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# Quantifying economic and ecological sustainability

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ABSTRACT

Sustainability is an important concept currently at the forefront of many policy agendas. Yet, the science of sustainability is still inchoate: What does it means for a system to be sustainable? What are the features of sustainable systems and how can they be quantified? The systems we deal with – ecological, economic, social, and integrated – are complex and operate by maintaining functional gradients away from equilibrium. While there are basic requirements regarding availability of input and output boundary flows and sinks, sustainability is centrally a feature of system configuration. A system must provide a basis of positionally-balancing, wholeness-enhancing centers of activity. One aspect of this system balance is between efficiency and redundancy which can be measured in ecological and economic systems using information-based network analysis. Specifically, the robustness indicator as developed by Robert Ulanowicz and colleagues offers deep insight into the structure and function of these self-sustaining autocatalytic configurations (through constant flows of energy and matter). In this paper, I overview these concepts and methods and provide examples from economic and ecological systems and discuss the meaning of the differences in outcome.

> Nature is perpetually renewed because the absolute causality constituted by the Dao never becomes immobilized in any one disposition, it remains forever inexhaustible.
>
> – Francois Jullien in *Propensity of Things* (1995)

## 1. Introduction

### 1.1. System sustainability: becoming not being

It is important that we think of sustainability as a continuous process not as a static state of the system. In the field of sustainability, an oft cited definition is the one given in *Our Common Future* by the United Nations World Commission on Environment and Development, also known as the Brundtland Commission (1987), which states, "Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs." This policy-oriented approach has great value due to both its simplicity and its ambiguity. This allowed for a general consensus to emerge that, yes; sustainable development is a good thing. In particular, note the contentious aspects are all packed in to the innocuous and vague sounding word "needs". Who defines our needs? Who defines the needs for future generations? By not addressing these personal and societal choices, this definition avoided the issue of scale necessary on a finite planet. Furthermore, the concept as expressed by the Brundtland Commission is explicitly anthropocentric. It refers to how humans manage the built environment in terms of the ubiquitous social, economic, and ecological triumvirate (triple bottom line). While this approach has great value in certain applications, it does not answer the deeper question of what makes a system sustainable or not. Therefore, I find it useful to always qualify the Brundtland definition, as originally intended, as *sustainable development*, not as sustainability (Box 1). Sustainability is a broader, more foundational concept that can and must be explored independently of human actions, intentions, and aspirations. It deals with the workings of a system, any system, and the features it possess in order to endure. It is strictly not an anthropocentric concept, but understanding it generally should help inform our application of it to socio-ecological systems.

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**Box 1**
Sustainable Development and Sustainability are NOT the same and should not be confused.

**Sustainable Development**: "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" — *Our Common Future*/Brundtland Report, 1987

**Sustainability**: a system's capacity to endure and maintain vital functions.

Sustainability is a holistic property of a system's capacity to maintain processes and *arrangements* to allow and support the continuation of those processes. Key structural aspects include:

- ► *organization, configuration, disposition, …*

These terms represent the construction of gradients that have purpose, not in a teleological sense, but that the configurations have the dual role of both being structural and that from which further function is possible. In Eastern philosophy, this idea is captured in the notion of 'Shi' which "consists in organizing circumstances in such a way as to derive [benefit] from them" (Jullien, 1995). From these structures, the sustaining functions emerge naturally and readily, working with the flow generated by the gradients. In this context, 'sustaining functions' refers to coupled–recursive actions where the process reinforces the structure and vice versa. This is a key feature of autocatalysis described further below. Generally speaking ecologically, the producer–consumer loop, soil formation, and chemical balance are key illustrations. In coastal ecosystems, one example is maintenance of seagrass beds which stabilize the substrate, provide food and habitat, and coastal protection (Barbier et al., 2011). These benefits are derived in the process of being organized as they are not explicitly designed to perform them. Sustaining functions occur whenever a circumstance arises in which a process that utilizes the available gradient does so in a way that builds or maintains structure for further gradients. In other words, the gradient has the propensity or tendency for further action. Then, in that process, some function is used to renew the gradients. Keep in mind that the systems in question are open thermodynamic systems and therefore depend on a constant and replenishable source of energy (Fig. 1). It is effective by virtue of its renewability; and in contrast, loses its potentiality when it becomes *inflexible* (or static).

Another aspect of sustainable systems is the holistic and self-supporting internal and external interactions that bind the configurations. For example, a useful distinction was made by Fiscus et al. (2012) between 'discrete life' and 'sustained life'. Discrete life is what most biology textbooks focus on—a living organism (from single to multi-cellular), which, during a specific period of time, is alive. While a single organism may possess all necessary aspects to be considered to be alive, it is not sufficient to sustain life. It holds an obligate environmental dependency for all abiotic and ecological interactions. The organism cannot persist in isolation, needing supporting and interactive external flows. Here, the textbooks are clear that an organism along with its biotic and abiotic defines an ecosystem. Therefore, it is at the ecosystem scale that possesses all necessary aspects to sustain life obligatory (Keller and Botkin, 2008). In fact, the life–environment interactions permeate so fully that on a living planet, the very notion of abiota loses its meaning. Life conditions the environmental factors that we typically associate with abiota such as temperature (both local and global), humidity, soil moisture and percolation rates, stream flow, ocean salinity, nutrients concentration, etc. A more apt term would be *conbiota*—the 'physical' environment only makes sense as expressed *with life*. This gives an important clue into the features of sustainable systems.

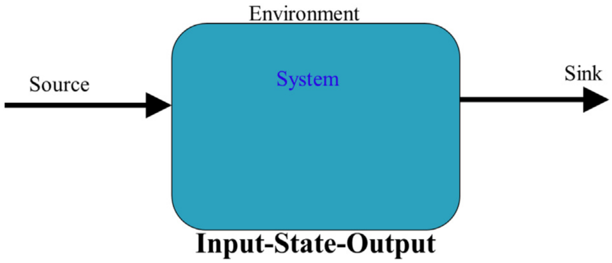

**Fig. 1.** Representation of an open system receiving inputs and generating outputs to and from an external environment.

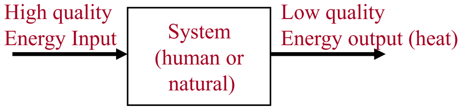

**Fig. 2.** Thermodynamic systems receive high quality input and discard low quality output.

### 1.2. Necessary and sufficient conditions of sustainability

Open systems connect to their environment through both inputs and outputs. The configurations referred to above are possible only in the presence of an external energy gradient which can be tapped, utilized, and ultimately degraded. It is through this constant input—taking in high-quality, low-entropy energy—and passing degraded waste energy outside that living, sustaining systems are able to build and maintain order and organization (Fig. 2). Therefore, when we consider sustainability, a first principle is to consider these basic input and output constraints. A system must have *input availability* and *output absorbance* capabilities. These mirror Daly and Townsend's (1993) sustainability requirements and should be the universal first consideration regarding the sustainability of a system (see Fig. 3). We can formalize this in mathematical terms using propositional logic of necessary and sufficient conditions (Box 2).

Building within this framework, we can posit, "What are the necessary and sufficient conditions of sustainability?" I offer the proposition that meeting Input–Output requirements are necessary but not sufficient conditions for sustainability. For ecosystems, the input constraints are fundamentally energy and matter flows that manifest themselves in terms of solar radiation, global carbon cycle, rate of nutrient cycling, rate of hydrological cycle, etc. The ability of the environment to accept the system output is constrained by the rate of decomposition, the rate of accumulation of unwanted by-products, and the synergistic couplings that allow material reuse (finding others to take your waste). The adjacent system (environment) receiving the output must be at a lower

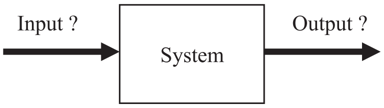

**Fig. 3.** Sustainability of the system depends on the continuation of the input and output flows.

**Box 2**
Necessary and sufficient conditions

- ***necessary*** condition of a statement must be satisfied for the statement to be true
  - *P* is necessary for *Q* is equivalent to "*Q* cannot be true unless *P* is true," or "if P is false then *Q* is false"
- ***sufficient*** condition is one that, if satisfied, assures the statement's truth
  - If *P* is sufficient for *Q*, then knowing *P* to be true is adequate grounds to conclude that *Q* is true

gradient than the system generating them. These Input–Output constraints taken together, however necessary, are not sufficient because it is also necessary for the continual renewal (persistence) of the configurations that emerge out of these flow gradients. Therefore, we must seek answers not only in terms of the external flows, but also to the internal system dynamics. Or, in the words of insightful systems thinker, Jane Jacobs, "an ecosystem can be thought of as a conduit through which energy passes, with many or few transformations of energy matter during its trip through the conduit. The interesting question is what happens in the conduit" (Jacobs, 2000, p.46).

Here, we can turn to properties of complex adaptive systems such as autocatalysis and self-organization. Autocatalysis is a system function in which the action of each participating member facilitates the next (Fig. 4). Note, our Western worldview, implies discrete objectification, A, B, C, etc., but in order to highlight the point about integration and interdependence of the components in an autocatalytic cycle we can refer to them not as separate components, A, B, C, etc., but rather as A′, A″, A‴, etc. representing different stages of the same overall phenomena. In either case, whether one considers more an object-oriented or process-oriented perspective, the essential feature here is the recursive and reinforcing coupling among the system compartments. This classic positive feedback loop amplifies small asymmetries, moving the system further from its initial position as seen in examples in ecology (Ulanowicz, 1995) and society (Luhmann, 1995; Marion, 1999). In terms of thermodynamic gradients, one can say that the new configuration is moved further from equilibrium. Sustaining systems possess a configuration of autocatalytic processes – coupled and overlapping at different scales. This self-organization function, allows systems to pull toward greater activity and tighter organization countering the inevitable entropic drift toward disorder. This brings us to the key question, which is how can we measure this degree of self-organization one observes in natural systems (Odum, 1988, Kauffman, 1993). One place to start is to track the changes that occur during succession, and EP Odum (1969) provided a good place to start with his seminal paper that identified some trends to be expected in ecosystem growth and development. These metrics indicate the direction of change from early stages to later stages and therefore implicitly contain information about the increase in ecological complexity that innately occurs during these stages. Much research has revolved around the issue of identifying these ecological goal functions (e.g., see Müller and Leupelt, 1998; Fath et al., 2001) that can track this development. One approach to quantify ecosystem growth and development specifically employs network analysis such that the ecosystems are portrayed as networks of material or energy flows such as food webs or nutrient exchanges (Ulanowicz, 1986; Fath et al., 2004). In the next section, details of one method are provided.

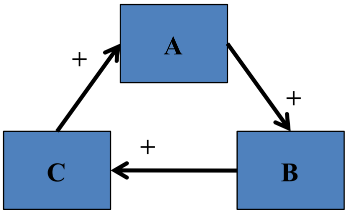

**Fig. 4.** An example of an autocatalytic process in which each compartment promotes the activity of the next in a closed loop positive feedback.

## 2. [Eco]system growth and development

Growth and development represent the two supporting aspects of [eco]system dynamics.[1] As stated above, systems are portrayed as networks of material or energy exchanges using network analysis. **Growth** is a quantitative change in a system property as measured by an extensive variable such as total system throughput, which is the sum of all exchanges within the system and between the system and its outside (imports, exports). **Development** is a qualitative change in the system as measured by an intensive variable such as information or network connectivity or cycling. As in physics, the total capacity of some feature is the combination of how much and what quality, an extensive variable times an intensive variable. Building off the work of Rutledge et al. (1976), Ulanowicz (1986) introduced a branch of information theory into ecosystem investigations. The foundational premise is that information can be defined as a reduction in uncertainty. In a network, the available pathways and knowledge of the observed flow linkages constrain the possible outcomes (the *adjacent possible* in Stuart Kauffman's (2000) terms), thus providing the reduction in uncertainty that leads to quantifiable information content. Note, only the basics of the mathematics are repeated here as many sources are available with more complete rendering (e.g., Ulanowicz, 2001; Scharler, 2008; Ulanowicz et al., 2009; Kharrazi et al., 2013).

According to Boltzmann (1905), the potential of each configuration contributing to system's complexity is given by:

$$s = -K \log p(a_i) \tag{1}$$

where $K$ is a scaling constant and $p(a_i)$ is the probability of event $a_i$ occurring. Therefore, the information is the *a priori* potential minus the uncertainty if $b_j$ is known. Combining these and using conditional probability, we arrive at an equation for the information:

$$I = -K \log p(a_i) - \left[ -k \log p\left(a_i \middle| b_j\right) \right] \tag{2}$$

Deriving the probability from network flows, gives:

$$p(a_i) = \left(\frac{T_{ij}}{T_{..}}\right)$$

where $T_{ij}$ is the quantity of flow from compartment $i$ to compartment $j$. This allows us to apply Shannon (1948) index ($p$ log ($p$)) to arrive at a measure of flow diversity:

$$H = -k \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log\left(\frac{T_{ij}}{T_{..}}\right) \tag{3}$$

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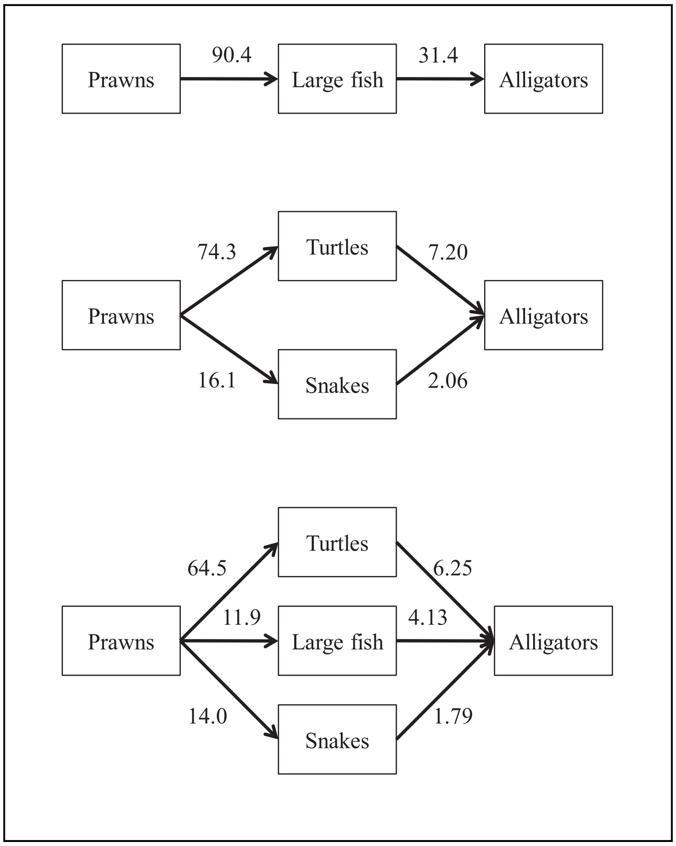
[1] Eco is presented in [] under the implication that these ideas, although originating in the ecological literature, are applicable to all systems, *sensu* general system theory.

## Box 3



Scaling the diversity of flows by the total system throughput gives the total development capacity that particular network is able to exhibit, an upper bound given those organizational constraints.

$$C = -\sum_{i,j} T_{ij}\log\left(\frac{T_{ij}}{T_{..}}\right) \tag{4}$$

Furthermore, the total development capacity ($C$) is equal to the information gained by reducing the uncertainty plus the residual uncertainty. This residual uncertainty, when scaled by the total system throughput is termed the redundancy ($\Phi$):

$$\Phi = -k\sum_{i,j} T_{ij}\log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \tag{5}$$

Putting all the pieces together into one simple equation that indicates the total capacity ($C$) is the sum of the organizational information ($A$) (referred to as Ascendency in the previous literature, but here I prefer the term Articulation) and the redundancy ($\Phi$):

$$\mathrm{C} = \mathrm{A} + \Phi \tag{6}$$

**Table 1.**
Network information properties for three simple ecosystem examples in Box 3.

| | Capacity | Articulation | Redundancy | TST |
|---|---|---|---|---|
| Top | 100.29 | 100.29 | 0 | 121.8 |
| Middle | 112.64 | 44.46 | 68.18 | 99.6 |
| Bottom | 175.19 | 53.89 | 121.29 | 102.6 |

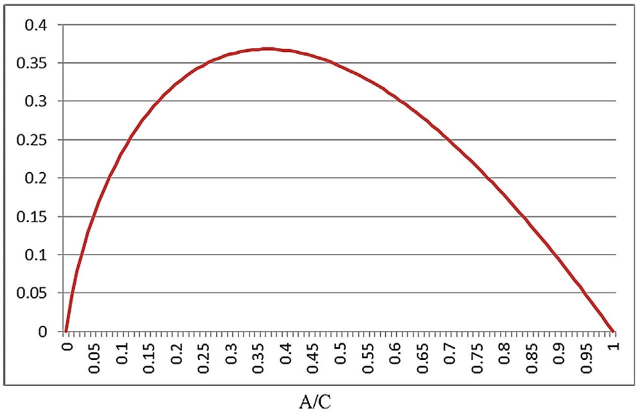


**Fig. 5.** Theoretical curve representing values of ($A/C$)*log($A/C$), when $A/C$ varies between 0 and 1.

Box 3 reproduces a worked example of three network topologies demonstrating the combination of these three terms. In the first network, the flow is constrained such that each subsequent pathway is known with complete certitude leaving zero uncertainty and zero redundancy. In the second network, the addition of another compartment sets up a bifurcation of flow from Prawns introducing indeterminacy into the model; redundancy is nonzero. The third network includes three potential pathways from Prawns, raising the redundancy even higher, but also increasing the total system capacity such that there is higher information and as well as greater redundancy (Table 1).

Early efforts looked at Ascendency's ability to measure reduction in uncertainty as a possible goal function for ecosystem growth and development (Ulanowicz, 1998), but it became clear that this rewards efficiency and undervalues redundancy. Ecosystem functionality relies on both efficient use of resources and also redundant options in times of disturbances. “Systems with either vanishingly small ascendency or insignificant reserves are destined to perish before long” (Ulanowicz et al., 2009). Therefore, maximizing Ascendency itself is not suitable as an ecological goal function. Rather, a combination of the organizational constraint and the redundancy would provide a better measure. The ratio A/C provides a normalized value of the system's degree of order. We once again apply the Shannon formula

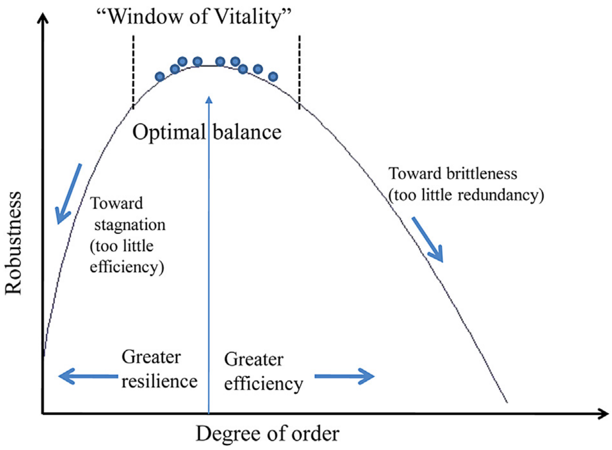


**Fig. 6.** The window of vitality occurs around the optimal position of the robustness measure.

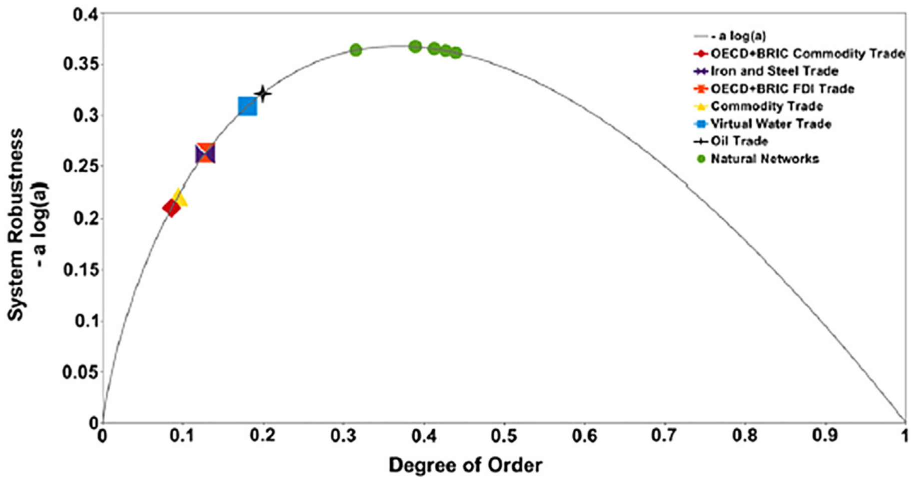


**Fig. 7.** Robustness values for 6 trade networks. Reproduced with permission from Kharrazi et al., 2013.

to construct an index that provides a balanced tradeoff between efficiency and redundancy. This new term is called robustness, $R$:

$$R = \left({}^{A}\!/_{C}\right)\log\left({}^{A}\!/_{C}\right) \tag{7}$$

The choice of Equation (7) for the trade-off is not absolute, but this formula provides two advantages. First, it is zero when $A/C = 1$ and approaches the limit of zero when $A/C \to 0$; and second, it has a single maximum between the two end points (Ulanowicz et al., 2009). Since $A/C$ ranges between 0 and 1, all values of Equation (7) will fall on the theoretical curve (Fig. 5), with the maximum occurring when $A/C = 0.367879$ (which can be shown to be $1/e$). Note, if one prefers that the robustness curve range between 0 and 1, all values can be normalized by $1/e$. Robustness, therefore, combines both efficiency and redundancy and is a quantifiable way to measure and assess the configuration we referred to above as a necessary aspect of sustainability. Ulanowicz (2009) referred to the peak where the trade-offs are optimally balanced as the Window of Vitality (Fig. 6). Further intriguing was the discovery that experimentally derived networks from ecosystem models—most of which were of aquatic and coastal networks—clustered around this optimal area (Goerner et al., 2009, Lietaer et al., 2010). One question is whether our human constructed systems would do likewise. The motivation is first to determine if similar patterns emerge in both system types and second if they are different, then to understand why. Building on the recent application of practices such as ecological engineering and biomimicry, there is much interest to construct human systems with ecological design principles. Given the apparent evidence that ecosystems optimize the robustness value, knowing how they differ could inform design decisions.

This definition of robustness is not the only measure available to express the configuration of a system, but also it has a solid theoretical foundation and is practical since many systems can be represented as flow networks. This has now been applied to ecological and socio-economic case studies.

## 3. Results and discussion

In this section, the robustness index is demonstrated using previously published results. When Ulanowicz first introduced this measure, he applied it to available ecological network data sets. Note that early development of this theory was based on observations and applications to coastal and estuarine ecosystems namely the Chesapeake Bay (Ulanowicz and Platt, 1985, 1989; Baird and Ulanowicz, 1989). Similar network-based analysis has been applied to coastal ecosystems in China (Chen et al., 2011), Germany (Fath et al., 2013) and South Africa (Scharler and Baird, 2005). Most interestingly, the ecosystems Ulanowicz inspected plotted near the apex of the robustness curve showing a good trade-off between the system organization and redundancy. This was taken as evidence that over evolutionary time, these systems have positioned themselves in the space that provides good articulation in terms of efficiency, but not at the expense of built-in redundancy which is useful during times of minor perturbations (of course, no system can protect against all perturbations). This approach has been applied to socio-economic network data with different results. Kharrazi et al. (2013), using data from 6 global trade networks,[2] showed that all networks fell to the left-side of the optimum (Fig. 7). This indicates the systems are overly redundant. Through greater efficiencies they could moving further up the curve to the right. Of course, this begs the question, why they indicate a higher level of redundancy, particularly considering the market forces that drive these economic networks are believed to be efficient, even hyper-efficient. The exact reason is unknown and requires further investigation, but some informed speculation is provided here.

First and foremost, I believe this is an issue of data collection and availability, which affects networks of both ecological and economic systems in opposite and therefore gap-widening ways. Collecting ecosystem data—particularly energy flow data, which is inherently difficult to measure—is arduous, laborious, and operose, resulting in infrequent observations that are hard to repeat and replicate (note this is not to denigrate the outstanding work of field ecologists who collect the data). There is also generally less interest in the data, as it is seen as an academic exercise whose outlets are other scientists through peer-reviewed journals. Economic and trade data, on the other hand, consist of easier to numerate and count quantities such as dollars, liters, kilograms, etc., are collected on regularly occurring intervals, and, have institutionalized teams of collectors serving many clients in government, finance, and industry. One result is that the data sets are more complete. So whereas, ecological data are fortunate to identify the large primary flows, economic data sets include more small flows connecting more compartments. The overall connectivity of the economic networks is therefore much higher; whereas, the sparser nature of

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[2] Oil Trade ($n = 137$), Global Commodity Trade ($n = 197$), OECD-BRIC Commodity Trade ($n = 36$), OECD-BRIC Foreign Direct Investment ($n = 31$), Iron and Steel Trade ($n = 199$), and Virtual Water Trade ($n = 227$).

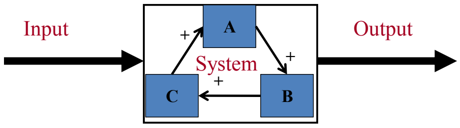

**Fig. 8.** Sustainable systems combine autocatalytic processes within input output flow constraints.

the ecological networks makes them more articulated (connectivity of ecological data sets is typically around 30% compared to over 90% in economic networks (McNerney et al., 2013). This higher connectivity produces a higher redundancy, therefore, placing the robustness to the left-side of the optimum.

A second difference is the scale of the networks. Many of the empirical ecological networks are quite small—of the forty-eight ecological networks at Ulanowicz' website only thirteen are greater than 12 compartments and most are 5 or 6 compartments. In contrast, the economic and trade networks were large ranging from 31 to 227 compartments. Paradoxically, smaller, more aggregated networks tend to have higher connectivity, but the ecological networks are still sparse compared to the economic data. Nonetheless, the larger networks therefore have a higher overall development capacity ($C$) which contributes to a lower $A/C$ ratio, all other things being equal.

A third reason for the higher efficiency of ecological networks might be simply that those networks are more specialized and more articulated. This pattern of organization functions well for nature. While there is diversity and redundancy, and modularity and adaptability, there is no safety net or fairness doctrine. Every day there are winners and losers in nature in the ultimate sense. The flows represent not just energy but loss of life for the 'donating' compartment. Nature is 'red in tooth and claw' (although with overall synergistic benefits (Fath and Patten, 1998)), in ways that human systems are unable and unwilling to do. Therefore, perhaps the higher redundancy is a design feature of human systems. An ancillary 'benefit' could be that the higher connectivity and redundancy puts more nodes in direct contact with others allowing the 'winners' to sweep up even more of the resource flows. In other words, there are positive feedbacks directing the outcome, not only altruistic or regulatory motivations. This level of trade-off might represent some tacit compromise between survival and success. Note, this last reason is speculation. Further research on a much larger variety of networks is needed for a better understanding of the differences and similarities between ecological and economic networks.

## 4. Conclusions

Ecosystems have developed for long time periods under varying conditions making them good model systems regarding sustainability. In particular, ecosystems have been shown to demonstrate an organizational trade-off between the efficiency and redundancy of the inter-connected flows. The importance of coastal and marine ecosystems make them data rich in terms of the ecological energy flow needed to conduct this analysis. They are also vitally critical for the human well-being adjacent to and connected with coastal areas. Therefore, a research priority is development of sustainability indicators for ecological and socio-ecological systems (de Jonge et al., 2012; Kabat et al., 2012). This 'Goldilocks' perspective of not too little and not too much, observed in ecosystems, can potentially guide the design of human constructed, socio-ecological systems.

The main conclusion is that sustainability is a property of configuration, which is manifest in the system networks and interactions. An obvious set of necessary conditions regard the Input–Output constraints. Clearly, a system that is dependent on inflows that cannot be maintained (such as our current fossil fuel-based society) is not sustainable. Nor is it sustainable if the outflows exceed the capacity of the receiving environment to absorb those wastes (as is the case regarding atmospheric carbon balance and hydrospheric nutrient balance (eutrophication) to name a few). But beyond those self-evident boundary aspects of sustainability, it matters what happens within the system itself, and what it does with those flows, how they are managed and put to use. Over time, ecosystems have become arranged in a manner that combines autocatalytic self-organizing processes that use the energy flows in useful ways that provide further emergence of organization, moving the system further from equilibrium. Combining concepts, we expand on the basic input–output model with explicit inclusion of the autocatalytic, gradient building, whole-enhancing interactions (Fig. 8). Our vision of sustainability is now more complete by considering potential necessary and sufficient conditions. In particular, this research makes the case for the importance of system organization as a necessary property of sustainability. It is the author's opinion that we will not find one simple sufficient condition that satisfies for all systems, but further research is needed to explore if other necessary conditions exist regarding the development of system dynamics.

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