Quantifying sustainable balance in ecosystem configurations

Robert E. Ulanowicz [a,b,*]

[a] Arthur R. Marshall Laboratory, Department of Biology, University of Florida, Gainesville, FL 32611, USA
[b] Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD 20688, USA

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ABSTRACT

The literature on sustainability is overwhelmingly occupied with conservation and efficiency as they pertain to individual actions and processes. At the whole-systems level, however, functional redundancy, which imparts flexibility, is mutually exclusive with efficiency and becomes a necessity for systems persistence. Data on ecological flow networks indicate that systems do not progress to maximal efficiency. Rather, sustainable systems are attracted to a propitious balance between efficiency and reliability. Network analysis even provides a quantitative method for directing networks towards the empirical sustainable balance point – a quantitative methodology which already is being considered for fail-safe designs in power grids, water distribution networks and urban planning.

1. Sustainability – the larger view

It is becoming increasingly obvious to most alert individuals that the current Western lifestyle is not sustainable. Most readers are likely already aware that business as usual will eventually lead to disaster. It is not obviously clear, however, how humanity should respond to this crisis. How can the activities of society be reformed to achieve sustainable operation? In the quest for sustainability, it is only natural to start with actions at an immediate or even a personal level, such as curtailing consumption, reusing or recycling resources, etc. Such measures are critically important, to be sure, but are they sufficient to rescue the human enterprise?

One can institute many conservative and efficient behaviors at the local level and still fail to achieve sustainability in the large, because whole systems do not operate entirely at the local level. The system-level organization of society and its economy can affect lower level dynamics and contribute to whether humanity will be able to persist over the centuries to come. To investigate higher-level dynamics, it is helpful to introduce a metaphor for the activities of society as a whole – the network – which, although quite popular these days, nevertheless exhibits properties that remain largely overlooked (Barabasi, 2003).

Systems portrayed as networks consist of two types of elements – nodes, which denote the elements, and links, usually depicted as directed arrows, which identify which elements affect which others and by what magnitude. Each link is identified as T_{ij}, where T indicates the magnitude of the link and the subscripts i and j declare that the effect is exerted by element i upon element j. The magnitudes T_{ij} can be considered as elements of a matrix of flows [T]. Many who take the physicist's view upon nature will consider such networks as deterministic descriptions of the constraints binding the elements one with another. This they do, but, as Gregory Bateson (Bateson, 1972) often complained, physics as applied to practical ends is an overwhelmingly positivist endeavor. That is, focus is almost exclusively upon the laws and constraints that guide how events transpire and virtually no emphasis is laid upon that which is missing – the apophatic. Physicists are reluctant to depart from this obsession with positivism – the Pauli exclusion Principle and Heisenberg's uncertainty being rare exceptions – but to properly assess the sustainability of systems it becomes necessary to focus upon and quantify what is absent in causal networks.

2. Networks – more than meets the eye?

A link by itself, almost by definition, represents the mutual constraint that binds two elements. Furthermore, from any node, i, of a network one usually cannot reach all the other nodes directly. One is *constrained* (often for unspecified reasons) from doing so. So apparent are these depicted constraints, that some misidentify networks as deterministic structures. One notes parenthetically how the overwhelming majority of papers dealing with networks are devoted to elucidating the *mechanisms* (mechanical

* Corresponding author at: Arthur R. Marshall Laboratory, Department of Biology, University of Florida, Gainesville, FL 32611, USA
E-mail address: ulan@umces.edu..

constraints) that give rise to various types of network structures (such as small world, scale-free, Renyi, etc.).

Virtually all networks, however, remain decidedly indeterminate. To see this one need only consider that any node in a network is usually indeterminately linked to several other subsequent nodes. In deference to a conventional faith in the lawfulness of macroscopic natural events, the figure of speech used is euphemistically and epistemically referred to as one's "uncertainty" as to which link will next be activated. But without abrogating any of the universal laws of physics, numerous investigators (Peirce, 1892; Popper, 1990; Elsasser, 1981; Kauffman, 2019; Ulanowicz, 2009a; Fiscus and Fath, 2018) have argued that the universal laws remain *insufficient* to impose determinacy upon systems that are heterogeneous, dense and significantly interacting. The laws constrain what can happen, but in a massively heterogeneous world they are incapable of determining specific outcomes. Networks are replete with indeterminacy – pure and simple! Although there is no avoiding this reality, most would rather close an eye to this inconvenient ontology – a behavior, which some in ecology have lamented as "one-eyed ecology" (Ulanowicz et al., 2009).

Indeterminacy is the *absence* of determinacy, which places it outside the ambit of positivist endeavors. Whilst in physics the absence of something rarely plays an explicit role in analysis, in ecology the absence of a predator or a prey item can have major repercussions that affect system sustainability. Perhaps even more importantly, the obverse notion of indeterminacy is flexibility – a requisite attribute for reliable systems. Fortunately, it happens that absence can be signified and even quantified, actions that could provide significant new insights and novel methodologies. For example, a flood of advances in mathematics followed upon the Ninth Century invention of the cipher 0 as a positional number (Deacon, 2011). Of more recent origin is the mathematics of information, which was constructed independently by Boltzmann (Boltzmann, 1970) and Shannon (Shannon, 1948) upon the *absence* of constraints.

3. Quantifying absence

The lack of constraint is but one class of absence, or non-being. Traditionally, the extent to which a contingent event i appears (its degree of being) is measured by its probability, p_i, where p_i is normally reckoned to fall between the limits of 0 and 1. Under this convention, the probability of i *not* occurring (its non-being) would be assessed as $(1 – p_i)$. It may be ascribed to the genius of Ludwig Boltzmann (Boltzmann, 1970) that he did *not* use this conventional measure of non-being. He chose instead the function $–\log(p_i)$, which can be mapped onto $(1 – p_i)$ in one-to-one fashion. Boltzmann's function, however, is heavily skewed towards imparting more weight to rare events, and his bias proved to be a useful tool for quantifying the second law of thermodynamics.

Under Boltzmann's schema,[1] the product $–p_i\log(p_i)$ becomes a joint measure of both the presence and the absence of event i. One may sum such products over all possible events to obtain a measure, H, which gauges the variety inherent in a system (Shannon, 1948):

$$H = - \sum_i p_i \, \log(p_i) \geq 0 \tag{1}$$

That *both* presence and absence have been built into H hints that the measure might be useful for quantifying attributes of networks, which, as was argued above, incorporate both the constraints and the lack thereof. To demonstrate this let the magnitude of any arc in a directed network be represented by T_{ij}, where i represents the origin of the arc and j the node in which it terminates. As a measure of the total magnitude of the system one may sum the magnitudes of the individual arcs to

yield $T_{..}$ ($= \Sigma_{i,j}T_{ij}$). (A dot in the place of an index represents summation over that index.) An estimate of the joint probability, p_{ij}, thereby can be taken as

$$p_{ij} \sim \left(\frac{T_{ij}}{T_{..}}\right) \tag{2}$$

and then the consequent H-function appears as

$$H = - \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log\left(\frac{T_{ij}}{T_{..}}\right) \geq 0 \tag{3}$$

In words, H quantifies the variety of the arcs constituting the network. Traditionally, H has been identified either with the entropy of a distribution (an apophatic notion) or with the positivist attribute of "information". Strictly speaking it is *neither*, but rather an entanglement of both. The question then arises whether one can separate out the degrees of constraint from those of the freedom that inhere in this measure?

Setting aside the derivation of this segregation, it is sufficient to report that such parsing is always feasible (Rutledge et al., 1976; Ulanowicz and Norden, 1990). One may always write.

$$H = A + \Phi \tag{4}$$

where

$$A = \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) \geq 0 \tag{4a}$$

and

$$\Phi = - \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \geq 0 \tag{4b}$$

It is helpful to recapitulate what has been accomplished. The measure of arc variety, H, has been decomposed into two independent, positive terms. The first term, A (which in information theory is called the "average mutual information"), quantifies the overall constraint in the system, or how tightly the network is organized (a positivist notion). Its complement, Φ, gauges how unconstrained the flows remain (an apophasis), or how flexible the system remains to reconfigure and sustain itself.

4. The origins of constraint

Constraints sustain a system by holding it together – whence the question, "What might account for the origin of constraints in living systems?" In addressing this question one gives voice to the side of the Darwinian narrative that has mostly been dropped from consideration. As a result, Neo-Darwinian theory has come to emphasize only the eliminative aspects of evolution – or what falls under the rubric of "natural selection". Conspicuously missing, and almost forbidden, is any discussion about the generative nature of life made so apparent to Darwin by Thomas Malthus.

Alfred North Whitehead (Whitehead, 1929) and Karl Popper (Popper, 1990) both pointed towards configurations of processes as the sources of constraint in living systems. In particular, the focus here is upon a class of configurations known as "autocatalysis", or indirect mutualism (Ulanowicz, 1997). Autocatalysis is that dynamic whereby processes amplify one another in cyclical fashion. For example, in Fig. 1 is depicted the relationship between three generic processes, X, Y and Z. If the action of X is such that it enhances the action of Y, Y does likewise to Z and Z in turn abets X, then the system is said to be autocatalytic. Such an arrangement is growth-enhancing by definition, but in reality processes will be kept from attaining excessively high rates by the dissipations that are mandated by the second law of thermodynamics.

As a consequence of this asymmetric pattern of interactions, autocatalytic arrangements come to exert constraints upon their constituent
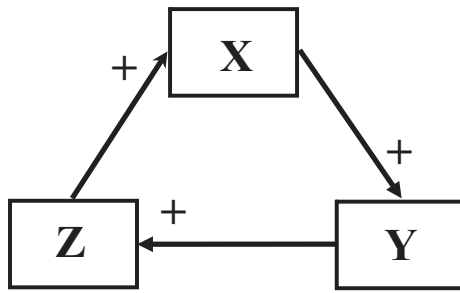
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[1] The same formula is also attributed to Shannon (Shannon, 1948). John von Neuman jokingly suggested to Shannon that he call his index "entropy" due to its similarity to the Boltzmann-Gibbs formula and that it will put him at an advantage in any argument, because no one really understands what entropy is (Tribus and McIrvine, 1971). Unfortunately, Shannon took him seriously, and science has been burdened with the misattribution ever since.

Fig. 1. A typical three-component autocatalytic cycle.

members. For example, if some arbitrary change should happen to the action of Y that makes Y either more sensitive to enhancement by X or a better catalyst of Z, then that change would be rewarded by additional amplification from X. Conversely, if the change makes Y either less sensitive to A or a poorer stimulant to Z, then the effect of X upon Y would be decremented. This asymmetry in effect constitutes a selection pressure (constraint) upon how Y can change, favoring only those alterations that contribute to increased overall autocatalysis. Similarly, X and Z are subject in their turns to heightened constraint by the ensemble configuration.

Now, the action of Y does not occur in a vacuum; it requires inputs of material and energy. It follows from the previous argument that, if a change in Y occasions an increment to its inputs, the change will be rewarded, and vice-versa. Autocatalytic action thereby fosters ever-increasing inputs into each member – an effect that could be termed "centripetality" (Fig. 2). Centripetality is the tendency of a system of processes to entrain necessary resources unto itself. It is a characteristic of *all* living systems, and is evident in ecology, for example, when coral reef communities aggregate material and energy out of the surrounding ocean desert, or when species of *Utricularia* dominate production in nutrient-poor karst lakes (Ulanowicz, 1995).

Centripetality is a fundamental attribute of living systems, although it appears on virtually no one's list of the prerequisites for life. An exception was Bertrand Russell (Russell, 1960), who acknowledged centripetality (which he called "chemical imperialism") as the drive behind *all* of evolution. Ontologically speaking, this form of mutualism supersedes competition, because it is impossible to observe competition at any level that does not owe its existence to centripetality at the next level down.

5. A balance of processes

It is now useful to ask whether the positivist origins of constraint in ensemble systems impart any directionality to ecosystem organization? For example, a longstanding scenario in ecosystem science has been the *succession* of ecosystems from sparse, inchoate assemblies on newly created
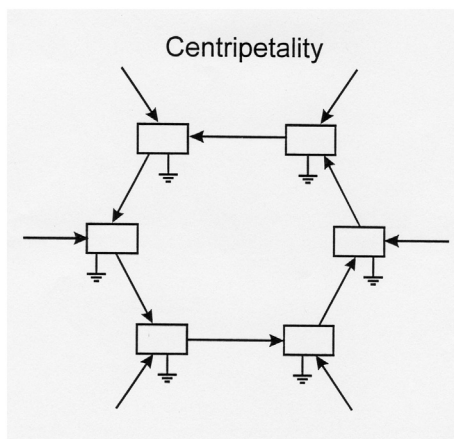

Fig. 2. Centripetal action as engendered by autocatalysis.

habitat towards species-rich ensembles wherein flows are channeled over efficient pathways, i.e., a progression from relatively unorganized towards more organized networks of exchanges (Odum, 1969). Here it is important to note that A serves as a surrogate for efficient network operation. To see this, one need only imagine enumerating all the pathways in the network that lead from primary inputs to exogenous outputs. Some will invariably be more efficient than others and over time will come to dominate system performance. Such dominance serves to increase A. Under the common assumption that more efficiency is always better, it was therefore naturally assumed that A would increase over the course of succession.

To test this hypothesis a number of ecosystem scientists have estimated numerous networks of trophic exchanges from a variety of different ecosystems. Such data allow one to calculate values of H, A and Φ for each ecosystem using the estimated flow magnitudes, T_{ij}, of some conserved medium (matter or energy) from prey i to predator j. Furthermore, it is convenient to normalize the degree of organization, calling it $a = A/H$ as well as the entropy, $\phi = \Phi/H$, so that $a + \phi = 1$. That is, with succession one expects a to approach unity.

Nature has a way of pushing back against pet theories, however, and after a quarter century of collecting quantified networks, no such trend of uniformly increasing a has emerged from the data. Rather, what one observes is that well-articulated networks of sustainable trophic flows from a wide variety of ecosystems cluster around values of $a \approx 40\%$ and $\phi \approx 60\%$ (Ulanowicz, 2009b). I.e., there appears to be some balance between constraint and freedom that characterizes naturally persistent, sustainable ecosystems. In fact, one may take as a definition of sustainable systems those that achieve a stable balance between efficiency and flexibility.

## 6. Quantitative clues towards sustainability

To help elucidate this clustering, it is useful to define a measure for ecosystem robustness along the lines that Boltzmann used (Ulanowicz, 2009b). That is, if a represents how organized a system is, rather than use ϕ (i.e., $[1 - a]$) as the measure of flexibility, one chooses instead -log(a). The product $-a \log(a)$ would then characterize the encounter between the opposing trends towards efficient operation (a) and increasing opportunity for re-configuration ($-\log[a]$). When this product is normalized by the factor ($e/\log[e]$), the result is F, the fitness or potential to evolve (become reliable). Scaling the fitness by the total activity yields the robustness, $R = T..F$. When R is plotted against a for 17 articulated networks representing a variety of ecosystems, the results were seen to cluster just beyond the maximum in R (Fig. 3).

From the standpoint of pure phenomenology, the cluster around $a \approx 40\%$ characterizes a natural balance point for *sustainable* ecosystems. The center of this cluster lies slightly beyond the maximum of the function $F = -a\log(a)$, which occurs at $a = 1/e$ (where e is the base of the natural logarithms). It is likely that other types of sustainable systems might cluster elsewhere along the interval $0 < a < 1$. To plan for such possibility, an adjustable parameter, β, is introduced into F, and F is normalized so that $F = 1$ (maximal) at $a = e^{-(1/\beta)}$.

$$F = -\left[\frac{e}{\log(e)}\right] a^\beta \log(a^\beta) \tag{5}$$

(For the cluster of sustainable ecosystems centered around $a = 0.401$, β works out to be 1.0914.) The stage is now set to maximize the robustness, R, of any starting network so as to improve its sustainability. Towards this end, one calculates the partial derivatives of R with respect to each of the existing flows, T_{ij}:

$$\frac{\partial R}{\partial T_{ij}} = F + \frac{F'}{H}\left\{\log\left[\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right] + a\log\left[\frac{T_{ij}^2}{T_{i.}T_{.j}}\right]\right\} \tag{6}$$
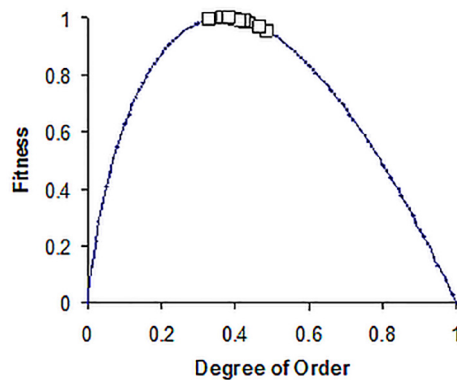
Fig. 3. The degrees of order and corresponding magnitudes of robustness for the subset of 17 ecosystem flow networks (Ulanowicz, 2009b).

where $F' = e\beta a^{(\beta-1)}\left[\frac{log(a^\beta)}{log(e)} + 1\right]$ is the ordinary derivative of F with respect to a.

To move the system towards sustainability, one increases each flow, T_{ij}, for which $\partial R/\partial T_{ij} > 1$ and decreases those for which $\partial R/\partial T_{ij} < 1$ in some small proportion to the magnitude of the derivative. One then starts over with the resulting adjusted network and iterates the procedure until F approaches arbitrarily close to unity and all F' become vanishingly small, that is, the network approaches natural sustainable balance.

Those system configurations with significantly less organization than balance point, $e^{-(1/\beta)}$, will be out-competed by others that are more efficient at processing matter or energy. Those that significantly exceed the balance point are what Holling (Holling, 1986) has termed "brittle". They eventually succumb to some novel perturbation, because they lack sufficient flexibility to reliably adapt to it. Only system configurations in the neighborhood of the balance point, $a = e^{-(1/\beta)}$ remain sustainable.

It is important to note that the balance here is between two opposing attributes, efficiency and flexibility. Too little or too much of *either* will prove fatal. (Yes, systems can indeed become too efficient for their own good!) That the balance can be portrayed quantitatively in terms that trace back to the constituent flows provides engineers and managers with a propitious tool for system remediation.

As an example, Fig. 4 portrays the exchanges among six compartments in an oyster reef ecosystem (Dame and Patten, 1981; Ulanowicz, 2011). The degree of organization, a, for this system and the corresponding robustness, R, can readily be calculated, as can each $\partial R/\partial T_{ij}$. The derivatives are shown in parentheses in Fig. 5 below the magnitudes of their respective flows. Notice that a for the system is 0.436, so the system is not very far from balance. As a consequence, each marginal contribution does not differ too much from unity.

Suppose now that the system is shocked by a significant increase in the input of suspended detritus (Ulanowicz, 2011). Experience shows that such perturbation usually results in an inflation of the pathway from filter feeders to deposited detritus to microbiota, as indicated by the heavy arrows in Fig. 5. One notices immediately that most of the altered marginal contributions now differ significantly from unity. The system is now deeply out-of-dynamical-balance. Furthermore, the directions indicated by the revised marginal contributions accord well with the intuitive notion of what needs to be changed to bring the system back towards a sustainable configuration: The marginal contributions of the eutrophic pathway actually become negative, indicating the high priority that must be given to reducing these magnitudes. Several of the flows connecting the predators, deposit feeders and meiofauna make heavy contributions, indicating that these routes call for significant repletion. Taken as a whole, the marginal contributions provide what might figuratively (and almost literally) be called "vectors toward sustainability".
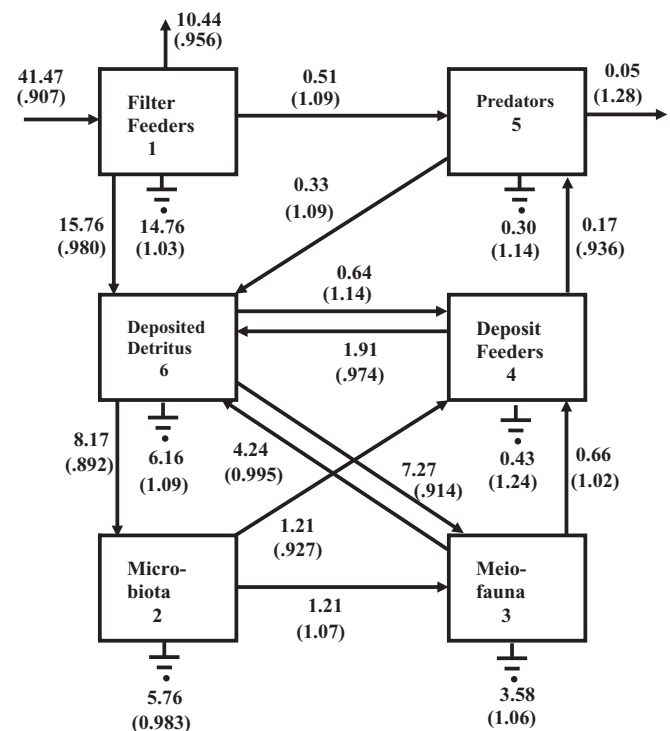
Fig. 4. Schematic of the The values of the exchanges of energy (kcal m² y⁻¹) in an oyster reef community (Dame and Patten 1981). The marginal contributions of each flow toward sustainability are presented in parentheses below their flow magnitudes.
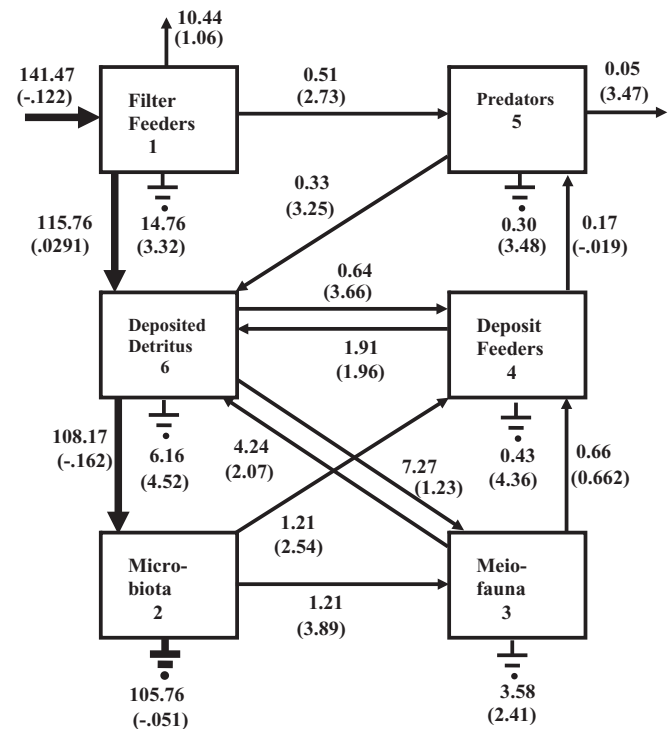
Fig. 5. Hypothetical eutrophication in the Oyster Reef community of Fig. 4 created by adding 100 units to the pathway →1→6→2→. The revised marginal contributions appear in parentheses.

7. The fuller dynamics of life

These vectors are exciting prospective tools that possibly could assist the quest for sustainability. Several philosophical implications of this exercise should be stressed as well. One notices how the dynamics of the ecosystem are *not* simply a mechanical juggernaut that grinds inexorably towards some maximal efficiency. Furthermore, the temptation to seek sustainability in some steady-state solution to a coupled system of mechanical constraints is not only a fatuous notion, but could prove downright misleading.

Rather, ecosystem dynamics are conceived here in Heraclitean fashion as an inherent tension between the buildup of constraints and the loosening thereof – both the positivist *and* the apophatic (Ulanowicz, 2009b; Brenner, 2008), or, as Claudia Pahl-Wostl (Pahl-Wostl, 1995) put it, "chaos and order entwined". Opposition between the two is not absolute, however. In true Hegelian fashion, each attribute requires the other at some higher level: The development of new adaptive repertoires requires a cache of what formerly appeared as redundant, inefficient, incoherent and dissipative processes. On the other hand, greater constrained and efficient functioning always generates increased dissipation.

It is now apparent why Gregory Bateson was so concerned about how the popular mode of problem solving often only makes matters worse (Bateson, 1972).[2] Approaching a dialectical system as if it were a monist machine is almost certain to result in catastrophe. In the economic realm, Bernard Lietaer (Lietaer et al., 2010) has warned that a monetary system designed to give unfettered reign to market efficiency ineluctably leads to market crashes. As the economic system is driven well to the right of maximum robustness, it becomes an instability awaiting the inevitable destructive perturbation. Such failure is systemic in that monetary policy imposes a strong monist drive upon what should be an agonistic balance. Lietaer urged the introduction of alternative (and efficiency reducing) non-interest currencies to keep overhead, Φ, from being driven too low.

The engineering applications of dynamical dialectical balance have begun to be probed. For example, the quantitative "vectors toward sustainability" in Section 6 have recently been applied to the design of more fail-safe power grids (Panyam et al., 2019), to networks of shared water supply among contiguous industries (Dave and Layton, 2019; Pizzol et al., 2013), to urban planning (Kiss and Kiss, 2018) and to economics (Korhonen and Seager, 2008; Kharrazi et al., 2013; Fath, 2014).

Back in the realm of ecology, much effort has been justifiably invested at the global level towards the conservation of biodiversity. Society intuitively senses that maintenance of biodiversity is necessary for global ecological health. What is hardly ever mentioned, however, is that solid theoretical justification for preserving biodiversity has been lacking. In retrospect, one now sees why this is so: Biodiversity is actually an apophasis. With only positivist tools at one's disposal, one cannot hope to encompass the interplay between constraint and looseness that characterizes sustainability.

It is important to note that agonistic dynamics remain, in general, non-algorithmic. This circumstance should warn scientists about the possibility that relying solely upon the fundamental materialist/mechanical assumptions that undergird contemporary science is wholly inadequate to, and likely will impede, a deeper understanding of the nature of life (Kauffman, 2019; Ulanowicz, 2009a). Life is process, not material, and simple dimensionality suggests that any fuller exegesis of life be grounded in interactions among processes (Ulanowicz, 2016). Fortunately, such interactions lend themselves conveniently to representation as networks, which, as has been argued, portray the apophatic as well as the apodictic. In fact, decades of studying ecological flow networks have led Ulanowicz (Ulanowicz, 2009a) to formulate what he called an "ecological metaphysic" – a process-based set of alternative fundamental assumptions about how nature operates.

The conclusions to be drawn are dramatic: Ecosystems are not giant machines! Biology is not mechanics writ large! Evolution is not simply, as Francisco Ayala[3] characterized it, "matter moving according to universal laws". It becomes necessary to take seriously Karl Popper's call for a thorough reassessment of what constitutes legitimate causality (Popper, 1990). Sustainability – nay, the very survival of humanity – depends on it!

Declaration of Competing Interest

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

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[2] The common approach is to choose an endpoint and perform maximization of some form of that goal (very often maximal efficiency).

[3] Darwin's revolution. Presented at *Biological Evolution: Facts and Theories*. Pontifical Gregorian University, March 3, 2009. Rome.

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