

Appendix D

Quantifying Sustainability

This appendix presents the theoretical framework on which the proposed scientific approach towards sustainability used in this Report is based. It does that by using three very different languages of the same framework.

The first language, used in section D1 gives a concrete example of how the methodology of complex flow networks is applied on a natural ecosystem – in this case including alligators, prawns, large fish and turtles in the Cypress wetlands of Southern Florida.

Section D2 is graphic. It represents in three dimensions what is in fact the four dimensional object that is required to capture all major variables affecting the sustainability of a complex flow network.

The second section D3, is mathematical. It is completely based on conventional Western science, integrating thermodynamics, network theory and information theory.

Appendix D1: Measuring Sustainability in Natural Ecosystems.

An example of a simplified ecosystem is portrayed in Figure D1.1 Our case depicts three pathways of carbon flow leading from freshwater prawns to the American alligator, via three intermediate predators: turtles, large fish and snakes, located in the Cypress wetlands of South Florida.

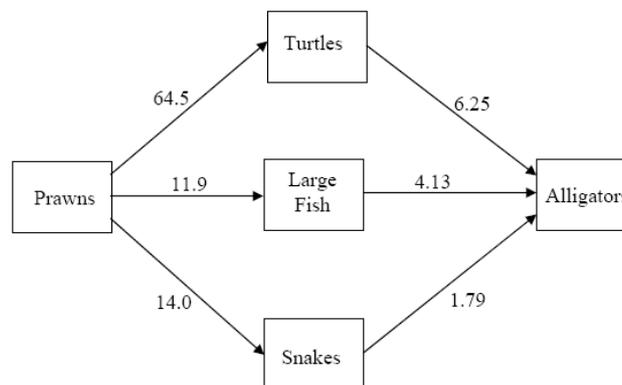


Figure D1.1: Three pathways of carbon transfer (in $\text{mgCm}^{-2}\text{y}^{-1}$) between prawns and alligators in the Cypress wetland ecosystem of South Florida¹

Of course, these species are entwined in a myriad of relationships with other populations, but for the purposes of illustrating our point, this sub-network will be considered here as if it were in isolation. Ecologists measure size the same way economists do, as Total System Throughput (TST), which measures system size as an overall volume of flow. TST is a close match for the economist's GDP, which is a simple sum of all the flows that occur in a country's economic network.

The total throughput per year for the prawn-alligator ecosystem is measured as 102.6mg of carbon per square meter of that wetland ecosystem ($\text{mgCm}^{-2}\text{y}^{-1}$). This single measure of throughput, however, captures only a part of what is going on. As stated earlier, two key additional factors are required to

¹ Robert E. Ulanowicz, C. Bondavalli and M. S. Egnotovich, "Network Analysis of Trophic Dynamics in South Florida Ecosystems, FY 96: The Cypress Wetland Ecosystem", Annual Report to the United States Geological Service Biological Resources Division (Coral Gables : University of Miami, 1996).

measure this system's sustainability: throughput efficiency and resilience. In this specific prawn-alligator ecosystem, efficiency works out to $53.9 \text{ mgC-bitsm}^{-2}\text{y}^{-1}$, and its resilience is $121.3 \text{ mgC-bitsm}^{-2}\text{y}^{-1}$.

Inspection of the pathways reveals that the most efficient pathway between prawns and alligators is, in fact, via the large fishes. If efficiency were the sole criterion for the evolutionary development of this ecosystem, the route via the fish would grow at the expense of the less efficient pathways, i.e., turtles and snakes, until it completely dominated the transfer, as seen in Figure D1.2.

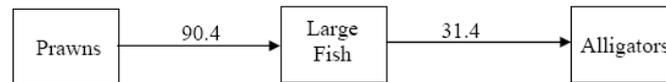


Figure D1.3: The most efficient pathway in Figure D1.1 after it had eliminated parallel competing pathways

As a result of the increase in overall efficiency, the TST rises from 102.6 to $121.8 \text{ mgCm}^{-2}\text{y}^{-1}$. But the greatest jump is actually seen in the efficiency, which almost doubles to $100.3 \text{ mgC-bitsm}^{-2}\text{y}^{-1}$. Meanwhile, the resilience has now vanished completely (resilience = 0).

So, to use a cliché, to maximise efficiency the system has put all its eggs in one basket (the prawns-fish-alligators channel). Should some catastrophe occur, such as a virus wiping out the fish population, all transfer from prawns to alligators would directly suffer in proportion.

In contrast, if healthy populations of turtles and snakes were present when the fish population was incapacitated, the other pathways would provide a buffer against the loss, as in Figure D1.3.

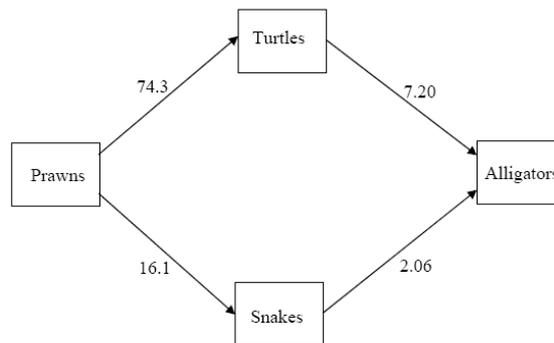


Figure D1.3: Possible accommodation by turtles and snakes to the disappearance of fish as intermediaries between prawns and alligators

Rather than a complete system collapse, the total throughput drops modestly (TST goes from 102.6 to $99.7 \text{ mgCm}^{-2}\text{y}^{-1}$) and the efficiency falls back (throughput efficiency drops only from 53.9 to $44.5 \text{ mgC-bitsm}^{-2}\text{y}^{-1}$). The chief effect of the disappearance of the fishes is a significant decrease in resilience (resilience falls by almost half to $68.2 \text{ mgC-bitsm}^{-2}\text{y}^{-1}$). In other words, the system adapts to protect total throughput and buffers efficiency by expending resilience. Note that this resilience is not palpable storage, like a cache of some material resource. Rather, it is a characteristic of the system's structure itself that reflects the absence of emphasis on efficiency.⁹

What can be learnt from this exploration of sustainability through combining network and information theory with data from real-life ecosystems?

The main point is that nature does not select for maximum efficiency, but for an optimal balance between the two opposing poles of throughput efficiency and resilience. These poles, as we have mentioned before, pull in opposite directions because resilience increases with diversity and with backups through multiple pathways (i.e., connections), while efficiency increases by eliminating diversity and redundant pathways through streamlining. The healthiest ecosystem is the one that has struck an optimal balance between these two opposing pulls because both are indispensable for long-term sustainability and health.

We now have a way of quantitatively measuring all the relevant components separately: total throughput, throughput efficiency and resilience. Furthermore, the underlying mathematics are well-behaved enough so that there exists only one single maximum for a given network system. Also, there is an asymmetry: to attain optimality, resilience is more important than efficiency. So the shape of the relationships between sustainability and its constituent elements can generically be shown to be an asymmetric hump, as in Figure D1.4. This is of course a graphical simplification of a four-

dimensional object, which we use in the Report as a short-hand for didactic purposes.

This four dimensional object is shown in its full four dimensions in a minute long movie where the timing of the movie is the value beta (going from the value available by clicking [HERE](#)).

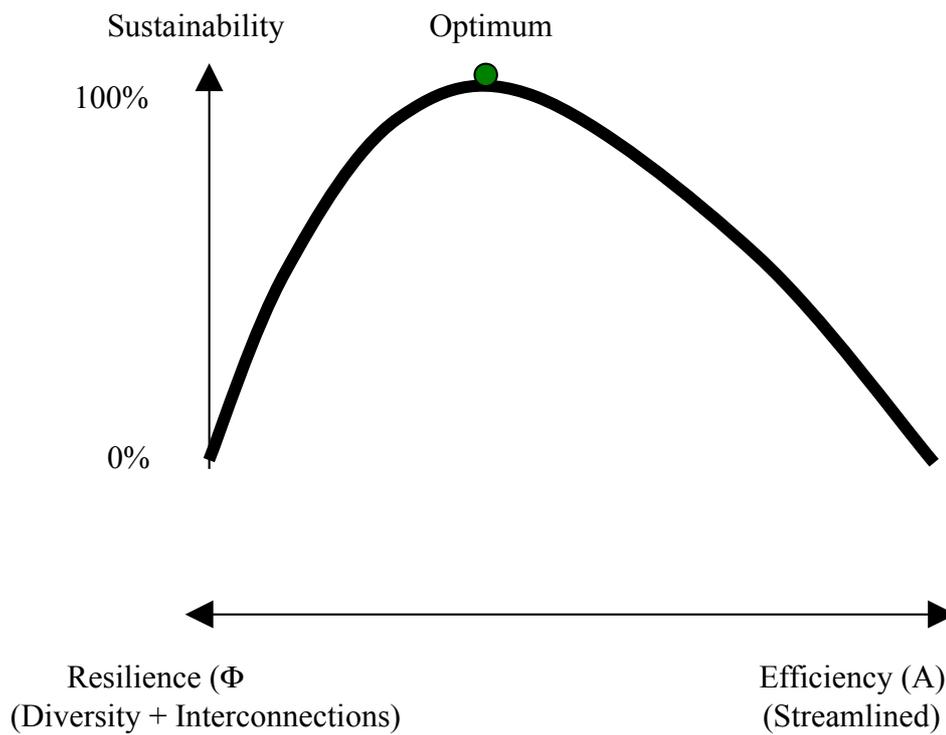


Figure D1.5: Sustainability curve mapped between the two polarities of efficiency and resilience. (Notice that this two-dimensional graph is a didactic simplification of what is, in reality, a four-dimensional object. More complete explanations and a 3-D graphic analysis are available in Appendix C on website ????)

Appendix D2: Graphic Analysis

As demonstrated in section B2, efficiency as measured by throughput volume is definitely not a sufficient criterion to determine the sustainability of any complex flow network. Also necessary is that it possesses a resilience, the capacity to recover from undefined and contingent responsiveness to the unpredictable challenges thrown up by its own workings or its environment. It is thanks to this resilience that an ecosystem can withstand shocks and adapt itself when necessary. We have also seen that sustainability (F) is a function of the two key structural variables (n) and interconnectivity (c). Finally, a fourth critical variable that shapes sustainability is beta, the variable that indicates the weight given to efficiency as opposed to resilience.

The following 3 dimensional graphic analysis provides an insight into the shape of the 4 dimensional object that the mathematical evidence of D2 D2 has provided. These graphs were graciously provided by Maria-Lovisa Amundadotir, PhD student in mathematics at ETH university in Zurich.

The vertical axis represents the sustainability F of a complex flow network. The two horizontal axes are respectively the interconnectivity and the diversity of the same complex network. In natural ecosystems the weight on efficiency has empirically been determined from a regression analysis using actual data from a wide variety of ecosystems of different scales to have a value of $\beta = 1.288$. Figure D3.1 illustrates the conditions where natural ecosystems seen as complex flow networks are the most sustainable (color yellow).

What the graph shows is that a natural ecosystem will tend to evolve towards sustainability preferably by increasing diversity, and secondarily through increasing interconnectivity. For instance, a forest will tend to become more sustainable by multiplying the diversity of fauna and flora that can survive in the environmental conditions of the area. To a lesser extent will it encourage animals to feed on other plants and prey than what they had evolved to feed from in their specific ecological niche.

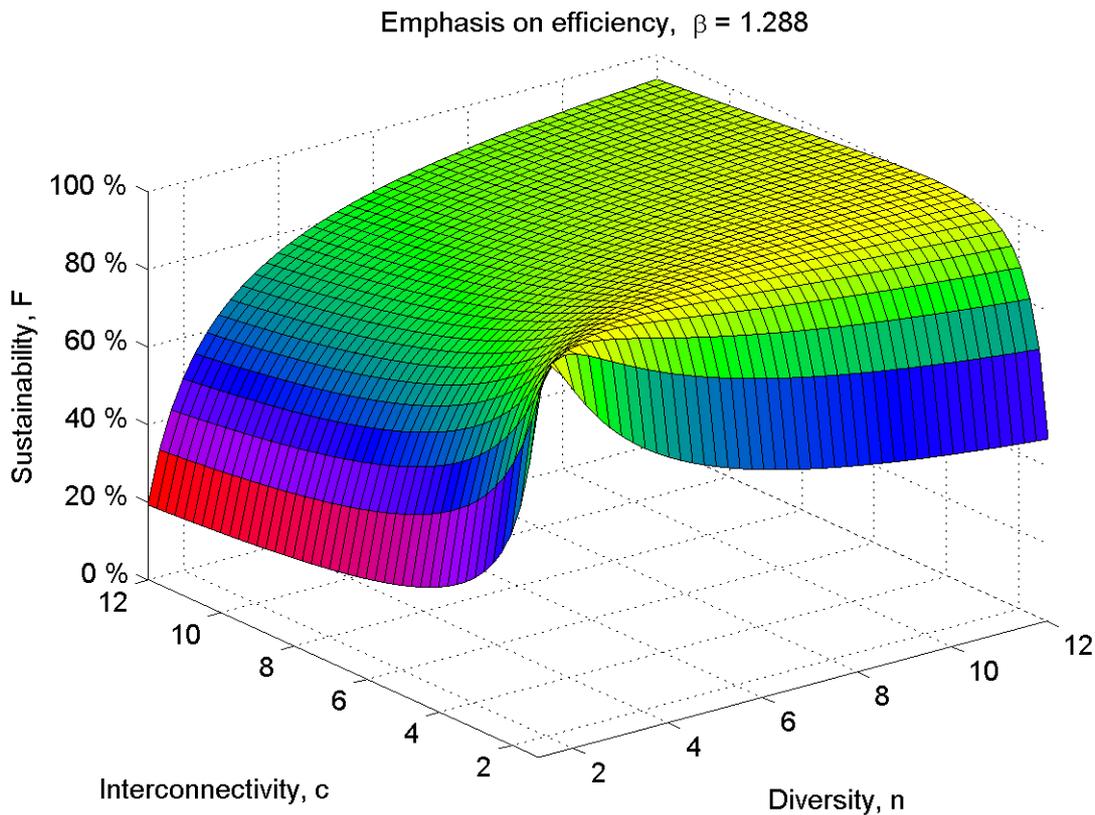


Figure D2.1 : Sustainability as a function of diversity and interconnectivity in natural ecosystems (with $\beta = 1.288$ determined empirically). The shape of the highest sustainability zones (colored in yellow) shows that a natural ecosystem will tend to evolve towards sustainability primarily by increasing diversity, and secondarily through increasing interconnectivity.

In human designed systems, there may be a tendency to over-emphasize growth of volume, at the expense of resilience. In short, to emphasize efficiency more than resilience. One reason is the presence of autocatalytic forces that the theory warns can be problematic for the sustainability of the whole network. In an economy, that takes the form of the larger economic actors that succeed through lobbying to obtain laws and rules that favor their growth at the expense of the smaller ones.

In the financial domain, it takes the form of banks that are “too big to fail”, and thereby obtain implicit guarantees from governments that they will be bailed out in case of trouble.

Figure D2.2 shows what tends to happen when such a bias is introduced.

The sustainability is dramatically reduced, because the interconnectivity collapses. Only a narrow zone, requiring a lot of diversity remains sustainable. However, in the monetary domain, as long as we remain stuck with the idea of a single national currency, this diversity is systematically eliminated. Such a system will predictably collapse, and if it is restored to “normal” will collapse again and again.

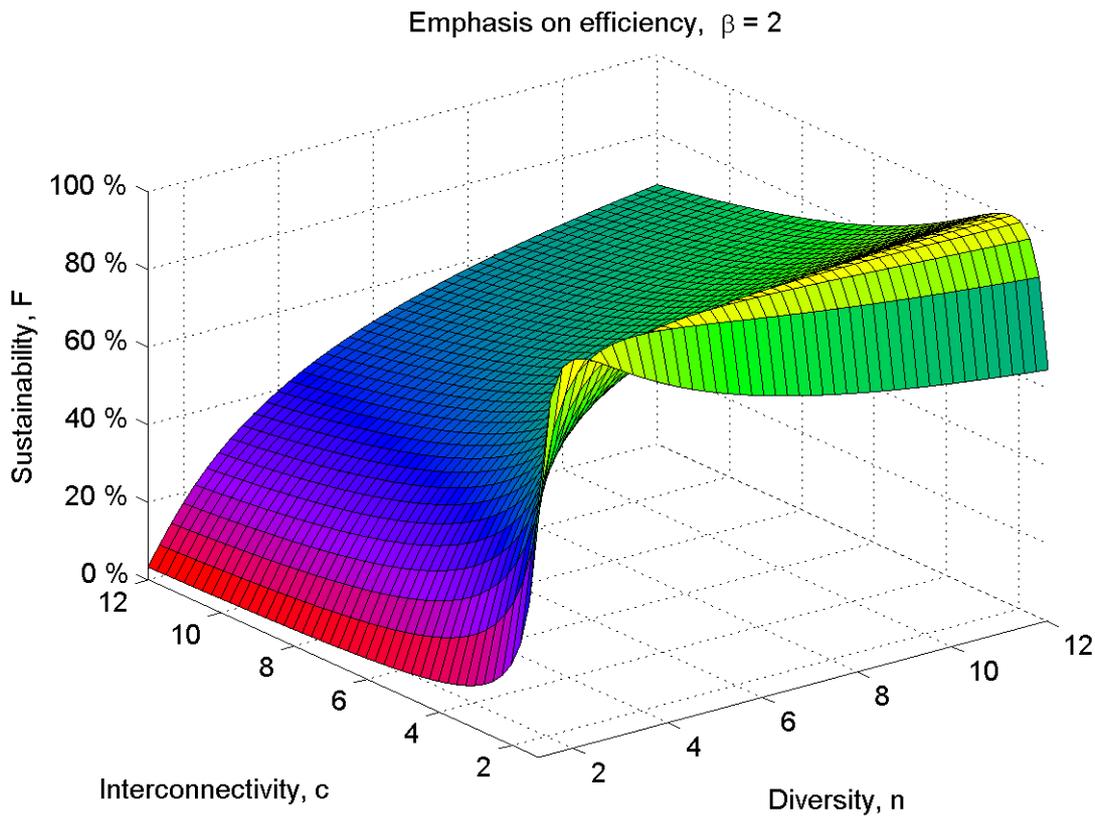


Figure D2.2 Reduction of sustainability when efficiency is overemphasized ($\beta = 2$). Sustainability is reduced to a narrow band requiring a lot of diversity.

When this bias towards favoring efficiency is pushed still further, the collapse of interconnectivity and sustainability gets accentuated still further, as illustrated in Figure B3.3. In other words, the more the the bias towards efficiency prevails, the quicker the system will collapse.

Emphasis on efficiency, $\beta = 4$

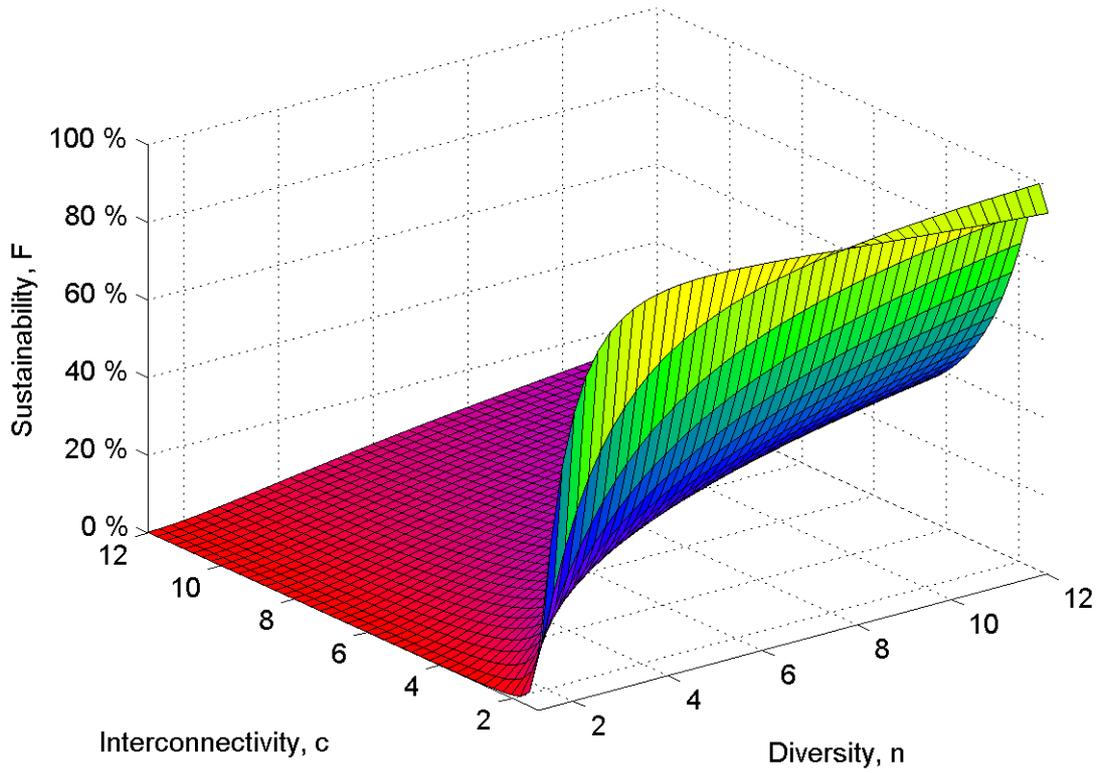


Figure D2.3 When overemphasis on efficiency is pushed still further ($\beta = 4$), a complex flow network becomes a totally unsustainable system.

Appendix D3: Mathematical Demonstration for Quantifying Sustainability of a Complex Flow Network: Evidence for Yin-Yang in Nature²

Contemporary science is preoccupied with that which exists; it rarely accounts for what is missing. But often the key to a system's persistence lies with information concerning lacunae. Such unutilized reserve capacity is complementary to the effective performance of the system, and too little of this attribute can render a system brittle to the point of collapse. We can now measure with a single metric any complex flow network system's sustainability in terms of the tradeoff allotment of each. This approach provides heretofore missing theoretical justification for efforts to preserve biodiversity whenever systems have become too streamlined and efficient.

It is critically important to understand that the findings described below arise from *structural* variables of a network. This means that they apply to any other complex flow network with a similar structure. This makes them directly applicable to economic processes and particularly to the flow of money in a financial network or an economy.

.The starting point is Boltzmann's classical equation of surprisal,

$$s = -k \log(p) , \quad (\text{B2.1})$$

where s is one's surprisal at seeing an event that occurs with probability p , and k is an appropriate (positive) scalar constant. One can read this equation as defining s to gauge what p is not. That is, if p is the weight we give to the presence of something, then s becomes a measure of its absence. If p is very small, then the ensuing large magnitude of s reflects the circumstance that most of the time we *don't* see the event in question.

We will show that the interplay between presence and absence plays a crucial role in whether a system survives or disappears. It is the very absence of order (in the form of a diversity of processes) that makes it possible for a system to persist (sustain itself) over the long run.

The product of the measure of the presence of an event, i , (p_i) by a magnitude of its absence (s_i) yields a quantity that represents the *indeterminacy* (h_i) of that event,

$$h_i = -kp_i \log(p_i) \quad (\text{B2.2})$$

When $p_i \approx 1$, the event is almost certain, and $h_i \approx 0$; then when $p_i \approx 0$, the event is almost surely absent, so that again $h_i \approx 0$. It is only for intermediate, less determinate values of p_i that h_i remains appreciable, achieving its maximum at $p_i = (1/e)$.

It is helpful to reinterpret (2) in terms germane to evolutionary change and sustainability. When $p_i \approx 1$, the event in question is a virtual constant in its context and unlikely to change ($h_i \approx 0$). Conversely, whenever $p_i \approx 0$, the event exhibits great potential to change matters ($s_i \gg 1$), but it

2 This appendix is summarizing parts of the paper by Ulanowicz, Goerner, Lietaer and Gomez "Quantifying Sustainability: Resilience, efficiency and the Return of Information Theory" in the *Journal of Ecological Complexity* Vol 8 #1 (March 2009). In this appendix only the bare mathematical bones of the argument are extracted from this paper. The reader who wants a step by step justification for the underlying logic, its implications and concrete examples of this process should consult the original paper. A variation on this Appendix has also been published separately in Simon Mouatt and Carl Adams (ed.) *Corporate and Social Transformation of Money and Banking* (Palgrave MacMillan, 2010) pags 238-245.

hardly ever appears as a player in the system dynamics (so that, again, $h_i \approx 0$.) It is only when p_i is intermediate that the event is both present frequently enough and has sufficient potential for change. In this way, h_i represents the capacity for event i to be a significant player in system change or evolution.

Seeking a perspective on the entire ensemble of events affecting a system motivates us to calculate the aggregate systems indeterminacy, H , as

$$H = \sum_i h_i = -k \sum_i p_i \log(p_i), \quad (\text{B2.3})$$

which we can now regard as a metric of the total capacity of the ensemble to undergo change. Whether such change will be coordinated or wholly stochastic depends upon whether or not the various events i are related to each other and by how much. In order better to treat relationships between events, it is helpful to consider bilateral combinations of events, which for clarity requires two indices. Accordingly, we will define p_{ij} as the joint probability that events i and j co-occur. Boltzmann's measure of the non-occurrence of this particular combination of events (1) thus becomes,

$$s_{ij} = -k \log(p_{ij}). \quad (\text{B2.4})$$

If events i and j are entirely independent of each other, the joint probability, p_{ij} , that they co-occur becomes the product of the marginal probabilities that i and j each occur independently anywhere. Now, the marginal probability that i occurs for any possible j is $p_{i.} = \sum_j p_{ij}$, while the likelihood that j occurs regardless of i is $p_{.j} = \sum_i p_{ij}$ ³. Hence, whenever i and j are totally independent, $p_{ij} = p_{i.}p_{.j}$. Here the assumption is made that the indeterminacy s_{ij} is maximal when i and j are totally independent. We call that maximum s_{ij}^* . The difference by which s_{ij}^* exceeds s_{ij} in any instance then becomes a measure of the constraint that i exerts on j , call it x_{ij} , where,

$$x_{i|j} = s_{ij} - s_{ij}^* - k \log(p_{i.}p_{.j}) - [-k \log(p_{ij})] = k \log\left(\frac{p_{ij}}{p_{i.}p_{.j}}\right) = x_{j|i}. \quad (\text{B2.4})$$

The symmetry in (4) implies that the measure also describes the constraint that j exerts upon i . In order to calculate the average mutual constraint (X) extant in the whole system, one weights each x_{ij} by the joint probability that i and j co-occur and sums over all combinations of i and j :

$$X = \sum_{i,j} p_{ij} x_{i|j} = k \sum_{i,j} p_{ij} \log\left(\frac{p_{ij}}{p_{i.}p_{.j}}\right) \quad (\text{B2.5})$$

The convexity of the logarithmic function guarantees (Abramson 1963) that:

$$H \geq X \geq 0 \quad (\text{B2.6})$$

In words, (6) says that the aggregate indeterminacy is an upper bound on how much constraint (order) can appear in a system. Most of the time, $H > X$, so that the difference

3 For the remainder of this essay a dot in the place of an index will represent summation over that index.

$$\Psi = (H - X) = -k \sum_{ij} p_{ij} \log \left(\frac{p_{ij}^2}{p_{i.} p_{.j}} \right) \geq 0 \quad (\text{B2.7})$$

as well. In the jargon of information theory Ψ is called the “conditional entropy.”

Relationship (7) can be rewritten as:

$$H = X + \Psi, \quad (\text{B2.8})$$

and it makes a very valuable statement. It says that the capacity for evolution or self-organization (H) can be decomposed into two components. The first (X) quantifies all that *is* regular, orderly, coherent and efficient. It encompasses all the concerns of conventional science. By contrast, Ψ represent the *lack* of those same attributes, or the irregular, disorderly, incoherent and inefficient behaviors, which conventional science tends to overlook.

Up to this point we have spoken only vaguely about events i and j . Without loss of generality, we now narrow our discussion to consider only transfers or transformations. That is, event i will signify that some quantum of medium leaves or disappears from component i . Correspondingly, event j will signify that a quantum enters or appears in component j . We now identify the aggregation of all quanta both leaving i and entering j during a unit of time — or, alternatively, the flow from i to j (or the transformation of i into j) — as T_{ij} . Thus, T_{ij} might represent the flow of electrons from point i to point j in an electrical circuit; the flow of biomass from prey i to predator j in an ecosystem; the transfer of money on a microeconomic scale from economic actor i to actor j in an economic community; or the transfer of money or from sector i to sector j at the macroeconomic scale.

Here again we use the convention (introduced earlier in footnote 6) that a dot in the place of a subscript indicates summation over that index. Thus $T_{i.}$ ($= \sum_j T_{ij}$) will represent everything leaving i during the unit time interval, and $T_{.j}$ will gauge everything entering j during the same duration. In particular, $T_{..}$ ($= \sum_{ij} T_{ij}$) represents the total activity of the system and is given the name “total system throughput” (which corresponds roughly to the concept of GDP in economic theory).

These definitions allow us to estimate all the probabilities defined above in terms of their measured frequencies of occurrence. That is,

$$p_{ij} \sim \frac{T_{ij}}{T_{..}}, \quad p_{i.} \sim \frac{T_{i.}}{T_{..}}, \quad \text{and} \quad p_{.j} \sim \frac{T_{.j}}{T_{..}}. \quad (\text{B2.9})$$

Substituting these estimators in equations (3), (5) and (7), yields

$$H = -k \sum_{ij} \frac{T_{ij}}{T_{..}} \log \left(\frac{T_{ij}}{T_{..}} \right); \quad X = k \sum_{ij} \frac{T_{ij}}{T_{..}} \log \left(\frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right); \quad \text{and} \quad \Psi = -k \sum_{ij} \frac{T_{ij}}{T_{..}} \log \left(\frac{T_{ij}^2}{T_{i.} T_{.j}} \right), \quad (\text{B2.10})$$

Respectively (Rutledge et al. 1976).

The dimensions in the definitions (10) remain problematic, however. All of the ratios that occur

there are dimensionless (as required of probabilities). To change that into a useable metric, we will scale each index by the total system throughput, $T_{..}$, which conveys the overall activity of the system. In order to emphasize the new nature of the results, we give them all new identities. We call

$$C = T_{..} \cdot H = - \sum_{i,j} T_{ij} \log \left(\frac{T_{ij}}{T_{..}} \right) \quad (\text{B2.11})$$

the “capacity” for system development (Ulanowicz and Norden 1990.)

The scaled mutual constraint,

$$A = T_{..} \cdot X = \sum_{i,j} T_{ij} \log \left(\frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right), \quad (\text{B2.12})$$

converts into the measure of a system’s throughput volume per unit of time which we will define as “efficiency”⁴, measures the capacity of a system to process volumes of whatever that particular system deals with (e.g. biomass in an ecosystem, electrons in an electrical distribution system, or money in an economy).

The scaled conditional entropy,

$$\Phi = T_{..} \cdot \Psi = - \sum_{i,j} T_{ij} \log \left(\frac{T_{ij}^2}{T_{i.} T_{.j}} \right), \quad (\text{B2.13})$$

we rename the system “reserve”⁵, for reasons that soon should become apparent.

Of course, this uniform scaling does not affect the decomposition (8), which now appears as

$$C = A + \Phi. \quad (\text{B2.14})$$

In other words, (B2.14) says that the capacity for a system to undergo evolutionary change or self-organization consists of two aspects: It must be capable of exercising sufficient directed power, enough efficiency A , to maintain its integrity over time. Simultaneously, it must possess a reserve of flexible actions that can be used to meet the exigencies of novel disturbances. According to (B2.14) these two aspects are literally complementary.

A system lacking throughput efficiency has neither the extent of activity nor the internal organization needed to survive. By contrast, systems that are so tightly constrained and honed to a particular environment appear “brittle” and are prone to collapse in the face of even minor novel disturbances. Systems that endure — that is, are sustainable — lie somewhere between these extremes. But where?

In order to be able to answer that question, we define $a = A/C$ and notice that $1 > a > 0$. Here a is a relative measure of the organized power flowing within the system. Using Boltzmann’s formulation, $-\log(a)$, we shall call an ecosystem’s “fitness for evolution”,

$$F = -k a \log(a), \quad (\text{B2.15})$$

our measure of the system’s potential to evolve or self-organize. $F = 0$ for $a = 1$ and approaches the limit of 0 as $a \rightarrow 0$. One can normalize this function by choosing $k = e \log(e)$ (where “ e ” is the base of natural logarithms), such that $1 > F > 0$.

One way to permit the maximum to occur at an arbitrary value of a is to introduce an adjustable parameter, call it β , and to allow available empirical data to indicate the most likely value of β .

Accordingly, we set $F = -k a^\beta \log(a^\beta)$. This function can be normalized by choosing $k = e / \log(e)$,

so that $F_{\max} = 1$ at $a = e^{-\frac{1}{\beta}}$, where β can be any positive real number. Whence, our measure for

4 We will abbreviate this variable simply as efficiency. The original ecological literature refers to this variable as “ascendency”, hence the choice of the letter A for this variable. (Ulanowicz 1980)

5 From here on “reserve” will apply to what heretofore has been called “reserve capacity”.

Sustainability of a complex network - its “fitness for evolution” in natural ecosystems systems – becomes:

$$F = - [e/\log(e)] a^{-\beta} \log(a^{-\beta}) \quad (B2.16)$$

The function F varies between 0 and 1 and is entirely without dimensions. It describes the fraction of activity that is effective in creating a sustainable balance between A and Φ . That is, the total activity (e.g., the GDP in economics, or T.. here) will no longer be an accurate assessment of the robustness of the system. Our measure, T.., must be discounted by the fraction (1-F).

Equivalently, the robustness, R, of the system becomes

$$R = T.. \cdot F \quad (B2.17)$$

This measure of robustness, R, can be employed to indicate which features of a given configuration deserve most remediation to attain sustainability.

In terms of graphic representations of the relationships between all these variables, it has proven useful to plot the networks, not on the axes A vs. Φ , but rather on the transformed

$$\text{axes } n = 2^A \quad \text{and } c = 2^{\frac{\Phi}{2}}$$

The reasons for this choice of this particular exponential scaling are fully explained in Zorach and Ulanowicz (2003). The variable n gauges diversity a natural ecosystem, defined as multiplicity of parallel pathways effectively available in the network. Technically, in ecological literature it represents the effective number of trophic levels in the system; or how many transfers, on (logarithmic) average, a typical quantum of medium makes before leaving the network. The variable c measures the effective connectivity of the system in links per node, or how many nodes on (logarithmic) average enter or leave each compartment.

These two variables n and c have revealed themselves the two most important *structural* variables of any complex network. They are the common reference variables for all our graphic analyses in chapter 2, because they best capture the structural issues that emerge in complex flow networks.

What can we tell a priori, mathematically, about the shapes we should expect of the variable C, A and Φ in terms of these two structural variables?

The functions C, A and Φ all happen to be homogeneous Euler functions of the first order. This means that the derivatives with respect to their independent variables are relatively easy to calculate (Courant 1936.)

Starting from our definition of robustness (17), we seek to establish the direction in which this attribute responds to a unit change in any constituent flow. That is, we wish to calculate ($\partial R/\partial T_{ij}$.)

Employing the chain rule of differentiation, we see that

$$\begin{aligned} \frac{\partial R}{\partial T_{ij}} &= F + T.. \frac{\partial F}{\partial T_{ij}} \\ \frac{\partial R}{\partial T_{ij}} &= F + T.. F' \frac{\partial a}{\partial T_{ij}} \\ \frac{\partial R}{\partial T_{ij}} &= F + \frac{T.. F'}{C} \left\{ \log \left[\frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right] + a \log \left[\frac{T_{ij}^2}{T_{i.} T_{.j}} \right] \right\} \end{aligned} \quad (B2.18)$$

Where F' is the derivative of F with respect to a , i.e.,

$$F' = -e\beta a^{\beta-1} \left[\frac{\log(a^\beta)}{\log(e)} + 1 \right] \quad (B2.19)$$

In particular, when the system is at its optimum ($F = 1$ and $F' = 0$) we see from (18) that a unit increment in each and every flow in the system would contribute exactly one unit to system

robustness. Once away from the optimum, however, contributions at the margin will depend on which side of the optimum the system lies, and where in the network any particular contribution is situated.

When $a < a_{opt}$, then F' will be positive, so that those flows that dominate the inputs to or output from any compartment will result in a positive sum within the braces, and the contribution of that transfer at the margin will be >1 . For the relatively smaller flows, the negative second term in braces will dominate, and the contribution of those links at the margin will be <1 .

As we have seen, the notions of *both* presence and absence, respectively what the Chinese tradition called the Yang and the Yin energies, are explicitly built into this framework. Such architecture accounts for relationships like (8) and (14) wherein complementary terms of 'what is' and 'what is not,' share the same dimensions and almost the same structure. That is, one is comparing apples with apples. Furthermore, the effects of lacunae no longer remain external to the statement of the dynamics; they become central to it.

The model just discussed highlights the necessary role of underused capacities in sustaining ecosystems or any other complex flow system. It contrast with Darwinian theory, which unfortunately is espoused by many simply as the maximization of efficiency (e.g., the survival of the fittest.) Such emphasis on efficiency is evident as well in some mistaken approaches to ecology, such as optimal foraging theory; and is practically universally assumed in economic theory. Our results alert us to the need to exhibit caution when it comes to maximizing efficiencies. Systems can become too efficient for their own good. Autocatalytic configurations can expand to suck away resources from nonparticipating or marginally participating actors, leaving them to wither and possibly to disappear, and thereby increasing the brittleness of the whole system.

It is exactly what is claim to have happened, and is continuing to happen, in the monetary domain.

References

- Courant, R., 1936. P108 in *Differential and Integral Calculus*, vol. 2. Interscience Publishers, New York, p. 681.
- Rutledge, R.W., Basorre, B.L., Mulholland, R.J., 1976. Ecological stability: an information theory viewpoint. *J. Theor. Biol.* 57:355–371.
- Ulanowicz, Goerner, Lietaer and Gomez "Quantifying Sustainability: Resilience, efficiency and the Return of Information Theory" *Journal of Ecological Complexity* Vol 8 #1 (March 2009)
- Zorach, A.C. and R.E. Ulanowicz. 2003. "Quantifying the complexity of flow networks: How many roles are there?" *Complexity* 8(3):68-76.