Can Complexity Studies Advance Sustainability?
Scaling in Natural & Social Systems

Power Laws – All Too Common?
Or Tool to Save the Commons?

Or

Log-log & Pretty Soon
You Can't See the Forest or the Trees

Timothy Foxon[1], Debora Hammond[2] and Jennifer L Wells[3,4]
[1]Centre for Environmental Policy, Imperial College, London
[2]Hutchins School of Liberal Studies, Sonoma State University, California
[3]Environmental Sciences Policy and Management, University of California, Berkeley
[4]Department of Philosophy, University Sorbonne, Paris IV

Abstract:

The challenge of creating human socio-economic systems that are socially, economically and environmentally sustainable is highlighted by problems of local and global environmental impacts, including climate change and socially inequitable distribution of resources between rich and poor countries and individuals. Socio-economic systems are complex systems involving multiple actors interacting at many different levels. This paper explores power laws in social systems as a case study in the exploration of ways in which complexity studies might illuminate the challenge of achieving sustainability and perhaps provide tools to help address this challenge.

Power law distributions are common in natural systems and have been observed in social systems. They can illustrate underlying patterns of relationships and provide insight into relative measures of efficiency, in terms of energy and resource use, in biological and social systems. We examine the possible significance of the contrast between economic and ecological definitions of efficiency, particularly in relation to the increasingly inequitable distribution of resources. We explore such questions as: (1) How do power laws that have been observed in ecological systems relate to power laws in socio-economic systems? (2) How could measures of efficiency in ecological systems be applied to improving efficiency and equity in the allocation of resources in socio-economic systems? (3) How does innovation relate to sustainability? (4) Can we overcome the 'ingenuity gap', i.e. are we creating problems faster than we can find solutions for them?

Introduction

Our purpose is to evaluate power law distributions as a possible tool for examining contrasts between human and natural systems, specifically with regard to relationship between size and metabolism. Some preliminary research on power law distributions in social systems, conducted by Bruce Milne and colleagues at the University of New Mexico, reveals that industrial systems (such as road networks or oil pipelines) scale with a power law coefficient of 1, suggesting that large-scale industrial systems do not become more efficient with increased size, unlike ecological systems which typically scale with a power law coefficient of ¾ (Milne, 2005, *pers. comm.*). We suggest that further similar studies might provide a measure of the relative inefficiency of industrial systems compared with natural systems, with regard to energy use.

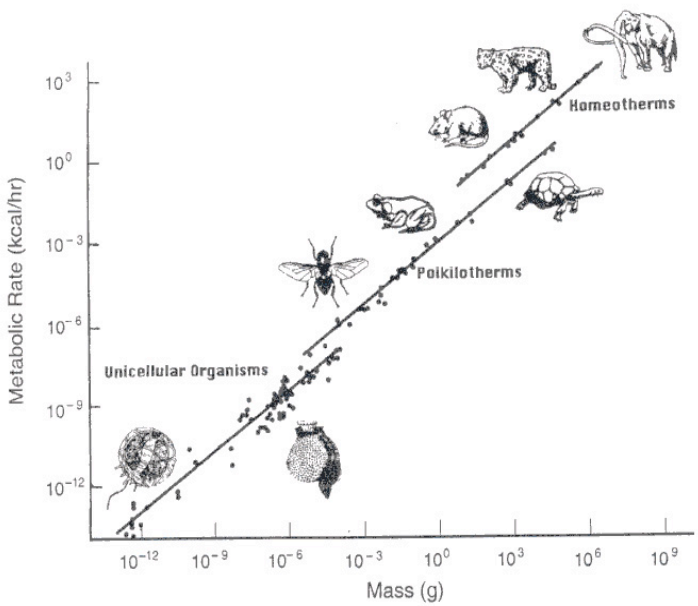


Figure 1: Power Laws in Nature [source: Brown and West (2000)]

The earth's human population has almost tripled from 2.4 billion in 1950 to over 6 billion by 2000, and is still growing by 1.6 percent a year. On a global average, real economic product per capita is also growing at 1.5 percent a year, leading to growth in the world's total economic product of about 3 percent annually, implying that current global product of US $25 trillion will exceed $50 trillion in today's dollars by 2020. However, this rate of increase has serious ecological and social consequences. Nearly all scientists now accept anthropogenic climate change: rapid growth in burning of fossil fuels and destruction of forests has been increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere which, if unchecked, will lead to an increase in global mean temperatures by 1.4 to 5.8°C by the year 2100, resulting in severe global and local climatic changes (IPCC, 2001). The extremely socially inequitable distribution of resources and wealth, both globally and locally, is creating pressures on existing social institutions, which are likely to be exacerbated by the consequences of ecological change falling disproportionately on poorer people. In 1987, the UN Brundtland Commission produced a report calling for sustainable development, i.e. development that meets the needs of the present without compromising the ability of future generations to meet their needs. Despite governments' endorsement of this principle, however, the above trends have mostly worsened in the intervening period.

Many approaches have been taken to putting the concept of sustainability into operation and here we follow the approach of ecological economist Herman Daly. Daly (1996) argues that the global human socio-economic system should be seen as a subset of the global environmental system. Over the last century the ratio between natural resources and human impact on the environment has reversed; the world was once overflowing with resources with mostly inconsequential human impact, whereas humans have now depleted many of the available resources, becoming the dominating driver of biospheric change and pushing the limits of carrying capacity for many resources and ecosystem services. Daly argues that modern economics was developed in the context of abundant natural resources, and that today we are still using the same economic theories, although natural resources - including the absorptive capacity of the atmosphere - are now scarce, and humans use 40% of the earth's biomass. We should therefore pursue policies aimed to achieving a socially equitable distribution of wealth, ecological sustainability, and economic efficiency.

However, the mainstream approach of neo-economics is limited, not least by its foundational assumption that people are perfectly rational actors with perfect knowledge of the economic alternatives available to satisfy their preferences. Neo-economics focuses on the generation of wealth through economic 'growth,' e.g. increasing the throughput of energy and materials through the economy. Ecological economists point out that this overlooks the environmental limits to providing resources and assimilating wastes. Unfortunately, mainstream economists, having failed to include these limits in their models, continue to reject arguments against economic growth. We argue that this is a case of 'mistaking the model for reality'.

The main argument against the need to consider ecological limits is that, in the past, technological innovation has enabled human societies to evade such limits. However, the experience of many societies, from that of Easter Island to the local Anastazi culture in New Mexico (Diamond, 2005; Gumerman et al., 2005), attest to failures in adapting to changing conditions, brought about by a combination of human action and environmental change. This raises the question of whether today's society is smart enough to deal with the problems of global environmental impact and extreme inequitable distribution of resources created by the narrow focus on economic growth, or whether we face an 'ingenuity gap' (Homer-Dixon, 1995, 2000) in creating the necessary social and technological innovations to solve these problems. As we shall see below, although there is some evidence that clustering of human populations in cities leads to disproportionately higher rates of innovation, which may be leading to faster cycles of growth, the present institutional systems and ways of thinking mean that this innovation is largely targeted at increasing economic growth within the current paradigm, rather than addressing the challenges of sustainability.

Social Equity and Sustainability

Herman Daly (1996) has identified three pillars of sustainability:

- Socially equitable distribution of wealth
- Economic Efficiency
- Ecological Sustainability

These general principles are echoed by Redefining Progress, an organization that "works with a broad array of partners to shift the economy and public policy towards sustainability." Redefining Progress has popularized the concept of the Ecological Footprint, measuring the relative footprints of cities and nations (Venetoulis, et al, 2004). In addition, they have developed the Genuine Progress Indicator (GPI), which includes social and environmental costs in its calculations, providing a more accurate indicator of overall quality of life than the GNP or GDP. According to this model, although GNP has continued to increase in recent years, the GPI in the United States, for example, has been declining since the 1970s (see www.rprogress.org).

Redefining Progress articulates the basic principles of sustainability as follows:

> Sustainability stands for finding satisfying ways of life for all, within the capacity of the planet, now and in the future. In other words, sustainability depends on:
>
> - Acknowledging that there are natural biological and physical limits to what we take from nature;
> - Agreeing roughly on where we stand now in relation to those limits; and
> - Understanding that in order to reduce our impact equitably, those that take the most will be required to scale back the most.

As they suggest, "accepting these propositions will require significant education and attitude changes. But these will be necessary to protect the biological assets on which all human (and non-human) activities depend."[1] Perhaps the greatest challenge confronting the human community is how to address the growing inequality in access to resources. Old arguments that unequal distributions of wealth in society are both natural and inevitable are coming under increasing attack.

One of the earliest and best-known examples of power laws in social systems is Pareto's Law. In the late 1800s, economist Vilfredo Pareto observed that wealth follows a "predictable imbalance," with 20% of the population holding 80% of the wealth. A web search on Pareto's Law reveals an intriguing variety of interpretations and applications of this general principle. Clay Shirkey (2003), for example, writes:

> Diversity plus freedom of choice creates inequality, and the greater the diversity, the more extreme the inequality. In systems where many people are free to choose between many options, a small subset of the whole will get a disproportionate amount of traffic (or attention, or income), even if no members of the system actively work towards such an outcome. This has nothing to do with moral weakness, selling out, or any other psychological explanation. The very act of choosing, spread widely enough and freely enough, creates a power law distribution.

Pareto's Law and other similar observations, including Tom Carter's agent-based simulation of random exchange, tend to objectify and justify the increasingly inequitable distribution of resources we are witnessing in the world today. However, as with game theoretical models, which rely on a very narrow interpretation of "rationality," both agent-based models and statistical representations ignore sociopolitical contexts and reify extremely limited criteria of choice (i.e. randomness in the agent-based model and decontextualization in both). Thus the conclusion that social inequality is inevitable. In this case we could say that our model has been sustaining our social reality.

---

[1] http://www.rprogress.org/newprograms/sustIndi/index.shtml

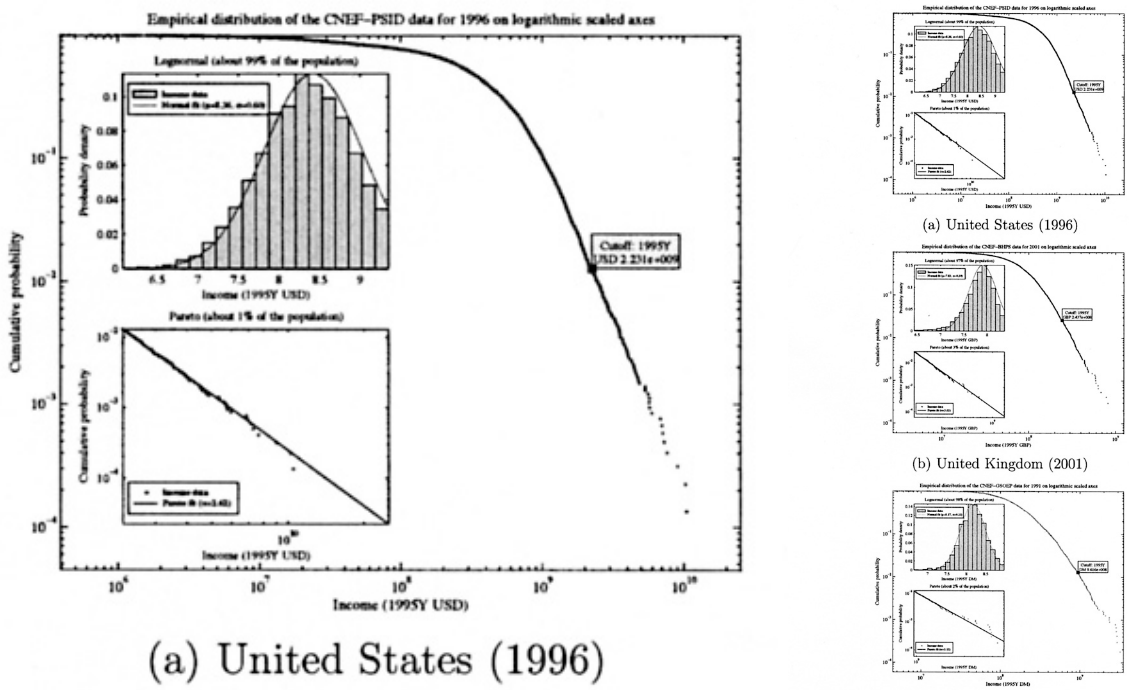


Figure 2: Evidence for Pareto's Law from the United States, the United Kingdom and Germany (Clementi & Gallegati, 2005). As the data illustrates, income distribution actually follows a log-normal distribution, except in the top 1-3%. Nevertheless, the data offers some useful insights in the distribution of income. Note the differences in steepness of slope between countries.

Reflecting on this conclusion, some interesting questions arise. First, there is the question of the relative degree of inequality (i.e. the exponent, or slope, of the power law curve as at least a first order approximation of the relative distribution of wealth). Robley George (2002) provides a provocative account of historical views on the appropriate distribution of wealth in society, beginning with Plato, who recognized that there would never be total equality among all members of society, but suggested that no one should have more than ten times as much as the poorest person. George traces a number of arguments along the same lines from such political philosophers as Thomas Jefferson, Thomas Paine, and Henry George.

There are clearly differences in the level of disparity between countries and over time. A 1989 study of CEO compensation discovered a ratio of CEO pay to lowest paid employee of 7:1 in Japan, 15:1 in Germany, and 100:1 in the United States (from study group member, Don Hammond, HP Labs, 1989, *pers. comm.*). That figure for the United States has since risen to roughly 500:1. Obviously there are many factors contributing to these figures and a thorough discussion is beyond the scope of this paper, but they reflect a disturbing trend toward increasing disparity. In discussing our project with Doyne Farmer, he noted that the ratio between the wealthiest and poorest, reflected in the exponent of the power law function, varies considerably between countries and over time, and that the factors contributing to these variations are not well understood. We believe that this is a critical area for further research.

The second and perhaps more interesting question arising from Pareto's Law relates to the significance of this unequal distribution of wealth for sustainability. In their report on the effects of inequality on economic performance, *Inequality, Collective Action and Environmental Sustainability*, Baland et al (2002) argue that sustainability requires cooperation and further that inequality diminishes the ability of individuals to cooperate, challenging the received wisdom of earlier theorists. Echoing arguments of "supply-side economics," Mancur Olson (1965) had suggested that "a high level of inequality supports cooperation because it increases the likelihood that one or a few wealthy individuals will be able to capture enough of the benefits of cooperation to induce them to provide the public good independently of the actions of the other group members."

In contrast to Olson's view, studies in the more recent Baland collection suggest that inequalities in wealth and power tend to undermine effective communication and trust, which they see as fundamental in efforts at environmental protection and preservation of the commons. As the editors note in their introduction, "in [some of] these cases, redistributive policies (like land reform or expansion of mass education) may have important beneficial side effects in matters of cooperation on common resources (which are not usually considered in the literature on land reforms or education)." Many traditional cultures have institutionalized various redistributive mechanisms. Assuming that such traditions evolved as a way of countering the "natural" tendency toward inequality in distribution of resources, and as a result preserving an optimum balance between individual and collective good, we suggest that current trends might merit similar corrections.

Distributive and Relational Power Laws for Social Systems

Another example of a distributive power law for a social system is Zipf's law on sizes of U.S. cities (Zipf, 1949; Krugman, 1996). This is that the distribution of sizes of metropolitan areas in the U.S. is well described by the rule:

$$N = k\, S^{-\alpha},$$

where N is the number of cities with populations greater than or equal to size S, and the co-efficient α is found to be very close to 1. Hence, a plot of the log of the city rank against the log of the city size shows a straight line with a slope of -1, and this power law has worked reasonably well for at least a century (see Figure 3 below).

This empirical result, that the population of a city is inversely proportional to its rank (e.g. the population of 10th ranked city Houston is 3.85 million people; while that of 100th ranked city Spokane is 370,000), seems to require an explanation. A simple model for this phenomenon was proposed by economist and AI pioneer Herbert Simon. Simon's (1955) model describes the population of urban systems as growing by adding discrete 'lumps', which are not too big or too small. With probability p, the lump forms a new city, and with probability $1-p$, the lump attaches to a specific existing city, with probability proportional to the existing population of that city. This model reproduces a power law distribution for cities with exponent $\alpha = 1/(1-p)$, and so gives a good approximation to the observed relation when p is small. The model may be interpreted as implying that 'lumps' represent number of people employed directly or indirectly by entrepreneurs, and that new entrepreneurs are 'generated' in proportion to the existing population of the city (Krugman, 1996).

Figure 1 The hierarchical differentiation in urban systems:
Rank-size distribution of French agglomerations (1831-1999)

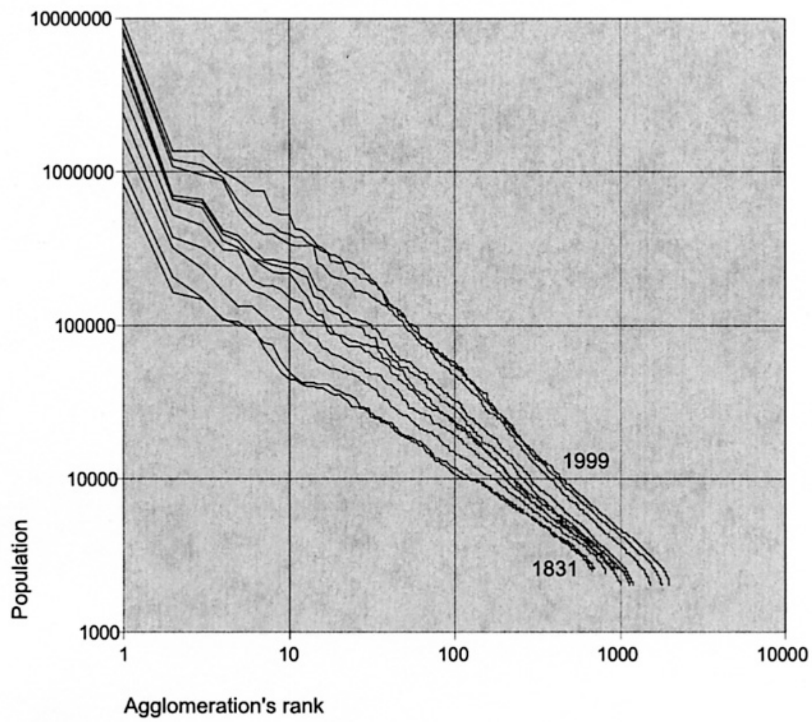
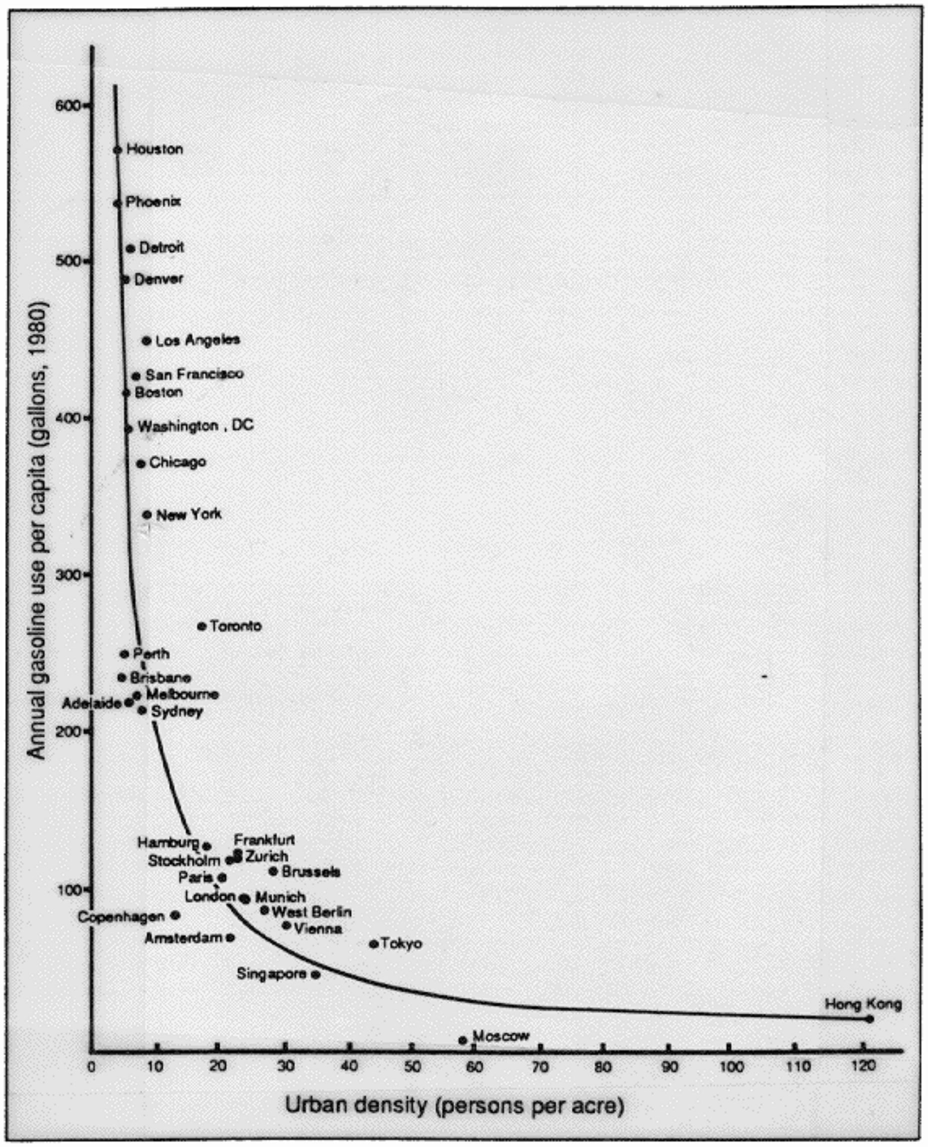


Figure 3: From Pumain (2003).

While this distributional power law is interesting, it sheds little light on the efficiency and sustainability of human socio-economic systems. For this, we must turn to proposed examples of power laws relating two variables within social systems. By analogy with the power law relations for metabolism in organisms and ecosystems, and in view of its fundamental role in human systems, we would expect energy use to be a key variable.

The transformation of free (i.e. low entropy) energy from natural energy flows (e.g. solar, wind, wave and tidal) and stored energy sources (e.g. oil, gas, coal and nuclear) into useful forms of energy is fundamental to current human societies. The rate of energy consumption has increased from an estimated 600 Watts (W) for Western societies in the 19th Century before the industrial revolution (Livi-Baci, 1997) to a global average of over 2000 W at the beginning of the 21st Century. However, this energy consumption, and the associated material benefits, is highly inequitably distributed, with an average U.S. citizen consuming energy at a rate of 11,000 W, compared with only 400 W for a citizen of a sub-Saharan African country (World Resources Institute, 2004).

FIGURE 4: Gasoline use per capita versus population density (1980)



Excerpted and reprinted by permission of the *Journal of the American Planning Association*, 55, 1:31.

Figure 4: From the International Council for Local Environmental Initiatives (http://www.iclei.org)

The relative environmental impacts are correspondingly skewed, with an average U.S. citizen being responsible for the annual emission of almost 20 tons of CO_2 emissions, compared to only 0.05 tons of CO_2 per African citizen. Despite relative improvements in the efficiency of energy use, increasing levels of consumption in industrialized and rapidly industrializing countries and increasing population and aspiration levels in developing countries, mean that global energy consumption is projected to increase by 60% over the next 30 years (International Energy Agency, 2004). CO_2 emissions are forecast to continue to grow at over 1% per year and reach double the pre-industrial levels before the end of the Century, unless there is a significant switch in the fuel mix or reduction in the rate of growth of energy consumption.

The rate of growth of energy consumption since the industrial revolution has been exponential, with increasing end-use energy demands stimulating search for additional sources of mostly fossil-fuel energy, and vice versa. So, can complexity theories in general, and power laws in particular, shed light on relations between energy use and other social variables, and thus better inform ways of moving towards more sustainable patterns of energy use? One result from the University of New Mexico group provides an example of how the availability and efficiency of energy use may fundamentally affect other social decisions, in this case, human fertility (birth) rates (Moses and Brown, 2003).

Moses and Brown draw analogy with recent work (Peters, 1983; West et al., 1999) arguing that, for biological organisms, whole-organism metabolism B, or rate of energy use, scales to the ¾ power of body mass M, i.e.

$$B = B_o \times M^{3/4},$$

while other biological rates R, such as heart rate, reproductive rate or cellular metabolic rate, are predicted and observed to scale to the -¼ power of body mass M, i.e.

$$R = R_o \times M^{-1/4},$$

so that these biological rates R scale to the -1/3 power of organism metabolism B, i.e.

$$R \propto B^{-1/3}.$$

They argue that the appropriate analogue to whole-organization metabolism for human systems is the per capita rate of extra-metabolic energy use E, i.e. E is the individual share of total national energy consumption, and includes end consumer uses (heating houses, driving cars, running refrigerators, etc) and per capita contributions to infrastructure (building and maintaining roads, airlines, communication networks, national defense systems, etc.). Hence, the model predicts that human fertility rates, F, should scale to the -1/3 power of per capita rate of extra-metabolic energy use E,

$$F \propto E^{-1/3}$$

This relationship is found in data plotting human fertility rates against extra-metabolic energy consumption for 98-116 countries in 6 periods from 1971 to 1997. Here, fertility rates refer to number of children raised by parents, i.e. live births per 1000 of population minus infant mortality. The slopes of the 6 regressions on the log-log plots are -0.33 to -0.37.

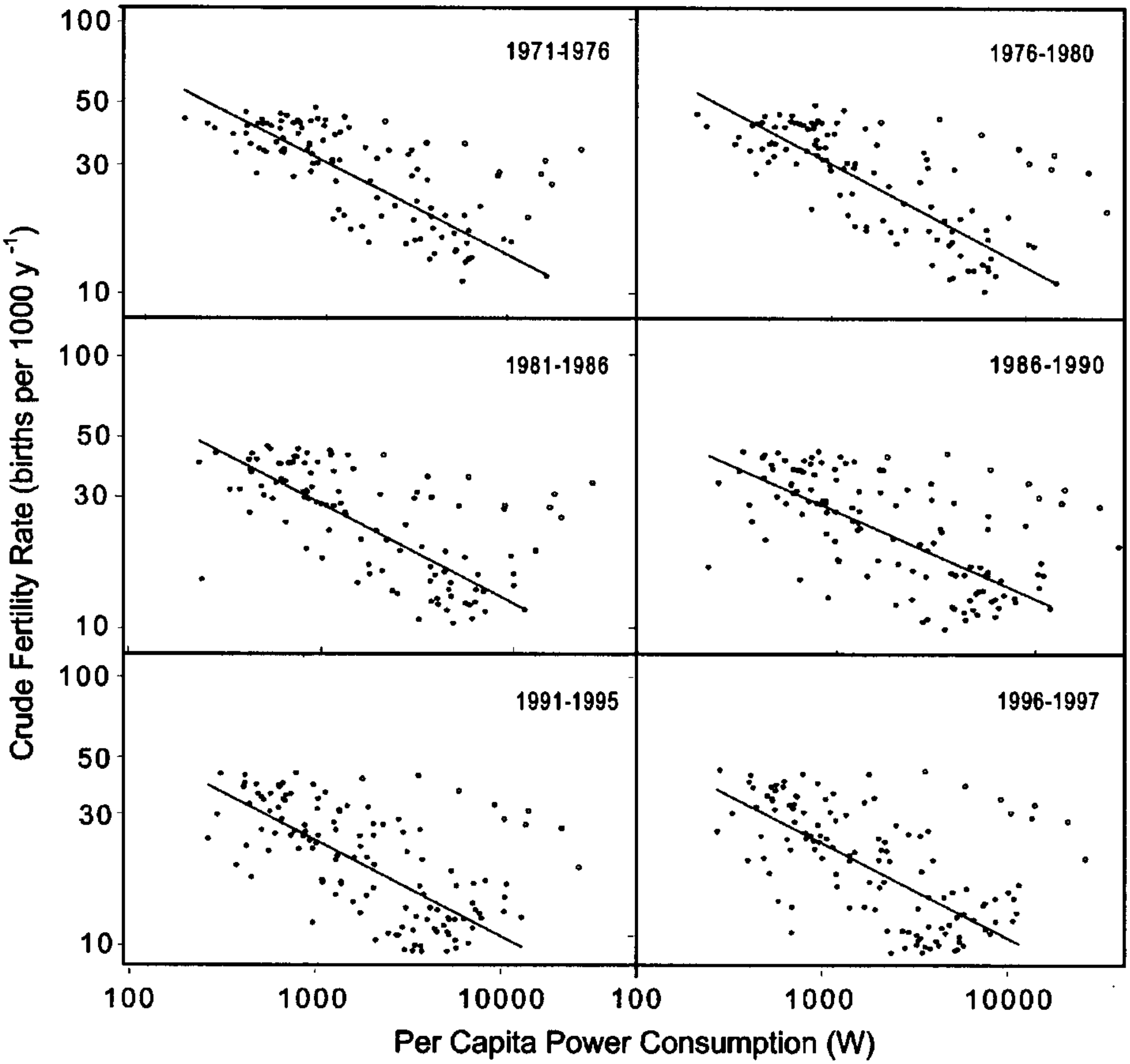


Fig. 5. Relation between fertility rates and per capita power consumption for 98-116 countries, 1971-1997 (source: Moses and Brown, 2003)

A similar dynamic relationship exists across time in the U.S. from 1850 to 2000 for both crude fertility rates (births per 1000) and total fertility rates (lifetime births per woman). Thus, fertility rates have fallen from 6.5 births per woman for pre-industrial average energy consumption of 600 Watts (W) to around 2 births per woman for present U.S. energy consumption of over 10,000 W per capita, corresponding to a slope of -0.27.

Moses and Brown's explanation for this observation starts by arguing that the required energetic investment per child (including resources and education) increases in direct proportion to the per capita rate of extra-metabolic energy use E. They then hypothesize that the scaling properties of extra-metabolic energy networks are similar to those of biological networks. In biological networks, mass scales linearly with the volume (V) of the metabolic network, i.e. total blood volume (West et al., 1999), and hence total energetic rate (E) scales as $V^{3/4}$. Furthermore, the distance (l) and time (t) it takes for a resource to travel from uptake to consumption (e.g. the distance from the heart to a capillary) scale as $V^{1/4}$, and hence,

$$l \propto t \propto E^{1/3}$$

Thus, biological rates are slowed by the increased time it takes to move energetic resources through greater lengths of network in larger organisms. It is argued that these scaling relationships can be generalized to describe the constraints on the efficiency of any three dimensional transportation network (Banavar et al., 1999).

This suggests that in human societies, larger networks deliver more energy, but with increased total transportation time t and greater network length l, leading to increased infrastructure costs. If human infrastructure networks are assumed to follow the same scaling relations as biological networks, then the cost and time required to gain energetic resources scale as $E^{1/3}$. Thus, if the cost and time required to collect and distribute energy resources to each offspring are assumed to scale as $E^{1/3}$, and total energetic resources per family are roughly constant, this would provide an explanation for the $E^{-1/3}$ scaling in number of offspring per woman (fertility rate).

This study provides only one example of a power law relation between per capita energy use and another social variable, and the proposed explanation is only a hypothesis, which requires further investigation. Nevertheless, it suggests that, while human social systems may have raised the limits imposed on fertility and other biological rates by increasing available energy through drawing on extra-metabolic sources, access to available energy may still influence and constrain human choices. The above result also has significant potential implications for sustainability, as it suggests that fertility rates in developing countries may not decrease until sufficient energy resources are available. This would provide a further argument for the need to meet this energy demand through the rapid expansion of the use of carbon-free energy sources.

The counter-argument proposed by those still wedded to the notion of economic growth is that 'technology will save us' if the ecological limits on human societies prove to be as severe as scientists predict. However, this assumes that, firstly, market signals will be strong enough to create the demand for these technologies, even though the environmental impacts are usually 'externalities', which are only slowly and incompletely now being 'internalized' into economic decision-making through the imposition of taxes or tradable permit schemes. Secondly, it assumes that markets function perfectly, when in fact, they are embedded in social institutions, power structures and established modes of thought. The next section discusses recent insights from the study of social systems that illuminate this inherent complexity.

Structure and Function of Inequities in Social Systems

Several scholars have begun to shed light on the meaning of complexity in social sciences. Leading among them are Edgar Morin, the French sociologist and philosopher of complexity, whose six-volume book *The Method* covers complexity throughout the disciplines, from physics to ethics; Niklas Luhmann, a German systems sociologist and author of *Social Systems*; and an interdisciplinary group of U.S. scholars working with ecologists Buzz Holling and Lance Gunderson, who describe the foundations of socio-natural thinking in their book *Panarchy*. The views of these scholars reinforce a distinction between the natural sciences and social sciences with regard to quantitative modeling, since the symbolic dimension of human systems provides greater freedom and flexibility of response than is possible in non-human systems.

Morin's major work, *The Method*, is perhaps the richest and most complete resource in the interdisciplinary complexity literature. In the fourth volume Morin discusses the realm of human ideas, the 'noosphere.' He highlights key aspects of the way we construct, manipulate and understand the systems that make up our choices and actions, including our impact on the environment. And he argues that the choice and construction of our ideas demonstrates a freedom of will. Thus we can decide policies such as those that govern wealth distribution, negating the inevitability of economic inequality.

Morin and Luhmann identify feedback as a major operational component interconnecting complex natural systems with emergent human systems. In the book *Panarchy*, the authors argue that feedback in ecosystems permits resilience, depending on an imbricate series of mechanisms, partly distinctive yet partially overlapping in return time and function. Imbrication is characteristic of evolved homeostatic processes at all levels of organismal biology. Feedback or reflexivity in social systems shares several aspects with that in ecosystems. Like ecosystems, social systems are dynamic; it is difficult to change any one part of it without considerable effects on other parts. Social systems must fulfill key functions: (1) be oriented towards certain goals or objectives, (2) create mechanisms for integration and adaptation, and (3) create mechanisms for self-reproduction.

On a similar note, Niklas Luhmann offers an account of the philosophical foundations of the social sphere seen in terms of systems. In *Social Systems*, he articulates the interrelations and distinctions between the natural and social spheres. He argues that the natural sciences deal with complexity, while the social sciences deal with *both complexity and the systems that emerge from that complexity*. Like Morin, Luhmann argues for the capacity of humans to engender social progress, a view reinforced by examples from human history. These views challenge naturalistic arguments for the inevitability of any fixed socio-economic order. The dramatic difference between Japan and the United States in the ratio of CEO compensation to lowest paid employee (7:1 as opposed to 100:1 in 1989) belies the logic of inevitability.

However, social systems have additional key features not found in ecosystems. The construction and manipulation of symbols creates the structure of social systems (Gidden, 1987). Structures of signification and domination can be seen in the flow of power and resources in a social system, whereas the 'structures of legitimation' are social groups' norms, rules, routines, and procedures.

The aspects unique to social systems then bring about the symbolic, the abstract, and the reflexive.

The process of abstraction may be the key difference of social systems in terms of human impact on the environment. Humans use symbols, language, and communications through which we collectively invent and reinvent a meaningful order around us, and then act in accordance with that invented world as if it were real (which Morin refers to as "placing our feet firmly in midair"). The important message about social systems is that while they have followed certain patterns and processes throughout human history, this is far less predictive of the future than the patterns embedded in the memory of ecosystems. Processes of symbolic abstraction and manipulation are highly malleable. Thus, clarifying the implications of this divergence from ecosystems is a key to potentially large shifts in the policy and structure of social institutions as we cope with myriad and mounting environmental challenges.

A first step is a typology of the processes of social systems, particularly that of abstractions. Processes of abstraction and the virtual realities they bring about have both positive and negative consequences. Positive consequences are very substantial, the basis of human adaptation and success throughout history. The ability to find and construct meaning through symbolic communication permits a higher level of self-organization than that found in ecosystems. Also, social evolution can be much more rapid than natural evolution; social systems can alter their organizational structures quite rapidly, compared to ecosystems. Humans have developed not just instincts and basic symbols regarding their environment, but the highly complicated language and theories that afford us much greater potentiality in understanding our environment. In this sense human agency is exponentially and qualitatively greater than the agency and choice of other species.

However, the negative consequences are just as significant. The ability of societies to shape and then be shaped by structures of signification creates biophysical illusions. We increasingly divorce ourselves from the critical organizing frameworks of time and space that have evolved in nature. Through such symbols as money and such technologies as modes of transportation and communication, we create both widespread ideas and infrastructures that are out of sync with the critical underlying organization of nature.

Initially time and place had meaning only in relation to each other; time was determined by local physical phenomena. But as time was systematized and rationalized, it became possible to keep track of it, irrespective of place. In this way we separated place and space in our minds in a way that is altogether different than in biophysical reality. Thus, geographic places are "thoroughly penetrated by and shaped in terms of social influences quite distant from them" (Ibid, 1990). Social institutions exist on a global scale, de-territorialized and cut off from their geographical location. We suggest that technologies such as modes of transportation and communication, which create distance between our reality and our ideas, are examples of mechanisms responsible for the decreasing degree of metabolic efficiency in large human communities as opposed to large natural systems.

Generally speaking, study of the abstraction of time and place in our minds vs. time and place in our environments can improve environmental understanding and policy. This brings us to one of the other significant qualities of social systems: feedback in our ideas, or 'reflexivity.' As agents within our environmental system, we are able to engage in forward-looking thinking and behavior. Prediction is ubiquitous to living systems in the sense that organisms thrive according to how well they 'represent' their environment. However, prediction in social systems implies a power and potentiality that goes far beyond this. Forward-looking behavior is one of the few characteristics of human societies that have allowed us to flourish so well, along with the capacities for reflection on the past, and the extension of our power through technologies.

Yet, historically, human societies have often failed to employ forward-looking behavior effectively, even when their very existence was at stake. Thus archeologist Charles Redman, echoing George Gummerman of the Santa Fe Institute, remarked that, "self-destructive situations occurs repeatedly. Individuals, groups, entire societies make decisions that are initially productive and logical, but over time have disastrous environmental consequences." Furthermore, if the cost to each agent of workable predictive models is relevant, then the potential for negative consequences increases with the level of complexity of the system!

This raises a key question. What concepts and models from the field of complexity can help us to better perceive problems and transform policies in pursuit of sustainability?

Conclusion

This paper has argued that concepts and models from complexity studies can help to define and advance our capacity to perceive problems and present persuasive arguments for transformations in politics, policy and ethics that can help us to address the challenges of sustainability and avoid our society repeating the mistakes of past human societies. In particular, we argue that exploring contrasts in scaling relations between natural and human systems can help us to better understand both the common properties and key differences between such systems. For example, Bettencourt et al. (2004) found a clear supralinear effect (power law with exponent larger than unity) between patenting activity and size of metropolitan areas in the U.S. over the period 1980-2001. Patents were found to be granted disproportionately in larger urban centers, thus showing increasing returns in inventing activity with respect to population size.

Further conversations with Geoffrey West highlighted the potential consequences of the differences between sublinear scaling for biological systems and linear or supralinear scaling for human systems. In either type of system, available resources may be allocated either to growth of the organism or system or to its maintenance. In biological systems, the sublinear (3/4 power) relation of metabolism to body mass implies that, after an initial allocation of resources to growth, the resources devoted to maintenance will come to dominate. This leads to a typical picture of biological growth shown in Figure 6 below. However, in human systems, the supralinear relation of energy use with increasing size means that resource allocation to growth will continue to dominate the allocation to maintenance, implying faster than exponential growth, as shown in Figure 7.

Of course, cut-offs will eventually prevent unlimited growth. However, one growth 'spurt' may trigger the next, which may have a shorter period to rapid expansion, and so on. The concern that

Typical biological growth curve

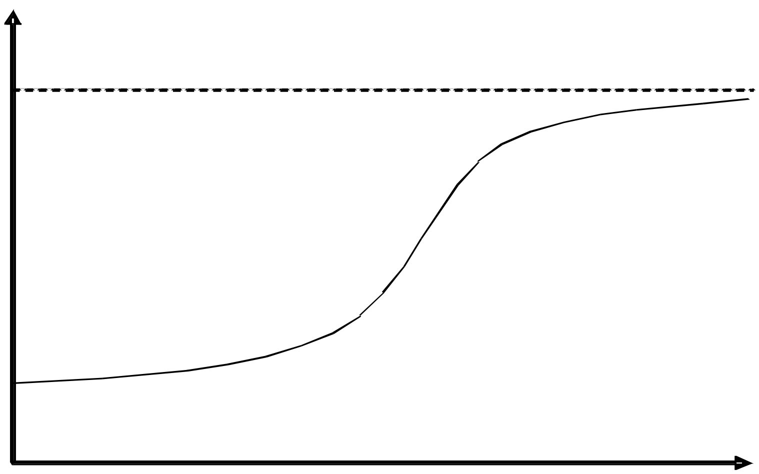


Figure 6: Metabolic constraints generally impose a limit on growth in natural systems.

Typical human innovation growth curve

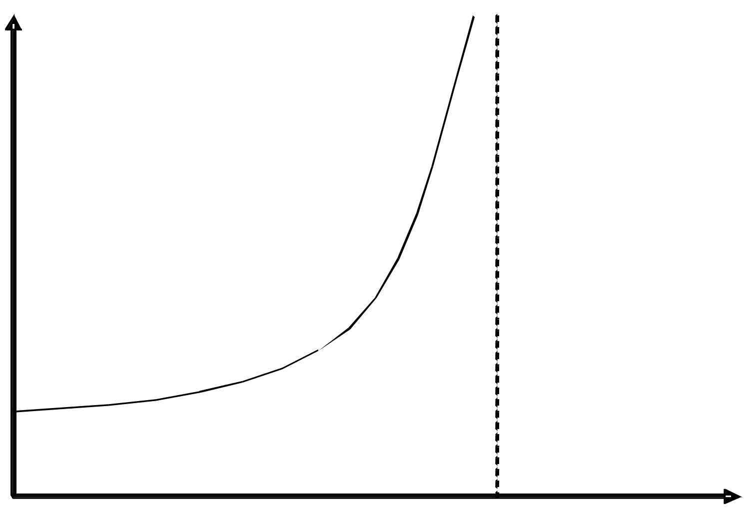


Figure 7: Through various forms of innovation, human systems have managed to generate accelerating growth patterns, which are nevertheless still subject to biophysical limits.

we articulate in this paper is that these growth spurts will sooner, rather than later, be constrained by limits imposed by the Earth's biophysical capacity, whether in the form of rapid climate change, depletion of food or water resources, or other factors, leading to severe ecological and social consequences.

References

Anderson, P, Arrow, K and Pines, D (1988), *The Economy as an Evolving Complex System*, Santa Fe Institute Studies in the Sciences of Complexity, Vol. V, Reading, MA: Addison-Wesley

Arrow, K, Bowles, S and Durlauf, S, Eds. (2000), *Meritocracy and Economic Inequality*, Princeton, NJ: Princeton University Press

Arthur, W B, Durlauf, S and Lane, D (1997), *The Economy as an Evolving Complex System II*, Santa Fe Institute Studies in the Sciences of Complexity, Vol. XXVII, Reading, MA: Addison-Wesley

Baland, J-M, Bardhan, P and Bowles, S, Eds. (2002), *Inequality, Collective Action and Environmental Sustainability*, Report from SFI Workshop on the Effects of Inequality on Economic Performance, available at http://discuss.santafe.edu/sustainability/papers

Banavar, J R, Maritan, A and Rinaldo, A (1999), "Size and form in efficient transportation networks." *Nature*, 399, 130-132

Bettencourt, L M A, Lobo J and Strumsky, D (2004), "Invention in the City: Increasing Returns to Scale in Metropolitan Patenting," SFI Working Paper 04-12-038, December 2004, http://www.santafe.edu/research/publications/workingpapers/04-12-038.pdf

Brown, J H, et al (2004), "Toward a Metabolic Theory of Ecology," *Ecology* 85:7, 1771-1789

Brown, J H and West, G (2000), *Scaling in Biology*, SFI Studies in the Science of Complexity, Santa Fe Institute, Oxford University Press

Clementi, F and Gallegati M. (2005), "Pareto's Law of Income Distribution: Evidence for Germany, the United Kingdom, and the United States," Preprint submitted to Elsevier, available at: http://ideas.repec.org/p/wpa/wuwpmi/0505006.html

Daly, H (1996), *Beyond Growth: The Economics of Sustainable Development,* Boston: Beacon Press

Diamond, J (2005), *Collapse: How Societies Choose to Fail or Succeed*, New York: Penguin

Ernest, S K M, et al (2003), "Thermodynamic and metabolic effects on the scaling of production and population energy use," *Ecology Letters* 6: 990-995

Farmer, J D and Geanakoplos J (2005), "Power Laws in Economics and Elsewhere" (Chapter from preliminary draft of book entitled "Beyond Equilibrium and Efficiency")

George, R E (2002), *Socioeconomic Democracy: An Advanced Socioeconomic System*, Westport, CT: Praeger

Giddens 1987 in Panarchy 2002

Gumerman, G (2005), "Alternative culture histories created through agent-based modeling", lecture at Complex Systems Summer School, June 16, 2005

Holling, C.S. and Gunderson, L.H., Eds. (2002). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington: Island Press

Homer-Dixon, T (1995), "The Ingenuity Gap: Can Poor Countries Adapt to Resource Scarcity", *Population and Development Review*, Volume 21, Number 3, September 1995, pp. 587-612

Homer-Dixon, T (2000), *The Ingenuity Gap*, New York: Knopf

Inter-governmental Panel on Climate Change (2001), Climate Change 2001: Synthesis Report (R. Watson *et al*., eds.), Cambridge University Press

International Energy Agency (2004), quoted on BBC News website, at http://news.bbc.co.uk/1/hi/sci/tech/3995135.stm (accessed June 25, 2005)

Kauffman, S (1988), "The evolution of economic webs," in Anderson et al. (1988)

Kauffman, S (1995), *At Home in the Universe*: *The Search for Laws of Self-Organization and Complexity*, London: Penguin Books

Krugman, P (1996), *The Self-Organizing Economy*, Maiden, MA: Blackwell

Levin, S. (1999). *Fragile Dominion: Complexity and the Commons*. Reading, MA: Perseus Books

Livi-Baci, M (1997), *A Concise History of World Population*, Oxford: Blackwell Publishers

Luhmann, N (1995), *Social Systems.* Stanford, CA: Stanford University Press

Marquet, P A, et al (2005), "Review: Scaling and power-laws in ecological systems," *The Journal of Experimental Biology* 208, 1749-1769

Morin, E (1986). La *Mèthode: Tome III La Connaissance de la Connaissance*, Paris: Éditions de Seuil

Moses, M E and Brown, J H (2003), "Allometry of human fertility and energy use," *Ecology Letters* 6, 295-300

Olson, M (1965), *The Logic of Collective Action: Public Goods and the Theory of Groups*. Cambridge, MA: Harvard University Press

Peters, R (1983), *The Ecological Implications of Body Size*, Cambridge University Press

Pumain, D (2003), “Scaling Laws and Urban Systems,” from SFI workshop on “Social Scaling.”

Schroeder, M. (1991). *Fractals, Chaos, Power Laws: Minutes from an Infinite Paradise*. New York: W.H. Freeman

Shirky, C (2003) “Power Laws, Weblogs, and Inequality,” from Clay Shirky's Writings About the Internet, at http://www.shirky.com/writings/powerlaw_weblog.html

Simon, H (1955), “On a class of skew distribution functions,” *Biometrika* 42, 425-440

Venetoulis, J, Chazan, D and Gaudet, C (2004), *Ecological Footprint of Nations*, Sustainability Indicators Program, Redefining Progress (http://www.rprogress.org)

West, G, Brown, J and Enquist, B (1999), “The fourth dimension of life: fractal geometry and allometric scaling of organisms,” *Science*, 284, 1677-1679

World Resources Institute (2004), *World Resources 2002-2004: Decisions for the Earth: Balance, Voice and Power*, World Resources Institute, Washington D.C. (http://www.wri.org/)

Zipf, G (1949), *Human Behavior and the Principle of Least Effort*, Reading MA: Addison-Wesley