E10 seJ/m^2/yr, network = 1.01E11 seJ/m^2/yr) systems.

4. Discussion

4.1. Static versus network transformities

Increases in transformity and empower are the expected result of acknowledging that there is more emergy input to each component than what the static methodology accounts for. While the network method reflects the total emergy used up by a compartment, the static methods shows only its requirements of imported emergy.

The fact that the effects were not uniform along the components of the network is, indeed, a crucial result. It suggests that besides

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Table 1
Changes in major groups' biomasses and throughput.

	CR			EV		
	Static (seJ/m^2/yr)	Network (seJ/m^2/yr)	% Change (%)	Static (seJ/m^2/yr)	Network (seJ/m^2/yr)	% Change (%)
Imports	1.26E+11	1.26E+11	0%	4.13E+10	4.13E+10	0%
Total System Throughput	2.70E+11	5.29E+11	96%	1.16E+11	1.13E+12	876%
Total System Biomass*	6.67E+09	1.33E+10	99%	5.95E+10	5.89E+11	891%
Living Compartments Throughput	1.64E+11	2.60E+11	58%	3.92E+10	3.92E+11	899%
Detritus Throughput	1.06E+11	2.69E+11	154%	7.65E+10	7.37E+11	863%
Living Compartments Biomass*	4.26E+09	7.16E+09	68%	3.68E+09	2.94E+10	699%
Detritus Biomass*	2.41E+09	6.11E+09	154%	5.58E+10	5.60E+11	904%

Imports, summation of all the emergy entering the system; total system throughput, summation of the emergy of all outputs of all compartments; biomass, summation of the emergy of all storages.

* Biomass units are seJ/m^2.

avoiding double counting, excluding feedbacks from the emergy algebra (as in static evaluations) alters the indirect relationships between the system's components, their hierarchical position, and ultimately changes the information content of the emergy network.

Transformity is considered a measure of energy quality, with potential to be used in trophic networks as an indicator of the expected importance of individual components (Odum, 1996). With alterations in trophic position that results from static versus network computation of emergy, shifts in importance of system components are unavoidable and likely of greater consequence the more interconnected a network. Indices such as the EOET (expected to observed emergy throughput; Brown et al., 2006) relates the deviation of a component's observed empower from its theoretical maximum empower and was postulated as an indicator of system condition. In order to provide a reliable representation, it is important that transformity values are computed based not only on the driving emergy sources, but emergy that is recycled. Only with network computation of emergy can system condition be evaluated in this manner. We are not advocating abandonment of static computations of transformities, but instead, offer these refinements as a way of providing needed insight into questions related to the role of cycling in emergy systems.

It needs mentioning, that emergy network accounting requires a significant quantity of detailed data on the material and energy flows of the larger system within which a component process is embedded. Therefore the method is only practical where this information exists and the general accounting method that treats components as static, steady-state components/processes is by necessity still very much a viable alternative.

4.2. The role of detritus

The asymmetry between changes exhibited by living versus non-living compartments observed in the results of this study make sense if we consider that almost all the links that were disregarded in the static calculation were inputs of detritus. Therefore detritus is the compartment that gets directly affected by the inclusion of the feedbacks, followed by the detritus feeders (who will receive the first level of indirect consequences), then elements that prey on detritus feeders, and so forth. The more an element depends on detritus, the more it is affected by the inclusion of the feedbacks.

It is interesting that higher transformity organisms did not exhibit changes in hierarchy. On one hand, the effect gets diluted by the time it reaches their trophic level, and on the other hand, their transformity is so much higher than the rest, that even when they suffered changes, they were not enough to get surpassed by others.

In food webs, two major classes of cycles can be identified: feeding cycles and non-feeding cycles. The most common, non-feeding cycles, refer to the recycle of nutrients and are mediated by detritus. Feeding cycles involve exclusively living components preying on each other. Feeding cycles are rare in trophic webs (because they are not captured by the level of resolution of most studies), whereas the number of non-feeding cycles is on the order of billions in highly resolved networks (Allesina, 2009). A previous study using the EV data found 24 billion non-feeding and 16 feeding cycles (Heymans et al., 2002). By definition, cycles have no end and no beginning and deciding which one of the several links forming a cycle is actually the one flowing "backwards" is a subjective designation based on the researchers' knowledge and the purpose of the model. In the case of detritus recycling loops, however, there is a generalized consensus in identifying the non-living components of the cycles as those responsible for the feedback. This may be an intuitive statement, but is coherent with changes in concentration and specificity of the materials. Decomposers take complex organic materials, and simplify them to be dispersed, and made available to a broad range of uses and users.

4.3. Open question: what is the emergy value of recycled materials?

In this study we did not make any a priori assumption nor did we constrain the transformity of feedbacks by any means. We recognize that it is essential that the value of feedbacks be discussed and a protocol defined. It may well be that a priori constraint of feedbacks is appealing for one reason or another, and the idea needs further discussion and analysis. We would like to encourage emergy researchers to embrace this endeavor.

In an earlier paper, Brown (2005) proposed that recycled materials carry the emergy of the material, and the emergy that was invested in upgrading the material (i.e. the emergy expended to give the material form) does not go with the recycled pathway. Thus depending on direction of flow (forward or backward) an output from the same component can have different emergy. Forward flows carry all the emergy required to make them, while backward (recycled) flows carry only the emergy of the material. Within ecological networks, this amounts to constraining the detrital flow (see inset in Fig. 3) to having the transformity of the material input flow, while the transformity of the transfer flow is dynamically computed. Or to say it another way, transfers between living components carry all the emergy required to make them, while transfers between living and non-living components are constrained to carry only the emergy of the input material. Thus forward transfers accumulate emergy while backward flows only carry it. Tilley (2011b) stated it this way… "Material that combines its emergy with emergy provided by an energy source will carry its emergy with it when it is removed from the product and cycled back to production processes in the upstream portion of the network. This implies that emergy is subtracted from the finished product at the point where the material is split from the product for recycling".

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4.4. Form information

Different from concentration, form information is not a property of a single component; rather it is an emergent property of the interaction between that element and the rest of the system. In this sense, form information is based on a trait of the element that makes it useful for another component of the system, and therefore there is a flow that connects them. We can consider that all flows are composed of the emergy in the material and the emergy of the form the material takes. The information content of a flow is that quantity which distinguishes its form from the emergy of the material. For instance, in the networks analyzed in this study, the currency on pathways was carbon, and while carbon is carbon, so to speak, the form of the carbon is important, and one measure of that information is transformity. Thus the form of carbon that is a top predator is different from the carbon that results from gross production, or the carbon in detritus. When the top predator dies, the dead predator no longer has the function (or form) it had when alive and therefore it loses the emergy of the form as it is recycled to the detritus pool. What this suggests is that the emergy of any object can be split, and as the object is transformed in a transformation process, the form and material emergy is "embodied" in the product, while only the material emergy is recycled to the detritus pool.

5. Conclusion

While emergy algebra, as originally conceived, did not considered feedback emergy to avoid double counting and other methodological complications, recent advances in the mathematical tools and principles of emergy algebra allow a reconsideration of these rules.

Studies interested in understanding internal processes and functions of whole systems should include emergy recycling. We argue that (1) feedbacks carry emergy that entered the system in the past and therefore it is not double counting to include them in the emergy accounting, (2) transformities should reflect all the information in the diagram, and (3) recycling is the expression of an important characteristic of system structure that cannot be captured through the static procedure.

In this paper we demonstrated that transformities calculated with and without feedbacks' contribution were significantly different, with implications on the relative importance of the network components as well as system-level variables. The combination of Dynamic Emergy Accounting logic with the minimum eigenvector method for estimating transformities appears to be a practical methodology that enhances the mathematical coherence of the system.

The emergy associated with a recycling flow is an important point to define. A promising line of inquiry has been suggested by Cohen (2003) and Tilley (2011b) from the standpoint of simulating dynamic emergy, and by Brown (2005) within a network framework.

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The present work of defining the emergy of recycle in trophic networks is part of an ongoing effort to investigate the opportunities and limitations of combining Emergy Theory with indices from the Ecological Network Analysis framework for quantifying ecosystem structure and function. Implications and theoretical aspects of the dynamic method benefited from deep discussions with the Systems Ecology and Ecological Engineering group at UF.

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