Ecological Modelling 220 (2009) 1893–1896

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Network calculations and ascendency based on eco-exergy

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ARTICLE INFO

Article history:
Available online 17 June 2009

Keywords:
Ascendency
Eco-exergy
Eco-exergy storage
Networks
Information
Kullbach's measure of information

ABSTRACT

Ascendency is an index of activity and organization in living systems calculated in terms of flows. The concern here is with how that quantity behaves when the flows in question are measured in terms of eco-exergy. The storage of eco-exergy has served as a goal function in assessing parameter values for structurally dynamic models, but network magnitudes and topologies can change in response to significant changes in the forcing functions. As storages are relatively insensitive to such changes, it is advisable in such cases to explore how changes in a flow variable, like ascendency, might capture network adaptations. It happens that changes in ascendency calculated in terms of flows of simple energy are small in comparison to corresponding variations in the storages of eco-exergy. But when ascendency is reckoned in terms of flows of eco-exergy, its changes in response to network changes are more comparable to those in the storages. Ascendency seems to be more sensitive to changes in flow topology, however, so that a combination of eco-exergy storage and eco-exergy ascendency would probably be most appropriate for situations where changes in flow topology are significant.

1. Introduction

Jørgensen et al. (2000) have shown that both the biomass and energy contents of components in a network increase along with the number of linkages between the components (See "growth of the network", Jørgensen et al., 2000.) Eco-exergy is calculated as *RTBK*, where *R* is the gas constant, *T* the absolute temperature, *B* the biomass and *K* Kullbach's measure of information (Jørgensen et al., 2000, 2004, 2005; Jørgensen, 2002). Because *K* tends to rise with the number of linkages, eco-exergy will tend to increase with link-density. A more developed, densely linked network provides more avenues for energy to be more fully utilized in the network. The power and the eco-exergy storage follow the same trends, in accordance with Jørgensen (2002), Fath et al. (2004) and Ulanowicz et al. (2006). If the loss of energy by respiration decreases with increased size of the organisms in the network (see Peters, 1983) or by increased information to better regulate efficiency of flows, the biomass, energy, eco-exergy, power and ascendency all will increase as well (see the three growth forms in Jørgensen et al., 2000; Jørgensen, 2002).

The calculations of the ascendency and the eco-exergy stored in a network have heretofore been based on energy, but it would be interesting to explore how these measures would change if they were calculated directly in terms of eco-exergy. Eco-exergy storage has been predicated as a goal function in structurally dynamic models, but because the network could change significantly in response to changes in the forcing functions, it might be necessary in such cases to consider ascendency as a goal function that might better be able to capture topological adaptations of the network. The contribution of ascendency to quantifying these differences has been relatively small, however, in relation to changes in eco-exergy, because the ascendency calculations have been based on straightforward energy. Thus, it might be worthwhile to investigate how much changes in networks contribute to differences in the eco-exergy based ascendency. Calculations of ascendency based on eco-exergy have, therefore, been carried out for comparison with corresponding energy-based calculations.

2. The calculations

The definition of exergy is shown graphically in Fig. 1 and that for eco-exergy in Fig. 2. Simply put, exergy is the capacity of the system to do work relative to its environment. As the environment of an ecosystem is likely another ecosystem, it may be more appropriate to formulate the eco-exergy in comparison with the ecosystem itself, but at thermodynamic equilibrium, when all work capacity and gradients have vanished. The eco-exergy would thereby measure how much the ecosystem has moved away from thermodynamic equilibrium. In this way it would represent the biomass and the information inherent in the many complex biochemical compounds of the ecosystem (see Jørgensen, 2002; Jørgensen et al., 2004, 2005, 2007). Ascendency jointly represents the activity of

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doi:10.1016/j.ecolmodel.2009.04.032

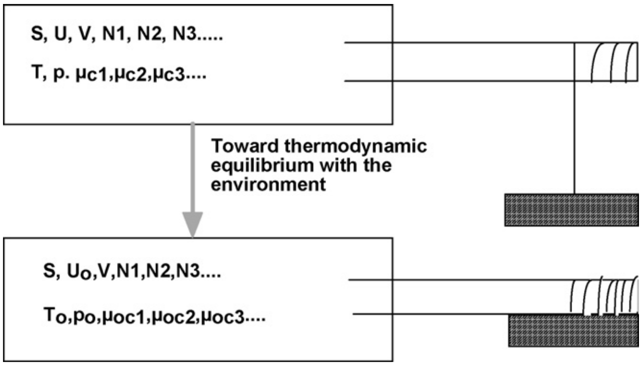


Fig. 1. Definition of exergy.

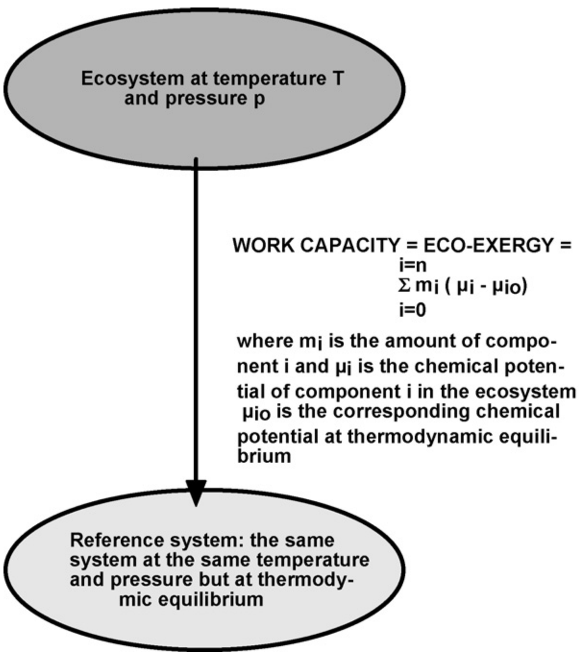


Fig. 2. Definition of eco-exergy.

the system and the information inherent in the network structure. Its definition is shown in Fig. 3.

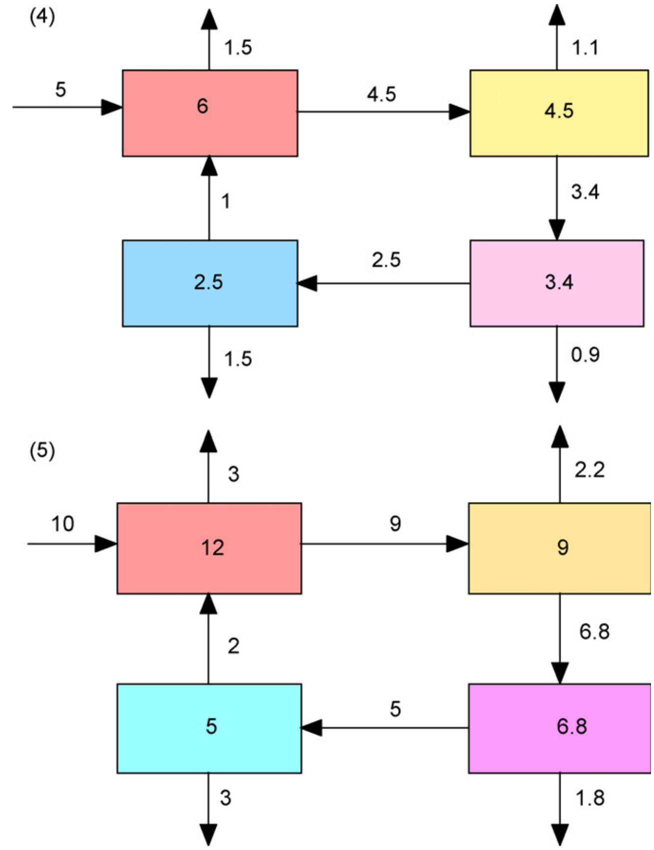
To facilitate the comparison, the four steady-state networks that were used in Jørgensen et al. (2000) as illustrations of the three growth forms (see also Jørgensen, 2002; Jørgensen and Svirezhev, 2004; Fath et al., 2004), have also been used in this exercise. Fig. 4 shows a four-component network with prominent cycling of energy. In all, the network is able to capture 5 units of energy, and the flows are donor regulated with a coefficient of 0.8. Of course, the sum of the outputs (1.5 + 1.5 + 1.1 + 0.9) equals the input (5.0), because the system is at steady state. The outputs represent the energy used for maintenance (respiration). The network in Fig. 5 captures twice as much energy (10 units). All the numbers in Fig. 5 are double their counterparts in Fig. 4.

In more quantitative terms, the formula for ascendency is:

$$A = \sum_{i,j} T_{ij} \log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right)$$

T_{ij} is the flow from compartment i to compartment j. T_i compartment i and T_j is compartment j. T is the sum of all flows.

Fig. 3. Definition of ascendency.



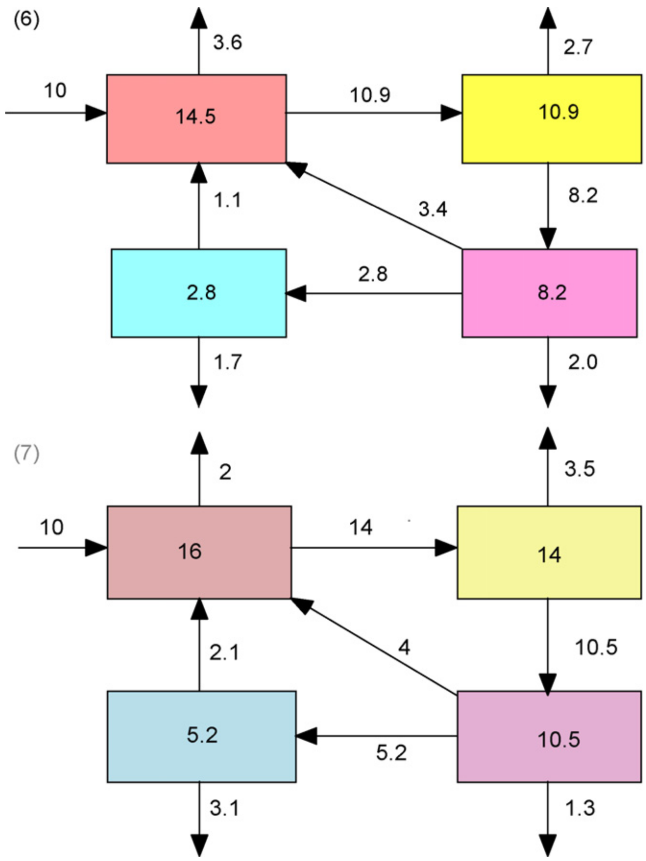
Figs. 4 and 5. The input to the network is twice as much in Fig. 5 than in Fig. 4.

Fig. 6 represents the network growth. An energy transfer from component 3 back to component 1 has been added, and the additional linkage implies that the energy storage increases relative to that in Fig. 5. Fig. 7 represents how a growth in the information stored in the system might affect flows. It has a relatively smaller respiration. Both the eco-exergy stored in the network and the ascendency should increase in Fig. 7 relative to Fig. 6. In the last three networks Figs. 5–7 have been repeated, only now eco-exergy has become the medium of storage and transfer. The eco-exergy is calculated as Biomass × β, where $\beta = RTK$ has been normalized so as to express eco-exergy in detritus equivalents. (That is, $\beta = 1.0$ for detritus [dead organic matter].) A list of values of β for different organisms has been published in Jørgensen et al. (2005). We will presume that all the networks in Figs. 4–7 represent aquatic ecosystems, wherein the first component is phytoplankton ($\beta = 20$), the second components is zooplankton ($\beta = 100$), the third component is fish ($\beta = 500$), and the fourth component is detritus ($\beta = 1.0$). Fig. 5 thereby is translated into Fig. 8, Fig. 6 into Fig. 9 and Fig. 7 into Fig. 10.

The energy or eco-exergy storage, the energy and eco-exergy ascendency and the energy and eco-exergy power have all been calculated for the seven Figs. 4–10, and the results are listed in Table 1.

3. Discussion

Perhaps not surprisingly, the results demonstrate that it is necessary to calculate the eco-exergy based ascendency, if one wishes to compare it with the eco-exergy storage. Then the eco-exergy storage and the eco-exergy ascendency will become comparable. The results further reveal that there are some differences between how the storage and the ascendency portray network topologies.



Figs. 6 and 7. In the first figure is added an extra flow from component 3 to 1. The last figure represents a growth in information corresponding to lower respiration rates.

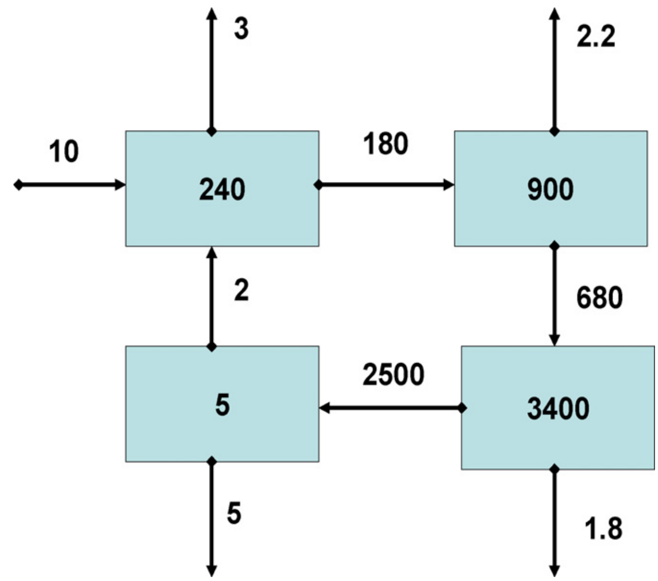


Fig. 8. Same network as in Fig. 5, but eco-exergy is calculated instead of energy.

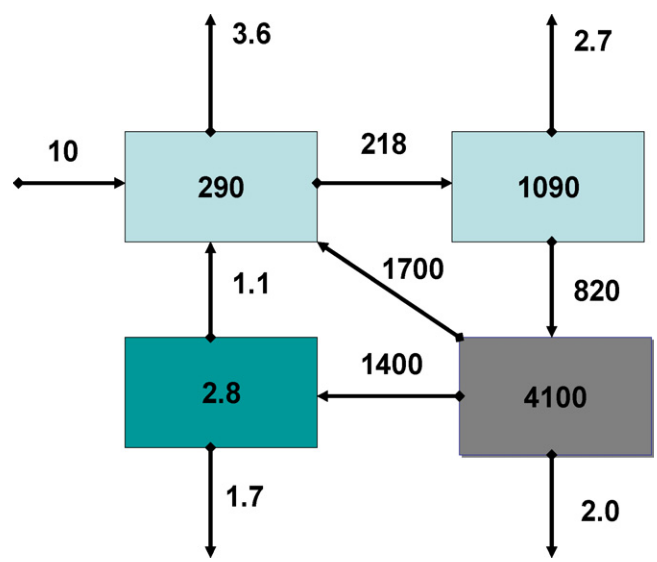


Fig. 9. Same network as in Fig. 6, but eco-exergy is calculated instead of energy.

Some function of both storage and ascendency might then serve to account for the full spectrum of network changes. The percentage changes in the storage, ascendency and power are portrayed in Table 2. (The percentage increase from Figs. 4 to 5 is not included, because it is merely a doubling of all flows, exergy storage, ascendency and power.)

The eco-exergy storage increases significantly more than does simple energy −20.8% versus 9.1%—when an extra transfer is inserted from components three to one. The reason behind the enhanced increase is that the increased cycling afforded by the new pathways is utilized mostly by the higher components in the food chain, and they all have a higher β-value. The result accords with the network rules reported by Jørgensen and Fath (2006). The eco-exergy storage increases 25.5% from Figs. 9 to 10 because of additional information in the system, which also serves to reduce community respiration. This increase mirrors that for energy from Figs. 6 to 7. That energy is diverted from respiration means that more energy or eco-exergy becomes available for the intercompartmental flows, which explains why the increase in power occasioned by this change in the network (Figs. 6 to 7 and Figs. 9 to 10) is greater than those in either the energy or stored eco-exergy.

It is interesting that there is a drop in ascendancy from the network in Fig. 5 (69.29) to that in Fig. 6 (65.13). The reason for the drop is that the new flow from 3 to 1 adds ambiguity to the network. Notice that ascendancy is *not* simply proportional to the total system throughput.

The very idea behind ascendency is to modify the total system throughput to quantify how well-organized (definitive) flow in the system is.

Table 1

Figure	Energy or eco-exergy storage	Energy or eco-exergy ascendency	Energy or eco-exergy power
Fig. 4	16.4	34.65	11.4
Fig. 5	32.8	69.29	22.8
Fig. 6	36.4	65.10	26.4
Fig. 7	45.7	86.92	35.8
Fig. 8	4545	3553	3362
Fig. 9	5483	4168	4139
Fig. 10	6975	4666	5932

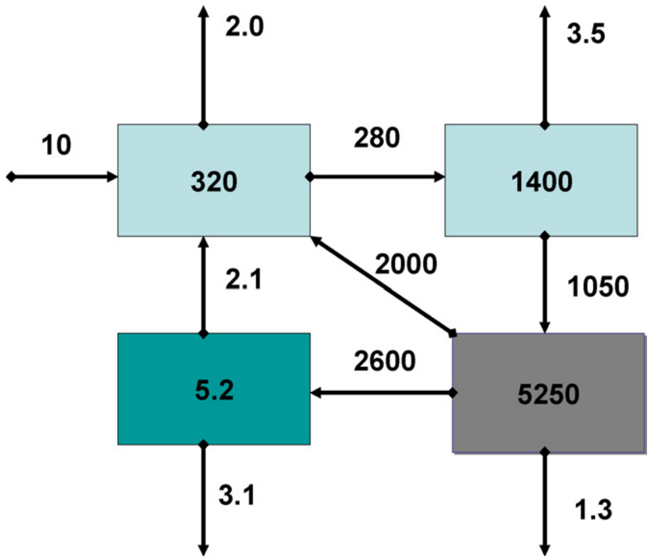


Fig. 10. Same network as in Fig. 7, but eco-exergy is calculated instead of energy.

Table 2
Increases in energy or eco-exergy storage, ascendency and power.

From figure to figure	Storage	Ascendency	Power
Figs. 5 to 6	9.1%	−6.0%	15.5
Figs. 6 to 7	25.5%	33.5%	32.2
Figs. 8 to 9	20.8%	17.3%	23.1%
Figs. 9 to 10	25.5%	12.0%	43.3%
Figs. 5 to 7	39.6%	27.1%	57.5%
Figs. 8 to 10	53.4%	31.3%	46.6%

Now, returning to Figs. 5 and 6, we notice that flow in Fig. 5 is not very ambiguous. In particular, if one is in compartment 3, the only other compartment to which quanta can flow is to compartment 4. (Of course, it could also leave the system as export.) In Fig. 6, by contrast, if a quantum is in compartment 3, there is some uncertainty as to whether it will flow to 4 or to 1. This lowers the ascendency, even though there is more total flow in 6 than in 5.

It is important to notice how each flow generates one and only one term in the formula for ascendency. In particular, the contribution of T_{31i} in Fig. 6 to the ascendency is:

$$A_{31} = T_{31} \log \left(\frac{T_{31} T_{..}}{T_{3.} T_{.1}} \right),$$

or

$$A_{31} = 3.4 \log \left(\frac{3.4 \times 46.4}{8.2 \times 14.5} \right) = 3.4 \log(1.327) = 1.388$$

That is, T_{31} contributes proportionately less than its magnitude to the ascendency.

T_{34} (=2.8) contributes 7.001 to the ascendency. So the total of T_{31} and T_{34} in Fig. 6 is 8.389. Contrast this to the amount that T_{34} in Fig. 5 contributes (=13.27), and the shortfall in Fig. 6 becomes apparent.

4. Conclusions

Calculations of eco-exergy storage, ascendency and power show that they generally follow the same trends when changes are made to the network, except that the energy-based ascendency does not increase as strongly when an extra connections are added. That is, although storage and power increase, ascendency decreases, because the addition of the extra flow contributes to the ambiguity where medium is flowing in the network.

The eco-exergy based ascendencies and powers are significantly higher than the energy-based ones. If one's purpose is to quantify the full consequences of changing a network, as it is, for instance, in evaluating the parameters of a structurally dynamic model, it would therefore appear advantageous to use some combination of the changes in eco-exergy and in eco-exergy ascendency as the goal function in lieu of only the eco-exergy. As ascendency is a flow variable and differs in units from the eco-exergy storage by a factor of 1/time, an appropriate combination might be to divide the eco-exergy by the system throughput time and add the result to the eco-exergy ascendency. Heretofore, using the eco-exergy storage as goal function in structurally dynamic modelling, has been highly successful in all of the 18 case studies that have been attempted. All such case studies have, however, involved changes in the properties of the key species, and it is possible that major changes in network topology could be more adequately addressed by using as a goal function the combination of eco-exergy storage and eco-exergy based ascendency just described.

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