Measuring Regenerative Economics:
10 principles and measures undergirding systemic economic health

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Abstract

Applying network science concepts and methods to economic systems is not a new idea. In the last few decades, however, advances in non-equilibrium thermodynamics (i.e., self-organizing, open, dissipative, far-from-equilibrium systems), and nonlinear dynamics, network science, information theory, and other mathematical approaches to complex systems have produced a new set of concepts and methods, which are powerful for understanding and predicting behavior in socio-economic systems. In several previous papers, for example, we used research from the new Energy Network Science (ENS) to show how and why systemic ecological and economic health requires a balance of efficiency and resilience be maintained within a particular a "window of vitality". The current paper outlines the logic behind 10 principles of systemic, socio-economic health and the quantitative measures that go with them. Our particular focus is on "regenerative aspects", i.e., the self-feeding, self-renewal, and adaptive learning processes that natural systems use to nourish their capacity to thrive for long periods of time. In socio-economic systems, we demonstrate how regenerative economics requires regular investment in human, social, natural, and physical capital. Taken as a whole, we propose these 10 metrics represent a new capacity to understand, and set better policy for solving, the entangled systemic suite of social, environmental, and economic problems now faced in industrial cultures.

Keywords: regenerative economics; resilience; economic networks; self-organization; autocatalysis; socio-ecological systems; network analysis

1.0 Introduction: Energy and the Transdisciplinary Science of Systems

Researchers in ecology and its allied field, ecological economics, have produced many of the key advances in the study of energy flow networks (see just below for definition of this term). Yet, even though ecological economists apply flow network thinking to economics, they often see these economic applications as metaphoric extrapolations from biology and ecology. So, while network methods are well known in ecological economics, their use in understanding systemic health in economic networks themselves requires some justification for why this approach is something more than mere biological analogy.

The newer literature on network science applied to economic problems or computational economics has shown us that – when informed by data, patterns, and features such as power law distributions – feedback effects, non-linearity, and heterogeneity can be found in numerous contexts and economic phenomena, from micro to macro [1,2,3]. While the literature on data driven, computational models of economic systems has become quite vast during the past decade, what this new evidence and context-specific results lack is a robust theoretical and conceptual framework that we are laying out in the following sections of the paper.

Note, a wide range of related work involving energy and flow network concepts and methods is emerging under a host of diverse disciplinary titles such as resilience theory, complexity theory, self-organization theory, non-equilibrium thermodynamics, ecological network analysis, network environ analysis, and Panarchy. The transdisciplinary nature of this science also requires some adjustments to terminology. For example, where ecologists call their flow network methods Ecological Network Analysis or Network Environ Analysis, to emphasize this work's broader applicability, we will replace the discipline-specific word "ecological" with the transdisciplinary term, Energy Network Analysis. Thermodynamics – the study of energy dynamics in all its forms – provides a logical basis for a transdisciplinary "systems" science because energy processes are highly generalizable and amenable to scientific inquiry and measurement.

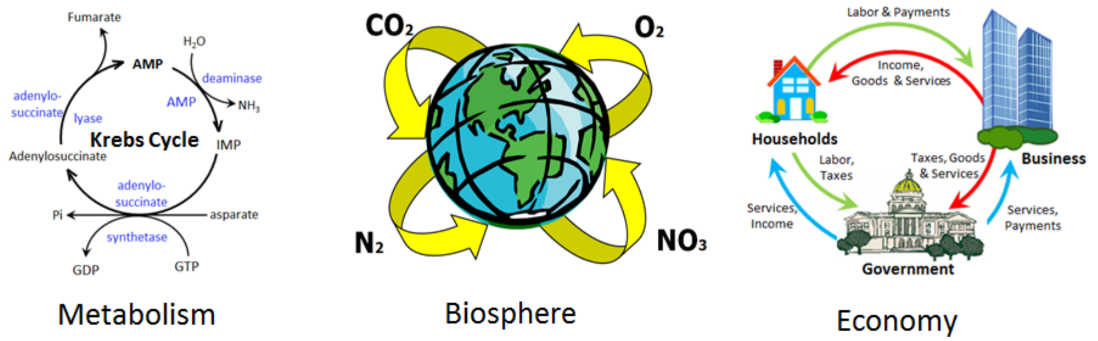
From resilience and complexity theory to self-organization and ecological network analysis, the disciplines we group under the umbrella term Energy Network Science (ENS) are all offshoots of the original General Systems Science impetus. General Systems Science is a transdisciplinary study built around two core pillars: 1) the existence of *universal patterns;* and 2) *energy's role in organizational emergence, growth, and development*.

In the 1950s, and 60s, biologist Ludwig von Bertalanffy [4] sought to connect energy dynamics and pattern formation as the basis of a unified scientific research program studying the behavior of complex systems *in general,* including the dynamics governing their formation, self-maintenance, and increasing complexity. A "system" was initially defined as 'any assembly of parts whose relationships make them *interdependent.*' The goal of this General Systems Science was a coherent, transdisciplinary, empirical science of "systems," including living, non-living and supra-living organizations such as ecosystems and economies.

In the 1970s, Belgian chemist Ilya Prigogine unified this work (and won a Nobel Prize) by explaining how an energy-flow process called *self-organization* drives the emergence of new configurations and creates pressures which drive the ongoing cyclical development of existing ones [5, 6]. Prigogine's work, however, produced a distinct disjuncture from classical thermodynamics. Where classical thermodynamics is built around the study of systems which are at or near equilibrium, the complexly organized systems that emerge from self-organizing processes are specifically designed to maintain their organization *far-from-equilibrium*. They do this by *autocatalytic* or autopoietic arrangements (i.e., self-feeding, self-renewing, "regenerative" ones), meaning they are designed to channel critical flows back into maintaining their organization on an ongoing basis.

1.1 Energy Flow Networks

The energy network research we do today is a continuation of this far-from-equilibrium work. Here, self-organizing processes naturally give rise to what researchers call *flow systems* or *flow networks*. A flow network is any system whose existence arises from and depends on circulating energy, resources, or information throughout the entirety of their being. Your body, for example, is an integrated network of cells kept healthy by the circulation of energy, water, nutrients, and internal products. Ecosystems are interconnected webs of plants and animals (including decomposers) that add to and draw from flows of oxygen, carbon, nitrogen, etc. Economies are interlinked networks of people, communities, and businesses, which depend on the circulation of information, resources, money, goods, and services (Figure 1).



Metabolism
Biosphere
Economy

Figure 1. *Some common flow networks.*

Flow networks are also called "open systems" because, in contrast to the closed "conservative systems," which are the main focus of classical thermodynamics, open systems are characterized by ongoing transfers of matter, energy and/or information into and out of the system's boundary.

The central role circulation plays in the existence and functioning of all flow networks brings us to another terminological adjustment. While most people associate the term "energy" with various forms of fuel (oil, gas, solar, etc.), in ENS, it refers to *any kind of flow* that is critical to drive the system under study. Ecologists, for example, study the flow of carbon and oxygen in the biosphere; food-security researchers study the flow of produce, grains, and commodities; and Industrial economists study the flow of minerals and industrial products. The circulation of *money* and *information* is particularly critical in socio-economic networks, and these flows are always closely linked to networks and processes of energy.

Yet, despite this broad applicability, energy's ability to support rigorous scientific study across vastly different systems is also borne out by some well-established empirical findings, particularly regarding growth and development. Ecologists, for example, have long known that ecological succession, the progression from grasslands to pine forests to oak forests, is accompanied by a parallel progression of Flux Density, a measure of internal circulation speed of energy/resources per unit time per, unit density [7]. The energy explanation for this matched progression of circulation and organizational complexity is straightforward. Robust, timely circulation of critical resources is essential to support a system's internal organization and processes – and, the more organization there is to support, the more nourishing circulation is needed to support it. This thought applies as much to human organizations as to ecosystems.

Network flow also ties directly to systemic health and development because, if critical resources do not adequately nourish all sectors or levels, then we can expect the undernourished segments of the economy to become necrotic. Like necrosis in living organisms, poor cross-scale circulation erodes the health of large swaths of economic "tissue" – typically specializations at the periphery, which in turn undermines the health of the whole.

The recurring structural patterns that arise from network flow represent optimal arrangements for circulation and flow selected by nature over long periods of time. Fractal branching patterns found throughout the living and nonliving world provide a clear example (Figure 2). Bejan's Constructal Theory, for example, states "for a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it" [8, 9]). A wide variety of systems – from leaves and river deltas to circulatory systems and ecosystems – exhibit a hierarchical branching pattern connecting a power-law ratio of small, medium, and large elements across scales. Your circulatory system, for example, has a few large, highly efficient conduits branching into successively smaller, more numerous, less efficient conduits below. The same arrangement is also seen in leaves, lungs, erosion patterns, lightning bolts, and network relationships in an ecosystem. This structure is ubiquitous because a power-law balance of small, medium, and large elements helps optimize circulation and diffusion across scales, from point to area or area to point. Big, efficient elements (arteries or multinationals) provide the speed and volume needed for rapid cross-level circulation, while the many small elements (capillaries or local contractors) reach every nook and cranny [10].

A number of researchers are already using fractal and power law patterns as targets for healthy arrangements in human systems. Salingaros [11], for example, shows how a fractal layout of roads/pathways helps catalyze a broad spectrum of city processes, thereby increasing conversation, innovation, and community cohesion. The balance of sizes found in healthy natural systems is used to explain the balance of resilience and efficiency needed to support optimal systemic health in economic and financial networks [12-14]. And, Goerner et al. [15] uses fractal designs to explain the Goldilocks Rule of Banking – why each scale needs banks that are "just right" to meet the commercial needs of that scale.

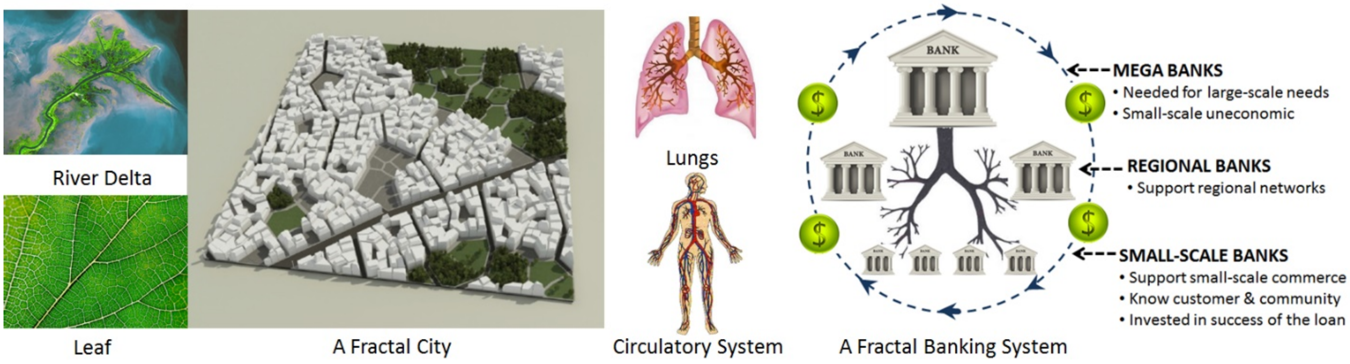


Figure 2. *Fractal structures maintain a power-law (x^n) balance of small, medium and large elements*

This well-documented line of research holds an encouraging possibility: *rigorous, quantitative measures* for the social sciences, including the potential for certain types of prediction and for anticipating systemic behavior. ENS' discovery of methods appropriate to "organized complexity" helps add rigor, albeit of a pattern and organization which differs from classical determinism. Thus, while energy methods cannot predict every specific behavior, they can help to understand phenomena dealing with the organization and relations of the network constituents such as the robustness index described below. Network science enables anticipatory action and policy to help guide socio-economic systems in ways that are compatible with the precautionary principle. One of the main links is through the quantification and understanding of redundancy as a crucial component of network adaptive capacity.

Combining the fact that energy processes (such as circulation) are behind causal factors (such as nourishment and necrosis) which directly impact system functioning, and the fact that optimal patterns appear to follow mathematical rules, means we can use universal patterns as *quantitative measures* and *targets* for systemic health (health, here, refers to the sustained, self-supporting performance and behavior of the system in question). Such measures are vastly more effective than traditional outcome metrics or statistical correlations because they assess *root causes*, i.e., ones that directly impact systemic health. The ten ENS principles presented below capture the phenomenology of the deep root causes looking for specific attributes that may show signs of imbalance or ill-health. We call these "intrinsic" measures because, where most traditional social, economic, and environmental metrics assess *symptoms* of socioeconomic health or dysfunction, they examine underlying causal dynamics.

In sum then, the fact that energy dynamics are logical, nearly universally applicable, and open to empirical study explains why rigorous findings apply as much to economic networks as to ecosystems. So, while ecologists are famous for using flow network concepts and methods to understand the behavior of ecosystems (e.g., [16–19]), economists have been using them to understand economies for decades as well (e.g., [20–26]).

2.0 Indicators of a Regenerative Economy

Energy ideas and concepts have been developing inside and outside of economics for decades, even millennia. The aforementioned vision of circulation, for example, is basically a recapitulation of Keynesian economic theory. Indeed, according to economist Kenneth Boulding [27], "Many early economists held energy views, until those who favored Newtonian mechanics channeled economics towards today's familiar mechanics of rational actors and the reliable self-restraint of General Equilibrium Theory."

We believe the framework these early economists were looking for is one of a *metabolic system*, particularly one that is designed to be naturally self-renewing (i.e., regenerative). In this metabolic view, economic vitality rests first and foremost on the health of the underlying human networks that do all the work and underlying environmental networks that feed and sustain all the work. In other words, systemic health depends largely on the care and feeding of the entire network of interconnected socioeconomic systems, including: individuals, businesses, communities, cities, value-chains, societies, governments, and the biosphere, all of which play critical roles in production, distribution, and learning. A healthy economic metabolism must also specifically be "regenerative," meaning it must continuously channel resources into self-feeding, self-renewing, self-sustaining internal processes. In human systems, this means reliable, steady and significant funding for education, infrastructure, innovation, and entrepreneurship.

In addition to the self-organizing and regenerating aspects, collective and collaborative learning is central to societal health and prosperity. The principles and measures of systemic health emerging from ENS can help illuminate a solid path to a *regenerative* society. Here, the *web of human relationships and values* is also more important than GDP growth per se because a society's vitality – i.e., its ability to produce, innovate, adapt, and learn – depends almost entirely on these relationships and values. Cultural beliefs are important because they determine the obstacles and opportunities, incentives and impediments extant in the society. Man-made incentives, for example, affect whether an organization works primarily to serve its customers and civilization, or to maximize its owners' profits regardless the harm done to people and planet.

Putting all these elements together suggests that the elements of regenerative economics fall into four main categories: 1) circulation; 2) organizational structure; 3) relationships and values; and, 4) collective learning. While we present them separately for clarity, all of these categories are in fact inseparably intertwined and mutually-affecting.

2.1 Circulation

As stated above, circulation affects economies in much the same way it affects living organisms and ecosystems as an essential factor in the metabolism, maintenance, and motive force. Robust cross-scale circulation nourishes, energizes, and connects all the complex collaborative functions a socio-economic system needs to thrive. Circulation's impact on the economic is easy to see. Major influxes of money, novel ideas, information, resources, and fuel sources (e.g., coal, oil, wood) have spurred major economic development throughout history.

Circulation also teaches us that *where* money, information, and resources go is just as important as how much of it there is. In Keynesian terms, poor economic circulation to the working public – including lost jobs, low wages, closed factories, and crumbling infrastructure – reduces aggregate demand, which undermines economic vitality regardless of the size of GDP. Using our economic metabolism model, we say poor economic circulation causes *economic necrosis*, the dying-off of large swaths of economic tissue with ensuing damage to the health of the whole.

2.2 Organizational Structure

Organizational structure is inseparably entwined with circulation, stability, relationships and collective learning. A system's structure can either enhance systemic health by channeling flow to critical processes or undermine it by blocking flow from where it really needs to go. As we have seen, repeated patterns produced by self-organizing processes are particularly helpful in understanding organizational structures because they represent relatively optimal structures selected over time [9, 10].

The role fractal structures play in optimal cross-scale circulation and functioning provide some important revisions to classical thinking about size. In particular, where some economists see large size and efficiency as the primary source of vitality and others emphasize the small and local, fractals and network science teach us that vitality requires *balance* and *integration* of sizes that combine the best of both worlds, i.e., large and small, resilient and efficient, diverse and focused. This need for balance is easy to see and evident in business firms [28, 29]. Big firms with economies of scale are generally more productive and offer higher wages, but towns dominated by a few large companies are vulnerable and brittle – if a mainstay company leaves, they have no other industries to fall back on. The 2008 crisis of too-big-to-fail banks shows the problem. A bevy of small businesses offers more choice, more redundancy, and more resilience, but economies dominated by small firms tend to be sluggish because economic surplus is hard to maintain. This leaves overstretched staffs with little money for specialization, expansion, or quality improvements.

Reformers seeking to revitalize local economies often argue that small is both beautiful and all we need [30]. However, smallness alone can never work forever because, in order to develop and handle volume, small businesses and individual farmers need economies of scale for buying, distributing, lobbying, and learning from each other. Today's challenge, therefore, is to build integrated, enterprise networks that connect small, medium, and large elements in common-cause and in service to the health of the whole. This challenge is also seen in such diverse fields as politics, healthcare, education, and urban planning.

Conventional thinking may suggest that enterprise networks in the market economy cannot be built, that they only self-organize semi-independently according to market constraints, government policy and related context factors. This view sees the capacity of socio-economic actors to serve broader goals and values as limited to each individual organization's mission, business model, and perspective. From this stance, any service to common values (see next section) necessitates the role of state in policy making, which is further limited by potential errors and misconceptions in the best way to incentivize and encourage positive behavior.

In contrast to this view, it is important to note that regenerative economics in general, and our proposed principles and metrics here, do not only focus on markets. Instead, the theory and methods are framed more broadly on communities, social systems, and other larger more complex human-natural systems. In this larger context we – compatible with work of Elinor Ostrom [3] – have shown many cases and many conditions in which communities of people do self-organize in ways that inherently protect and support the regenerative capacities of their economies, social systems, and environment with integrated natural resources.

3.3 Relationships and Values

Mutually beneficial relationships and common cause values are critical to long-term vitality because economic networks are collaborations built of specialists who produce more working together than alone, even if emerging as an unintended consequence. There have been identified several network effects, specific to social networks, in economic networks as well. Specifically, Metcalfe’s Law and Reed’s Law, which are laws specific to any type of network and can be applied to economic networks as well, mathematically state the overall value of those networks; they have shown to have non-linear effects at the level of the community, either proportional to the number of economic agents (individual or firms) in the network, or with the number of subgroups that form the network [2].

As another angle on the goal "to build enterprise networks" to realize systemic health, we could also think of values, policies, skills and norms that will "encourage the self-organization of enterprise networks" for systemic health. The constraints and context of socio-economic actors can include the knowledge, values, and tools that Energy Network Science and regenerative economics provide. As this mindset becomes more adopted – and tested – we expect it to lead to a new appreciation of the interdependence of the individual and enterprise self-interest with the larger interest of human communities and natural systems. This learning is rapidly developing via holistic education and collaborative learning as individuals and groups find new ways to communicate via the internet and related technologies. As these values, mindset, and knowledge become part of standard operating procedure in business and government it can influence the organic self-organization that can occur, similar to that now driven by micro-enterprise self-interest. Ostrom et al. [31] showed definitively that it is not an either/or choice that Garrett Hardin framed in Tragedy of the Commons [32]. We do not have only two choices - either capitalist market control or government control. Well-informed self-organization is a viable alternative path.

Common-cause values such as trust, justice, fairness, and reciprocity facilitate collaboration and are the bond that holds specialists together. Self-interest is part of the process, but mutual benefit/reciprocity and commitment to the health of the whole are vastly more important because specialists must work together in interlocking circuits such that the health of every individual depends on the health of the whole. Injustice, inequality, and corruption increase instability because they erode unifying values. A mountain of sociological research confirms these facts (e.g., [33-35]).

Furthermore, Ostrom [36] identified a set of 10 socio-ecological system (SES) variables most closely linked to the success of local communities self-organizing to achieve social and environmental sustainability, crucial common-cause values. Citing Hardin [32], she applied her 10 variables to answer the question, “When will the users of a resource invest time and energy to avert a Tragedy of the Commons.” She sub-divides SES variables into (1) natural resource systems, (2) governance systems, (3) natural resource units, (4) users (the people involved), (5) interactions and linked outcomes, and (6) related ecosystems. Her top 10 system variables from these six categories are a blend of human and natural factors associated with well-informed self-organization balancing benefits and synergizing processes of the individual and the whole.

3.4 Collective Learning

The self-organizing story of evolution sees humanity as a collaborative-learning species that thrives by forging new understandings and changing our pattern of life by changing our beliefs about how the world works. Here, effective collective learning is humanity's central survival strategy and the keystone to long-term vitality.

While regenerative investments in education and science are known to produce huge social and economic benefits, energizing collective learning requires more than science and education per se. A Royal Dutch Shell study [37], for example, found that companies that remain vibrant for extremely long periods of time do so by creating a *learning community*. Instead of slavishly serving short-term numbers, executives promote long-term profits by investing in the company's people and their ability to innovate and adapt. As the report concludes:

> "The manager …must place: commitment to people before assets; respect for innovation before devotion to policy; the messiness of learning before the orderly procedures; and the perpetuation of the community before all other concerns."

The speed and quality of our collective learning is also of the essence today because failure to learn can have severe consequences. Anthropologist Jared Diamond [38], for example, concluded that failure to learn is the underlying cause of most societal collapse. As he says, "Societies aren't murdered; they commit suicide. They slit their wrists, and in the course of many decades, stand by passively and watch themselves bleed to death."

4.0 Ten Principles and Measures of Regenerative Economics

ENS can aid the process of understanding and implementing the *rules of regenerative economics* – socially, politically, and economically as well as environmentally – by identifying certain basic principles and the measures that go with them. While scientists will no doubt find many more intrinsic measures over time, we believe the ten principles described below outline a critical path to a regenerative society. Figure 3 shows how they fit in our four key categories.

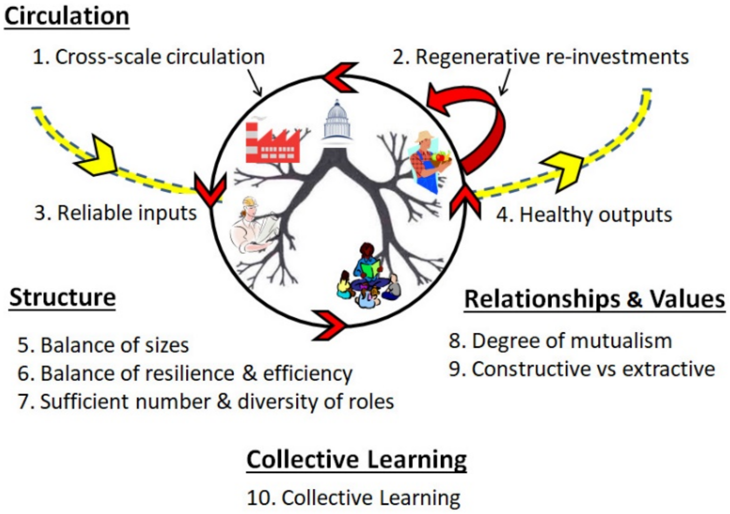


Figure 3. *How the 10 principles fit in our four key categories.*

NOTE: The measures presented below are derived primarily from Ecological or Energy Network Analysis (ENA). Appendix A provides a brief description of mathematical logic and the notation used.

4.1 – Principle 1: *Maintain robust, cross-scale circulation of critical flows including energy, information, resources and money.*

Cross-scale circulation of money, information, and critical resources is important because all sectors and levels of our economic metabolism play mutually supportive, interlinked roles. Workers, for example need employers for wages and products, and employers need workers to produce products. At the ecosystem and biosphere scale, flows of energy, water, carbon, nitrogen and other key biophysical currencies are both essential for the long-term sustainable operation of societies and economies, and they are amenable to quantitative analysis and whole-system understanding as for other flow networks.

The central role cross scale circulation plays in network health explains the Keynesian vision of how aggregate-demand (total spending in the economy) affects economic health. In flow terms, low wages, unavailability of commercial loans, and frequent layoffs reduce circulation to lower levels causing necrosis. When money does not reach the broad-scale public, aggregate-demand declines and economic depression ensues.

Cross-scale circulation can be measured using ENS by how rapidly and thoroughly resources circulate inside the organization. In economics, the Multiplier Effect metric assesses how many times a unit of currency entering a market will be exchanged before exiting that market. Again, flows can be tracked and analyzed for money and information in socio-economic networks, and for energy, water, and carbon in ecosystem networks, and in all such cases the knowledge will have profound relevance for economic and systemic health. We suggest measuring cross-scale circulation using Total System Throughflow (TST) as a fraction of the total input into the system, also termed network aggradation in ENS:

$$Network\ Aggradation = \frac{TST}{\sum_{i=1}^{n} z_i}.$$

4.2 – Principle 2: Regenerative re-i*nvestment*

The flow networks we care most about – living organisms, ecosystems, and societies – have naturally co-evolved to be *self-nourishing*. Their continuation requires they continually pump resources into building, maintaining, and repairing their internal capacities. This is what makes them regenerative, i.e., naturally self-renewing. Consequently, any society which hopes to live long and prosper must continually invest in its internal capacities, including its members' skills and well-being; its institutions' integrity and capacities; its commonwealth infrastructure from roads and schools to the Internet and utilities; and its supporting environment of ecosystem services.

Investing in human capital increases network productivity, motivation, innovation, loyalty, and learning simultaneously. This makes internal circulation vastly more important to vitality than GDP growth, which only measures the volume of flow (total system throughflow in ENS terms) not where it goes or how it is used. Studies estimate, for example, that every $1 spent on the G.I. Bill returned $7 to the American economy [39]. Investing in local businesses also improves economic resilience, which increases in step with the number of locally-rooted businesses and the amount of investment in local capacity. Conversely, austerity measures undermine the health of already ailing economies by curtailing investment, circulation, and socio-economic nourishment particularly at the grassroots level.

Regenerative re-investment can be measured using ENS by the percentage of money and resources the system invests in building and maintaining its internal capacities and infrastructure. Again, the same measures and principles apply to studies of essential ecosystem services responsible for regenerative, sustainable supplies of energy, water, food and all biological needs of people and economies. We use the Finn [40] Cycling Index (FCI), the fraction of total through-flow cycled in the network. Cycling of node $i (Tc_i)$ can be calculated as:

$$Tc_i = ((n_{ii} - 1)/n_{ii})T_i$$

Here: $FCI = \frac{\sum Tc_i}{TST}$

4.3/4 – Principles 3 & 4: *Maintain reliable inputs & healthy outputs.*

These two principles are coupled complementarily and are treated together. Circulation also applies to inputs and outputs. If a society runs out of a critical resource such as fuel or water, then it will collapse. The struggle to replace fossil fuels with more reliable energy sources demonstrates the problem. Since flows are inevitably circular, societies that foul themselves or their environment by generating outputs that cannot be assimilated by the local environment will also die.

Consequently, one major focus of the sustainability movement – the struggle to maintain reliable inputs of critical resources and healthy outputs from clean water to Green energy – can also be viewed as a network flow challenge. The science of flow, however, extends critical inputs to include accurate information, quality education, nourishing food, and robust monetary circulation.

Input reliability can be assessed by how much risk attends critical resources such as energy, information, resources, and monetary flows upon which the system depends. *Healthy outputs can be assessed* by how much damage outflows do both inside and outside the system. We would assess the input reliability driving the system using existing indicators, including sustainability indicators of renewability such as percentage of energy from renewable sources and declining energy-return on energy invested both based on overall flow amounts. We would assess system outflow using an index of human impacts (e.g., cancer rates) and environmental impacts (e.g., pollution and carbon levels). The latter can be gauged by measures of the local or global environment's capacity to absorb wastes, such as carbon-sequestration capacities of forests, safe nitrogen-input capacity of soils and natural lands, etc.

4.5 – Principle 5: *Maintain a healthy balance and integration of small, medium, and large organizations.*

Long-term vitality requires (at least) approximating fractal/power law balance of organizational sizes because this represents a (relatively) optimal arrangement for a multiscale system of a given size. Similarly, just as drainage basins evolve water systems that include tributaries and large rivers to serve the activity at different scales [9], so the Goldilocks Rule of banking [15] suggest that commercial activity promotes organizations designed to serve the financial needs of each scale, local to global.

We assess balance using the distribution of sizes, incomes, or resources within the system. Flow-network data can then be plotted using a weighted distribution of stocks and flows, compared against power-law distributions found in nature, and checked for indications of imbalance (e.g., [41]). Fertile soils, for example, have power-law distributions of carbon, nitrogen, organic matter and other essential resources, with large amounts near the surface and decreasing amounts going down to bedrock. This distribution provides functional and structural benefits, while also adding resilience to the communities existing on those soils. Unsustainable farming dissipates these structural and functional gradients, while regenerative agriculture restores them.

4.6 – Principle 6: *Maintain a healthy balance of resilience and efficiency.*

Ulanowicz et al. [12] also use the balance of sizes to identify the balance of *resilience* and *efficiency* needed for systemic health. Noting that the factors which contribute to efficiency (large size, high-capacity, streamlining) are opposite to those that contribute to resilience (small size, diversity, dense connectivity), Ulanowicz discovered that healthy ecosystems maintain a balance of both. He used data from healthy ecosystems to identify the "Window of Vitality," the range of balance within which healthy systems fell (Figure 4), speculating that extremes are not observed because too much efficiency creates brittleness, while too much small-scale diversity creates low-energy stagnation.

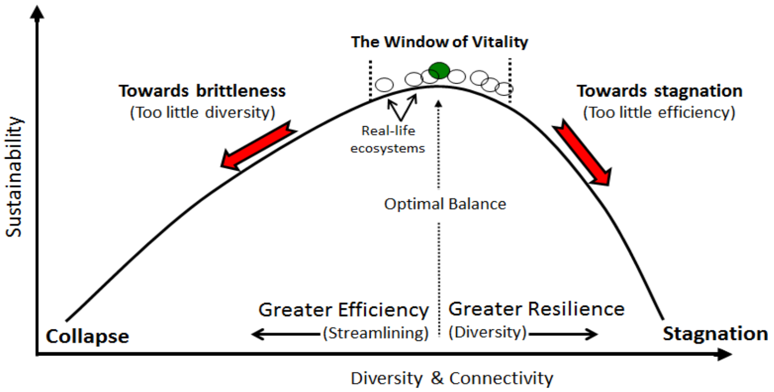


Figure 4. *The Window of Vitality delimits a healthy balance of resilience and efficiency*.

This work shows why today's emphasis on efficiency and "economies of scale" is useful *up to a point*, beyond which it is destructive to the organization as a whole. Lietaer et al. [42] used this discovery to show that today's excessive emphasis on efficiency and size in business and banking contributes to economic and banking crises, respectively. *A healthy balance of resilience and efficiency can be measured* using Ulanowicz' Window of Vitality metric [12] (see appendix).

4.7 – Principle 7: *Maintain sufficient diversity*

The endless diversity found in human beings, enterprises, and communities increases resilience, and helps fill niches and find new ways. Economic functioning requires a sufficient number and diversity of specialists serving critical functions to keep it going because systemic processing 'takes a village' of specialists, and because the bigger the society becomes, the more specialists – doctors, teachers, engineers etc. – of various types it needs. The number of groceries, schools, and hospitals, for example, must grow in step with population size in order to meet demand, and maintain access, choice and resilience.

The laws of sufficient diversity for populations of a given size are known to follow certain mathematical rules, which can be assessed by measuring the number and diversity of players in activities critical to system functioning. We use Zorach and Ulanowicz' [43] metrics for the number of roles needed in a specific network.

$$Roles = \prod_{i,j} \left(\frac{F_{ij} \quad F_{..}}{F_{i.} \quad F_{.j}} \right)^{Fij/_{F..}}$$

4.8 – Principle 8: *Promote mutually-beneficial relationships and common-cause values.*

Fath [44] has shown using network analysis that ecosystems exhibit overall positive levels of mutual benefit when considering the effects of all direct and indirect relations. We believe similar network assessments of direct and indirect benefit can be used to assess how the degree of mutual benefit impacts systemic health in socio-economic systems as well.

The degree of mutualism can be determined by a matrix of direct and indirect relational-pairings, which may be categorized as: exploitative (+, –); exploited (–, +); mutualist (+, +); and competitive (–, –) based on its flow relationships [44]. The number of positive signs is an indication of the overall benefit a node receives by participating in that network. Robust ecosystems display a greater number of mutualistic relations than competitive ones. A healthy economy should also display a greater degree of mutualism.

4.9 – Principle 9: *Promote constructive activity and limit overly-extractive and speculative processes.*

How can an economy differentiate between money made from Wall-Street speculation and that made by producing a product or educating a child? GDP growth cannot distinguish between a robust economy and a bubble because it only looks at volume of money exchanged (Total system throughflow in ENA terms), and counts damaging activity such as fraud, cancer, and oil spills as positive contributions. Today's disturbing result is that the failing health of real-economy networks is masked by an ephemeral cloud of speculation (Figure 5).

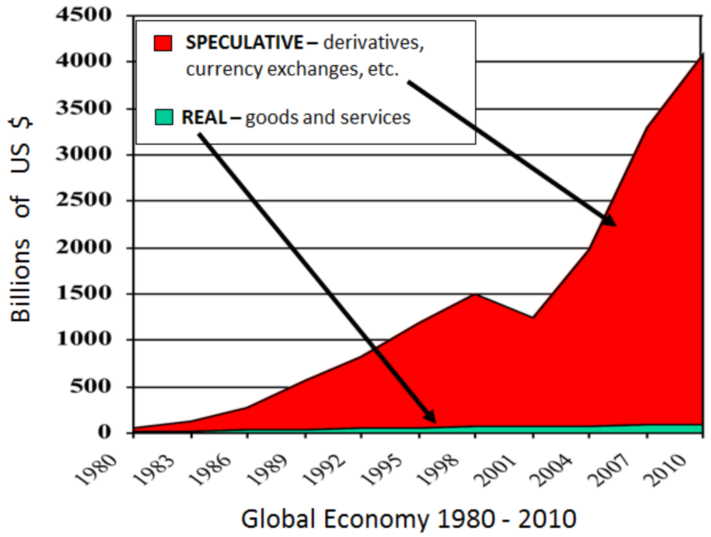


Figure 5. *Global GDP is more a function of speculation than of development in the real economy.*

In contrast, regenerative economists care a great deal about constructive activities because these build economic capitals and capacities. Regenerative economists, therefore, value activities that build infrastructure, productivity, power, and learning. They seek to limit: 1) excessive speculation because it creates bubbles of illusory wealth supported primarily by mania; and 2) excessive extraction because it causes economic necrosis.

We propose assessing the balance of constructive vs extractive/speculative activity as a ratio of value-add and capacity-building activities to extractive ones. Healthy systems (both human and ecological) are filled with numerous positive- and negative-feedback processes that together maintain a stable, self-sustaining flow pattern. Too much or too little of either amplifying (positive feedback) or dampening (negative feedback) processes leads to unstable, unsustainable patterns – explosive ones in the case of amplifying, and stagnant ones in the case of dampening processes. In flow terms, therefore, we are looking for imbalances, i.e., significant asymmetries between activities that build work-supporting gradients and ones that degrade them. A constructive network would have positive-feedback processes generating sufficient work-supporting gradients to maintain its capacities and activity. The number of autocatalytic cycles (i.e., closed-loops of length greater than 1) is one indicator of such "constructive" processes [45-46].

4.10 – Principle 10: *Promote effective, adaptive, collective learning.*

A society's ability to learn as a *whole* is the most important regenerative principle, and the hardest to measure. Relatedly, remaining adaptive is critical address novel and changing circumstances. Holling [47] has provided a powerful framework in terms of adaptive management. This approach has been implemented in an adaptive cycle that sees four stages of system growth and development (growth, conservation, collapse, and reorganization) [48–50]. Understanding ones place along this cycle will prepare next stages and focus the learning needs. Since there is no network-formula for effective learning and adaptive management, we suggest assessing it by creating a composite of existing indicators of:

1) Poorly addressed human needs, e.g., jobs, education, healthcare, nutrition, housing, etc.;
2) Underutilized human resources, e.g., unemployment, underemployment, inequality, poverty, etc.;
3) Poorly addressed critical issues, particularly environmental issues from pollution to global warming;
4) Educational priority such as school funding, educational attainment, tuition rates, community colleges, professional development, library programs; and
5) Levels of community involvement, e.g., voting, volunteerism, civic engagement, farmer's markets, sharing economy opportunities, community gardens, community art programs, etc.

5.0 Discussion

5.1 History of Systems Science in Global Transitions

The history of the transdisciplinary empirical science we have employed starts with the ancient Greek and Egyptian observation of mathematically precise, recurring patterns and principles of growth and development occurring in vastly different types of systems (Figure 6). The ubiquity of Fibonacci growth patterns and Golden spiral organizations are examples of this observation. The study of fractal patterns and nonlinear dynamics is a modern-day expansion of what is now called morphodynamics or the "geometry of behavior" [51-52]. While the observation of patterns and recording of recurring phenomena that seemed somewhat esoteric in the past, to various civilizations, has been helping us understand the old roots of the distributions and characteristics that modern day mathematics and computer science are only now starting to rediscover by using robust methodologies, we are nevertheless mentioning these in order to place our framework in historical context, without losing sight of the fact that many of these are now well documented by modern day science [53-54].

Work growing around the pillars of energy and universal patterns, especially of growth and development, began to come together in the early 1900s. In his 1917 book *On Growth and Form*, Scottish mathematical-biologist, D'Arcy Thompson [55] outlined the mathematical and scientific basis for morphogenesis, the universal processes of growth and development that give rise to the recurring shapes, patterns and forms found in plants and animals. In 1922, mathematical-biologist Alfred Lotka [56] expanded the study of energetics from biology to ecology and evolution, arguing that the selective principal operating in evolution was a physical law favoring "maximum useful energy flow transformation." Lotka's 1925 book [57], *Elements of Physical Biology*, even extended the energetics of evolution to suggest the physical (i.e., energy) nature of consciousness. General Systems ecologist, Howard Odum [58] used Lotka's research as the centerpiece of his work in Systems Ecology, and redefined Lotka's energy law of evolution into a Maximum Power Principle.

Writing in the 1940s through 60s, American scientist and mathematician Warren Weaver [59] then gave a proper name to the complexly organized systems that emerged from morphodynamic processes. In contrast to the simple, unidirectional causality that defined classical physics and the highly disconnected interactions that are the basis of statistics, Weaver explained that the "*organized complexity*" that fills our world is a natural product of the subtle relationships that connect diverse elements into profoundly organized, interdependent wholes (Figure 6). This mathematically-precise "organization" allows us to do empirical science on the extremely complex systems we care about most: living systems, human systems and ecosystems. Consequently, in 1961 urban anthropologist Jane Jacobs [60] used Weaver's work to define "the kind of problem a city is."

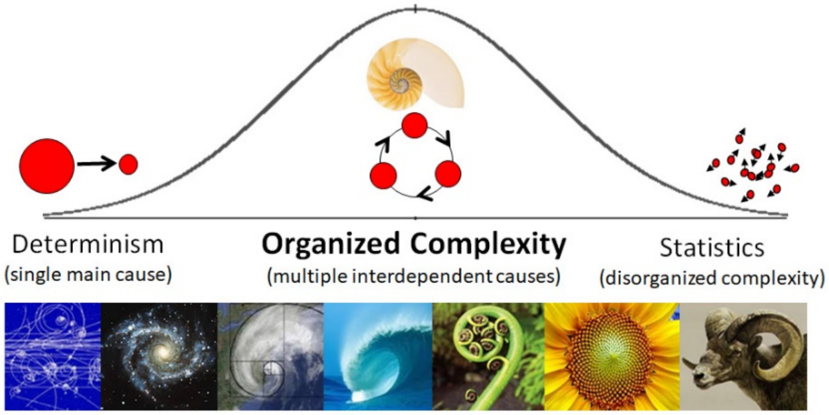


Figure 6. *Some universal patterns as examples of "organized complexity"*.

As mentioned, Ilya Prigogine won a Nobel Prize by explaining how an energy-flow process called *self-organization* drives the emergence of new configurations and creates pressures which drive the ongoing cyclical development of existing ones [5, 6]. Apropos of an energy-flow process, every round of emergence and development follows a similar process, which is found in a vast array of different systems. Energy buildups create pressures that drive change. Naturally-occurring diversity (inhomogeneity) provides the seed crystals that open new paths and catalyze new forms of organization. Meanwhile, the matrix of internal and external constraints determines the degree of flexibility or rigidity, which in turn shapes the outcome and whether flow moves toward constructive or destructive ends. For example, a tornado's funnel and a hurricane's spiral (organization) both emerge from the confluence of: 1) heat, i.e. a temperature gradient that creates pressure; 2) naturally occurring variations, i.e. small gusts, twists of geography, etc.; and 3) pressure or geographical constraints that block more gradual dissipative flow.

Such foundations in the science of complex systems provides both rigorous first principles and allows network methods to be very widely applicable with meaningful application including socio-economic systems, which are comprised of energy systems and networks of many kinds. Prigogine's work shows how cycles of self-organizing development, repeating over and over, are behind the succession of increasingly complex forms from the origins of atoms and galaxies to the latest incarnations of life and civilization (Figure 7). The same process repeats in every round: energy fuels, pressure drives, diversity catalyzes, and constraints shape the emergence of new organizations. Energy pressures periodically forge new levels of organization out of smaller existing bits. Atoms, molecules, living cells, multicellular animals, herds, cities, and civilizations all consist of smaller pieces coming together in new patterns of organization. Biologist Lynn Margulis [61], for example, shows that biological organisms become more complex by linking previously independent lifeforms into new unified organisms linked by synergy and mutual benefit: land plants are in an immortal marriage between photosynthetic algae and rugged, non-photosynthetic lichens; while the mitochondria, flagella, and nucleus of eukaryotic cells are built of previously independent prokaryotic cells. A complementary array of pressures and organizing influences propagate from the top-down, such as when global processes feedback to impact local environmental conditions. Overall, complex living systems arise and evolve in between the complex dynamic forces acting both bottom-up and top-down.

In the 13th century Europe, for example, the revival of long-distance trade (circulation), perhaps facilitated by the Medieval Warm Period, stimulated the emergence of cities, guilds, and new universities to spread new ideas. In the 15th century, trade and Gutenberg's press produced the Renaissance (supported by wealthy traders and bankers such as the Medici), and a new fascination with scientific inquiry that eventually spawned the Scientific Revolution. In the 19th century, new sources of coal and natural gas, and innovations such as the steam engine emerging from enlightened minds generated the Industrial Revolution and the free-enterprise democracies we live in today.

Though such self-organizing processes develop along directional trajectories, they never fully reach an end destination. As a result, evolutionary development appears as a recursive process of trial-and-error learning following a cyclical, punctuated, stair-step pattern of increasing complexity (Figure 7).

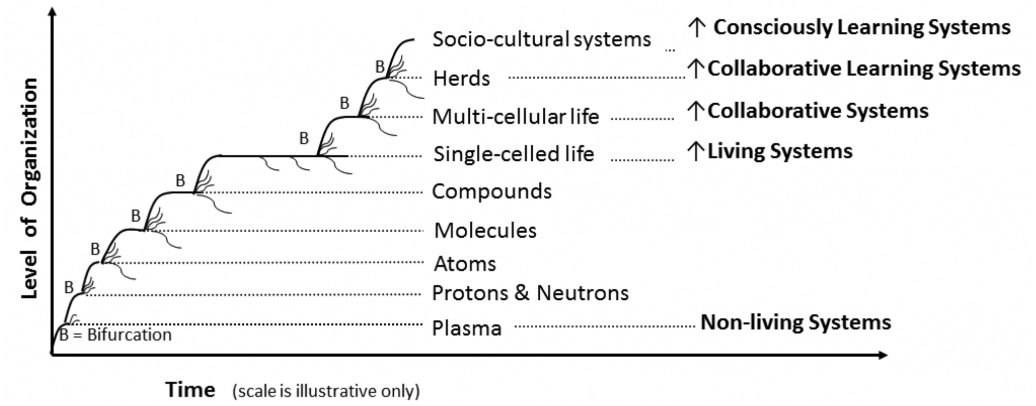
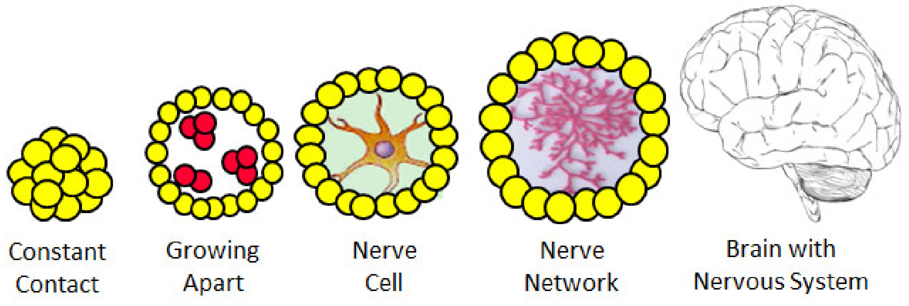


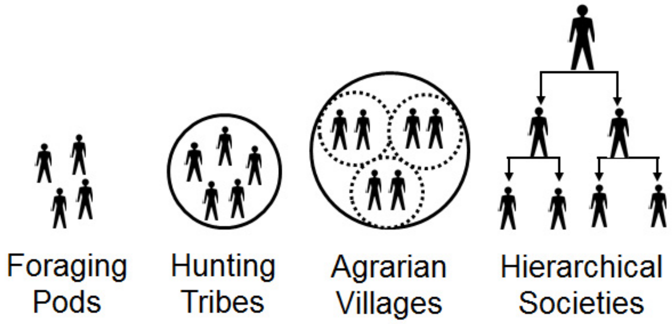
Figure 7. *Self-organization drives increasing complexity from molecules to mankind, periodically building new levels of organization out of old.*

Here, what we call "information" began as tiny energy nudges – a few photons of light or the chemical trail we call smell – that physically interacted with the system. "Intelligence" began when some energy nudge accidentally propelled the system toward a beneficial outcome, such as food to fuel continued activity. Information processing evolved rapidly after that because organisms that reacted fruitfully to informative nudges survived longer than ones that did not.

From the first living organisms to consciously-learning systems such as societies, information, organization, intelligence, and communication became ever more profoundly entwined and central to survival. As single-celled organisms evolved into multi-cellular organisms and eventually into herds of multicellular organisms, communication, i.e., circulating information among members, became essential to coordination and coherence in these increasingly vast wholes. Intelligence and communication eventually evolved into culture, language, and science because processing information and preserving lessons *collectively* vastly increases a group's chances of survival as well [62] (see Figure 8).



a. *Growth in size and complexity drives multicellular organisms to develop nerves, nervous systems and brains.*



b. *Growth in size and complexity drives human groups to develop new forms of cultural mores and organizational structure.*

Figure 8. *As living and supra-living organizations grow bigger they develop new forms of connective tissue (organizational infrastructure), information flow, communication and intelligence, which maintain their coherence and coordination.*

Humanity is the cutting-edge of this evolutionary learning process on earth. We are a collaborative-learning species that thrives by pooling information, collectively forging new understandings, and changing our pattern of life by changing our best hypothesis about "how the world works" [63]. This ability has allowed us to adapt more rapidly and innovate more powerfully than any other earthly species. It is directly responsible for all the marvels we live with today. Yet, human learning too is never done. Despite humanity's adaptive talents, every pattern of civilization eventually reaches limits that force a choice: cling to old ways and decline or innovate and transform. Today's most crucial innovation may well involve learning to live and flourish within the limits [64].

5.2 Comparing Regenerative Economics (RE) to Classical and Neo-Classical Economics

The classical story of economic health emphasizes innovation, entrepreneurship, competition, free enterprise, and laissez-faire markets in which optimal equilibrium (distribution) emerges automatically from rational agents pursuing their own self-interest. RE sees innovation, entrepreneurship, competition and free enterprise as contributing to the diversity and flexibility needed to fill niches, find new ways and enhance resilience. In addition, Complexity Science informs that fractals and other universal patterns represent the kind of optimal aggregate organization envisioned in Smith's invisible hand. Like an Efficient Market, a hurricane's spiral, for example, reflects a web of forces evolving toward an optimal pattern of distributive flow. This optimality emerges in the interplay of bottom-up and top-down influence: from the bottom-up via seemingly chaotic interactions of billions of individual particles, and from the top-down via global constraints and large-scale contextual factors. While innovative ideas and diverse individual enterprise are important to regeneration, economic behavior is also heavily shaped by a host of less traditional factors measured by the Regenerative Economy Principles (REP) above including:

- Robust cross-scale circulation of money, information, and resources (REP#1);

- Adequate investment in human, social, physical, economic, and environmental capital (REP #2);
- Emphasis on building capacities using renewable resources within a circular economy in which wastes become useful by-products (REP #3, 4, 9)
- A diverse and balanced economy with small, medium, and large organizations exhibiting a balance of efficiency and redundancy (REP #5, 6, 7);
- Systemic benefits from the complex interdependence of network interactions (REP #8);
- Processes for learning effectively as a society in the face of mounting evidence and pressures, including science, government, corporations, and politics (rep #10).

The science behind regenerative economics holds a much dimmer view of the current version of capitalism, because these principles have not been known let alone at the forefront of economic decision making, which has largely been focused on the single extensive factor of continual GDP growth. In this aim, as a result, global economics has been dominated for the last 40 years by deregulation, privatization, maximizing profit for owners, tax breaks for the rich and austerity for the general public, and increasing corporate size and efficiency. In recent years, a host of interlocking crises – from gross inequality and looming climate change to global economic instability as demonstrated by the financial crash of 2008 – have called this "trickle-down" theory into question. Additional tenets of conventional socio-economic wisdom, such as the environmental Kuznets curve, are likewise called into question as environmental crises surpass national barriers leading to persistent and wicked systemic planetary problems.

Neoclassical economists assume economics could be separated from social and political dynamics, and concluded that free-market vitality arose automatically as a result of independent agents making rational choices based on self-interest alone. However, a push to extreme self-interest, has resulted in instability and inequity. Boom-bust business cycles, occurring every 4 to 7 years on average, are now considered normal, despite their devastating impacts on the public at large. Today, financial instability is rampant, with crises afflicting Brazil, Greece, Italy, Iceland, Ireland, Russia, Spain, Turkey, Venezuela, the US, and others since 2001. Short-term profit-maximizing fueled by rampant deregulation, privatization, tax breaks for the rich, and austerity for the general public – fuel corporate gigantism and extreme concentrations of wealth and power. Violating a distribution balance leads to the usual sequence: excessive concentrations of wealth → excessive concentrations of power → positive feedback loops that accelerate the suction of wealth to the top. The result is economic necrosis – the dying off of large swaths of economic tissue due to poor circulation and malnutrition. Consequently, Institutional economists Acemoglu and Robinson [65] show that excessive extraction is the most common reason *Why Nations Fail*. RE #9 would identify, distinguish, and reward practices that construct capitals and capacities as opposed to simply exploiting existing natural or human-made capitals.

This imbalance of "too big to fail" corporations resulting in monopolies has a stifling effect on today's urgently needed, collective vitality and constitutes a serious threat to humanity's long-term survival. Today, for example, climate-change and the march of peak-oil are creating pressure for more distributed power based on clean, green renewables. The fossil-fuel industry is working to resist this change in opposition to REP #5 and #7 which call for balance of sizes and diversity of roles. Small-scale, distributed power generation would counter this trend while also increasing renewable supplies (REP #3) and build resiliency to the communities (REP #6).

We believe a global transition is on the horizon because the current practices violate the core rules of regenerative economics. Instead of supporting healthy human-networks and ecosystems, it minimizes returns to workers, cuts spending on education, ignores human needs that are not backed by sufficient money, and consumes natural capitals. Instead of supporting innovation and collective learning that resolve critical problems, it works against any advance that might reduce its ability to extract wealth and maintain monopolies on power. A vast wave of diverse reformers seeking better ways is sweeping through fields ranging from energy and education to finance and politics – but the outcome is still in doubt. Which way will we go, concentrated imbalances or flourishing with regeneration? We believe having a rigorous theory and quantitative measures of regenerative economics can help turn the tide in a positive direction.

5.3 Applications and Next Steps

The ten measures and associated principles we have described are derived from principles of sustainable and resilient ecological networks that have been successful over millions of years. These same organizing principles of natural energy flow networks have also been tested and confirmed by dozens of scientists working in multiple fields, as robust and rigorous explanations of fundamental to understanding ecosystem networks and living systems in general. While the applications and tests of these principles as applied to socio-economic networks are promising, we see the need for additional application, testing, interpretation and refinement of these metrics for best use in socio-economic studies and policy arenas.

Some applications of network principles to human systems reveal the need for modification and further study to understand how they must be applied differently to socio-economic networks. For example, using REP #6 and the robustness index, economic networks appear less efficient (more redundant) than ecosystems [66]. We continue to work to understand what explains this relative to a universally-observed pattern in ecological networks. One hypothesis is that networks in which exchange between components is crucial to “survival” will exhibit the optimal balance seen in natural ecosystems, while networks of optional, less critical exchange may not. This approach may require more nuanced understanding of the relative pressures or imperatives for “life and death” decisions, and for survival, in biological versus economic contexts.

Studies of food networks have also shown interesting results. One study of U.S. interstate food trade found the REP #6 measure of robustness near the curve peak [67]. However, the robustness index calculated for nitrogen flow in the U.S. beef supply network [68] plotted to the right of the peak. Work remains to explain when and why networks plot in the three regions of the robustness, Window of Vitality, curve. Our working hypothesis is that more linear networks (more like chains rather than webs) will plot to the right of the curve peak, since vertical integration prunes redundant connections. This work would be aided by additional research into whether more linear supply chains show different network results for the other nine RE measures, and more interpretation on the costs and benefits of chain versus web structures.

It will also be important to document when and how the ten measures of regenerative systems are linked to other key correlates of human health, environmental quality, and socio-economic health. Do the measures, which quantify network and systemic structure and function, show regular and meaningful correlations with 1) health outcomes of prime concern such as cancer rate, heart disease, etc.; 2) crucial economic quality outcomes of poverty rate, employment, etc.; and 3) environmental quality outcomes such as air and water pollution, species diversity, etc.?

6.0 Conclusion

The science of Regenerative Economics is based on decades of research into areas of complex adaptive systems, flow networks, and ecosystem and socio-economic dynamics. It provides a more accurate understanding of what makes a society healthy. RE's story of economic success mostly confirms what we already know while anchoring it in a more integrated and measurable empirical framework including robust circulation, balanced and integrated structures, investing in human and natural capacities, collaborative learning, and the dangers of concentration and extraction.

In this view, promoting the health of the underlying human network is vastly more important than increasing the volume of economic output (GDP growth) per se. Innovation, entrepreneurship, and capacities are important, but they need to be linked by common-cause values, supported by commonwealth infrastructure, and nourished by cross-scale circulation of money, information and resources. Large and small organizations both play important roles, and the goal is to maintain balance and integration.

It is time for us to choose. Systemic *death* does not happen automatically. It requires adhering to beliefs long past their usefulness in addressing the problems for which they were designed, while ignoring widespread evidence that they are not achieving systemically healthy outcomes. Of course, systemic health does not happen automatically either. It requires adhering to the rules of regenerative economics, development, and learning. The measures listed above can help us chart our course. Developing healthier patterns of organization, behavior, and power must be top on our list.

7.0 ACKNOWLEDGMENTS

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APPENDIX A: Ecological/Energy Network Analysis

The aim of this appendix is to provide enough background to understand the main terminology, assumptions, and notation used in Ecological (Energy) Network Analysis (ENA). For a complete description of ENA methodology the reader is directed to the many papers on the topic (see e.g., [12, 16, 40, 43, 44, 69]). In every system, the interactions of compartments can be realized as a network of nodes and arcs. Consider a network with n compartments or nodes, in which the compartments can be represented as x_i, for $i = 1$ to n. The transaction of the energy/matter substance flowing from node i and node j is given by f_{ij} and can be arranged into a matrix **F** containing all pairwise flows in the network. In addition, these systems are open to receive new inputs and generate outputs. Those flows that cross the system boundary are labeled, z_i and y_i, for $i = 1$ to n, respectively. In this manner, we can find the total flow going through any node as either the sum of all the flows into the node or all the flows out of the node (at steady-state these are equal).

$$T_i^{in} = z_i + \sum_{j=1}^{n} f_{ji}$$

$$T_i^{out} = y_i + \sum_{j=1}^{n} f_{ij}$$

The total system through-flow (TST) is the sum of all the individual nodal flows, given by:

$$TST = \sum_{i=1}^{n} T_i$$

The flows in the **F** matrix capture the direct transactions, but the methodology can be used to determine indirect flow paths and influences as well. First, we calculate a non-dimensional, output oriented flow intensity matrix, **B**, where $b_{ij}=f_{ij}/T_i$ (a symmetric input-oriented analysis is also possible). Ecological Network Analysis (ENA, see [69]) tells us that taking powers of this matrix gives the flow intensities along path lengths commensurate with the power, i.e., B^2 are two-step pathways, B^3 three-step, etc. Another fascinating discovery of ENA is that it is possible to simultaneously consider *all* powers in one term by summing the infinite series which converges to a composite matrix, we call, N, such that

$$N = \sum_{m=0}^{\infty} B^m = B^0 + B^1 + B^2 + B^3 + B^4 + \cdots$$

The N matrix is termed the integral flow matrix because it sums or integrates the flow along the direct and all indirect pathways. These basic network building blocks of direct, indirect, and integral connectivity and matrix algebra are used to develop the specific metrics in regenerative economics.

The application of ecological network analysis that uses an information-theory based approach in principle 6 utilizes three key factors of any system [12]: 1) the fraction of material or energy that an ecosystem distributes in an *efficient* manner (Ascendency (A)); 2) the maximum potential a system has to achieve further development (Developmental Capacity (C); and 3) the array of useful parallel pathways for exchange (Resilience (R))**.** Each property can be quantified from the flow data described above as follow:

$$\boldsymbol{A} = \textstyle\sum_{i,j} F_{ij}\, log\left(\frac{F_{ij}\quad F_{..}}{F_{i.}\quad F_{.j}}\right) \qquad\qquad \boldsymbol{C} = -\textstyle\sum_{i,j} F_{ij}\, log\left(\frac{F_{ij}}{F_{..}}\right)$$

$$\boldsymbol{R} = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(F_{ij}\right).\, log\left(\frac{F_{ij}^2}{\sum_{j=1}^{n} F_{ij}\quad \sum_{i=1}^{n} F_{ij}}\right)$$

The Window Vitality measures a network's degree of organization as $\alpha = \frac{A}{C}$. Systemic Robustness is measured as:

$$Robustness = -a \log a\,,$$

A healthy economy is presumed to maximize the robustness value, as is seen in ecosystems.