Some Perspectives on Linked Ecosystems and Socio-Economic Systems

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1. Introduction: Ecology, Economics, Societies and Complex Systems

Partha Dasgupta has been a pioneer in bridging the gap between two scholarly foci: on the one hand, the human socio-economic system and its development, and, on the other, the ecosystems on which the former are utterly dependent (Dasgupta 2001; Dasgupta 2003; Dasgupta et al. 2005). In his brilliant book, *Economics: A Very Short Introduction*, Dasgupta summarized the significance of ecosystems (which he categorizes in terms of types of capital assets) as follows: "The services they produce include maintaining a genetic library, preserving and regenerating soil, fixing nitrogen and carbon, recycling nutrients, controlling floods, filtering pollutants, operating the hydrological cycle, and maintaining the gaseous composition of the atmosphere" (Dasgupta 2007: 119). These and many other ecosystem services (Holdren and Ehrlich 1974), such as controlling crop pests, supplying fish from the seas and freshwater sources, and providing cultural, intellectual, spiritual, and aesthetic inspiration, indicate how deeply intertwined are the problems of improving the welfare of humanity, especially the half in need of "development" (basically increased capacity to command consumption), and the problems of maintaining these crucial services.

The importance of natural capital is reinforced by recognition of the accelerating pressures caused by increasing human influence on Earth's ecological systems—the use of land, forests, and animal resources for food and fuel and for space for living, sequestering of "wastes" such as CO2 and other human purposes.

Dasgupta has also been a pioneer in building bridges between ecology and economics, recognizing the similarities inherent in the organization and evolution of ecological and socio-political-economic systems.

Both the human enterprise and ecosystems are complex systems, in both the everyday and the technical senses. The elements of each have many direct and indirect connections. Perturbations in one sector will ultimately have consequences, large or small, on other sectors seemingly far removed. What is more, the consequences in remote sectors in turn affect the sector with the initial disturbance, possibly offsetting it, possibly magnifying it. The similarity of the names, ecology and economics, deriving as they do from a common Greek root, is no accident.

These intertwined systems are actually special cases of complex systems, termed complex adaptive systems (CASs) (Holland 1995; Levin 1998). That is, they are composed of individual agents that adjust their behavior or their relative numbers, with consequences for the system as a whole, and these consequences can in turn affect individual behaviors. There is also in both the notion that the reactions of any element to changes are governed by a motive of increasing utility—profit, power, resilience, security, efficiency or something else in the human and other animal species, and fitness more generally for all species, including humans, over evolutionary time.

It is not merely that the two complex adaptive systems have many parallel structures. They have direct interactions, and in a profoundly increasing way. The human economy, originally the province of one minor player among many species, has expanded to a position of dominance in the demands on the resources of Earth. Ecosystem services, the benefits humans derive from ecological systems, are under unprecedented assault as a result of a still rapidly growing human population, a considerable increase in per capita consumption, and the development of technologies designed to meet these needs with inadequate concern for their ecological implications (Ehrlich and Ehrlich 2009). In both realms, arguments have been given that the unrestricted and unregulated behavior of the systems leads to outcomes that are optimal for the participants. The doctrine that markets left to their own devices lead to economic outcomes that are efficient with respect to human welfare was held by French eighteenth century economists (as evidenced by the term, "laissez-faire," brought from French to English) even before Adam Smith enunciated the doctrine of the "invisible hand" (though Smith himself had many qualifications). Similarly, the concept of Gaia (Lovelock 1972; Margulis and Lovelock 1974; Schneider and Boston 1991) in its extreme form is sometimes taken to suggest that the biosphere will self-organize for the good of its inhabitants; such a view flies in the face of our understanding of the mechanisms of evolution.

Either system, left to its own devices, is likely to find some asymptotic configuration, not necessarily equilibrial, but possibly involving fluctuations and even chaos. However, in neither case, as we shall argue, is there any reason to expect that the outcome will optimize the collective good (if defined in any reasonable sense), and certainly not the collective human good. Indeed, many scientists fear that present threats to that good have brought humanity into a largely unrecognized state of emergency. (The view that the welfare of at least sentient nonhumans should be taken into account has been defended by such philosophers as Jeremy Bentham and Peter Singer, and informs actual ethical practice in the form of prohibitions against cruelty to animals.) In each case, the individual self-interest that drives the forces of self-organization will have unpredictable and frequently negative macroscopic consequences. Socio-economic and ecological-environmental systems alike, therefore, require some balance between free running and regulation, whether by government, by "mutual coercion, mutually agreed upon" (Hardin 1968: 1245), or by social norms more generally.

We explore broadly and tentatively these parallels and challenges in this essay. In Section Two, we address socio-economic and political systems from the point of view of complex adaptive systems. Section Three addresses the behavior of ecosystems and biosphere. In Section Four, we discuss some of the linkages between the socio-economic and ecological systems, particularly the strain imposed on the ecosphere by the increasing demands of the economy, fueled by the extent to which the price system fails to work with regard to common resources and to the future. In Section Five, we study some of the parallels between the socio-economic and ecological systems, including the role of modularity, the possibility of multiple basins of attraction, and the positive and negative values of robustness and resilience.

2. The Economy as a Complex Adaptive System

The competitive economy is perhaps the first social system to have been analyzed as what today would be called a complex adaptive system (CAS). It is built out of individual units, firms that engage in production by investing capital and buying labor and other materials and households that sell labor or other material possessions and buy the products of the firms. Products are exchanged through market transactions. That is, any given product (including materials bought by firms) is sold at a given price, the same for all participants (whether sellers or buyers).

Every member of the system is assumed to adapt in a way favorable to itself. Capital moves to activities and industries that yield a higher return. For any given output, firms choose factor combinations that will achieve that output at minimum cost. A household will sell its assets (labor, land, or whatever) at the highest price offered compatible with its preferences and will buy the consumption bundle that it judges best among those it can afford with its income. Finally, for any good, the amount desired is equal to the amount available on the market; the prices of the goods adjust until this equality holds. (More precisely, either equality holds or the amount supplied even at zero price exceeds the demand, as, for example, air, or, sometimes, water or land in thinly populated areas.)

This vision of the economic order as a system coordinated through prices and markets was articulated by Adam Smith (1776) and developed further in the nineteenth century, reaching grand syntheses in the works of Léon Walras (1874, 1877) and Alfred Marshall (1890). It was a vision by which an extremely complex series of transactions and activities could make available the commodities that facilitate life and improve its quality. The buyer of the goods need know little of the processes of making them.

Accompanying this understanding of the coordination role of the competitive economy, moreover, was a recognition that the outcomes of the system were in fact "good" for the participants—"good" in the sense of facilitating the accomplishment of the aims of the individual units. What appears as a struggle in which each unit is trying to achieve the best for itself results in an efficient allocation of resources, while being required to compensate others for any damages inflicted upon them.

This picture is not without merit and has served as a useful guide to many policy decisions. The remarkable increase in productivity after the Chinese adoption of markets as a primary form of economic organization is simply the latest manifestation of the principle. But none of the pioneers—Smith, Walras, or Marshall—held that the market allocation was all-sufficient. They all held that there was a major role for the government. As Marshall put it, "So I cry, Laissez-faire: Let the State be up and doing" (Marshall 1907 in Pigou 1925: 336).

The major problem is not the use of markets but rather their non-use—more precisely, their non-existence. The central concept of "capital," which has given its name to our current economic system is that of bridging a gap in time between deciding on production and purchasing inputs and the actual occurrence of the production. But this means that the profitability of an investment depends not on current prices but on the prices that will prevail in the future.

To complete the original intent of the theory, we would need to have markets today for deliveries of goods in the future. These do exist, but only to a very limited extent. For some agricultural goods and minerals, there are so-called futures markets, contracts for purchase and sale for a few years ahead. Much more important are bonds and other securities promising payments in money (the capacity to buy commodities) in the future, sometimes many years ahead. But clearly these are far from providing the coordinating function that makes the market such a satisfactory complex adaptive system.

If markets for the future would be so satisfactory, why do they not exist? One obvious answer is uncertainty. We really do not know what our situation will be the in the future. The process of innovation means that manufactured goods that will be available tomorrow, from the same plants being built today, cannot be fully specified. (It is not an accident that such futures markets as exist are confined to goods whose specifications will not be changing: wheat, copper, petroleum, and the like.)

It could be argued that futures markets would be possible if supplemented with markets that offer protection against uncertainties, in effect, insurance contracts against changes in specifications and against other uncertainties arising in economic life. What prevents anything like full or even meaningful protection against business uncertainties of all kinds is the fact that the information needed to specify the contingencies under which payment is to be made is not equally available to all parties. This problem has been addressed in theoretical and applied research in the last half-century under the heading of asymmetric information. The insurance industry has long known this problem under the headings of moral hazard and adverse selection. The first means that motivations are altered by insurance: one insured against fire will have less incentive to take precautions. Similarly, one insured against business failure will have less incentive to work hard; hence, such insurance, in whatever form it may take, will not be found on the market. The failure to have such insurance will in turn inhibit entry into business. Adverse selection occurs when some desiring insurance know more about the risks than the insurer does. Hence, the population of insured will not be given by the observable risks in the population, but will be higher to some uncertain extent: If the insurer initially sets rates according to the average risks in the population, those who know they bear greater-than-average risks will buy more insurance and those who know they bear less-than average risks will buy less. Hence, the insurer will find it is bearing losses and will have to raise its premiums. This in turn will lead to still further shifts in insurance coverage to riskier insured. This process might end in the complete disappearance of insurance coverage or its restriction to a relatively small high-risk group.

It might seem as if the limits on the existence of markets for the future and for risks would mean simply that the market is not as efficient an allocator as a simple reading of equilibrium theory would suggest. But the matter appears to be much worse than that. What this argument has implied is that economic behavior is driven to a major extent by information or, perhaps better put, beliefs. But these beliefs are driven in part by observations on the workings of the economic system. As Oskar Morgenstern (1935) pointed out already in the 1930s, investment is based on a forecast of the economy. But this is based on the investment and other economic activities of others, which, in turn, are based on their forecasts. In short, the belief structures of the different economic agents are dependent on each other. This situation clearly invites instabilities. If some people start to be pessimistic, for whatever reason, this will spread. Hence, the belief systems will be highly intercorrelated and so likely to exhibit unstable behavior. Disturbances are likely to propagate.

The fact that information is dispersed has implications for the behavior of individuals and for the internal organization of firms. Individuals may study the behavior of others as manifest in markets, including the securities markets, to draw inferences. Firms and individuals may engage in costly activities designed to improve their knowledge base. They may need to create incentives for their employees and agents to use the information they have to their advantage. But these incentive systems, though effective most of the time, can never be designed to as to insure against provoking outcomes that are unfavorable both for the firm and for the entire economy. Some of these issues were discussed in Arrow (1974), and there has been a rich development in the study of incentive mechanisms since. But a full analysis as to how these incentive schemes can produce unfavorable outcomes is still missing.

Indeed, some of the measures designed to create greater security for individuals can increase the instability of the entire system. In view of the limited information, lending is made safer to the lender by requiring collateral. But if there is a downturn so that the borrower defaults, the lender will throw the collateral on the market to recoup his or her losses. This will, however, increase the downward pressure on the securities markets and so create new defaults. To add to the problem, the drawing of inferences from what can be observed becomes increasingly complicated and therefore an additional cost on the economic system.

It was observed early in the history of capitalism that there were sudden inexplicable downturns in economic activity. By the middle of the nineteenth century, the idea that these downturns were a characteristic of the system became widely accepted (Juglar 1862). The study of so-called "business cycles" became standard, but little is known to this day of an explanatory nature. These cycles are sometimes, though not always, associated with crises in the financial sector. (Cycles are also evident in ecological systems, at scales from the forest patch and below to whole ecosystems).

An example of a possible changed attitude to policy due to complex system thinking might be views on modular design, particularly in international trade, and especially international capital flows. Economists, even those most inclined to favor government intervention, have always tended to favor free trade and, though less strongly, international capital movements. If there are risks, so it is argued, it is best that they be spread widely, so that the advantages of diversification can be achieved.

The physical image is that of a possible flood due to a river overflow. If we try to confine the river with high levees, there will be a concentrated disaster if there is a break somewhere. Hence, it is better to have widespread limited flooding. To those who advocate modular design, the image is rather that of a forest fire, where a small disturbance is multiplied. Here, firebreaks are clearly advantageous.

The Eurozone was indeed strongly supported on the grounds that it would average out disturbances (Mundell 1961). Its existence created an expectation that the consequences of irresponsible fiscal behavior by one member would be covered by the rest. However, it does appear, at least, that separation, in the form of separate currencies might have prevented Greece, after all a relatively small part of the Eurozone, from being in a position to create such havoc. (This is not meant to be a serious analysis of the current situation, but only to point out some connections to complex system analysis.)

3. Ecosystems and the Biosphere as Complex Adaptive Systems

Perhaps even more disturbing than shifts in socio-economic systems may be regime shifts in the global ecosystem complex adaptive system, where a historical accident can cause a vast epidemic, trigger an extinction episode greater than the one that wiped out the dinosaurs, or push the climate system into a new basin of attraction. Perturbing phenomena could include such things as political pressure to keep the GDP growing despite market failures and possible resource shortages; pro-natalist policies; resource wars; or simply that humans persist in being animals more comfortable in small groups than in a globalized world of some seven billion people.

Theodosius Dobzhansky wrote that "nothing in biology makes sense except in the light of evolution" (Dobzhansky 1973), and indeed the evolutionary perspective is the most important unifying principle in biology. Genetic lineages adapt to their environments through mutation, recombination, and selection within the context of population structure. Dramatically, they form partnerships with one another that become reinforced over time through genetic integration, leading to the major transitions in evolution, like multicellularity. Bacteria exude extracellular polymers that lead to biofilms, a unique form of cooperation in solving problems of the Commons, and more generally a variety of modes of cooperation within and among species is distributed widely across all of the biological kingdoms.

Still, understanding how and under what circumstances cooperation can arise remain among the great theoretical questions in evolutionary biology, and among the most hotly debated. Ecological systems, at all levels, are complex adaptive systems, as we have already learned, which means that the interests of individual agents may be in conflict with those of the group, or the ecosystem, or the biosphere. The parallel with similar issues in economic systems is not accidental. Ecosystems are economic systems, and vice versa, with competition for resources; the opportunity not only for cooperation but also for exploitation; and the emergence of differentiated systemic roles for different kinds of individuals.

The evolutionary story, at its core, is strongly analogous with the economic story laid out in the previous section. This is of course not surprising, given the similar natures of the two systems, ecological and economic. Agents in nature, from cells to genes to individuals to populations, compete with one another for common resources, and interact with one another directly through competition, exploitation or mutualism. As the result of these processes, agents receive rewards in terms of differential reproductive success, “fitness,” the biological analogue of utility.

Since fitness is differential reproductive success, it seems logical that natural selection will reward the most fit, increasing their representation in future generations, and furthermore that the mean fitness in the population will gradually increase towards a relative peak. This intuition is indeed captured in Sir Ronald Fisher’s Fundamental Theorem of Natural Selection, and in Sewall Wright's notion of the adaptive landscape. Fisher demonstrated that, subject to certain assumptions, the mean fitness of the population will increase monotonically over evolutionary time, at a rate proportional to the strength of selection and to a measure of the genetic variance (technically, the additive genic variance) in the population; in Wright's imagery, the population mean fitness is represented by a point that climbs a peak in the fitness landscape. Such landscapes, of course, may have multiple peaks; and so, even in this view, the peak reached is not necessarily the best of all possible peaks (Kauffman and Levin 1987).

The real problem with this description of the evolutionary process, however, is in the assumptions that underlie Fisher's Theorem, and in particular the notion that fitnesses are constant (i.e., that Wright's landscape is static). Environments change, and so adapting to today's conditions is no guarantee of an increase in fitness even in the next generation; uncertainty about future conditions, indeed, is a strong selective force on its own, and perhaps the most important driver of the life history evolution of species. Mutation and sexual recombination, in particular, to some extent have been shaped by the challenges of uncertainty, as ways for genomes to remain adaptive in changing environments. The issues are the same as those addressed earlier in the context of exploitation versus exploration, and the general issue of how agents in ecology and economics alike should balance current versus future success.

We worry today about rapid variation in environmental conditions due to climate disruption, toxification, and other global anthropogenic changes, and about the ability of populations to adapt to those changing environments. The real challenge to the simple view given earlier, however, is not exogenous variation, but variation in fitnesses that arise from the evolutionary process itself. (Indeed, one can argue that climate change is to large extent not an exogenous forcing, but is itself the result of the evolution of the ability of humans to over-exploit their environments; but that is an effect on a much longer time scale). As organisms with certain genomes exploit particular sets of resources, the depletion of those resources makes those with other genomes more fit. The ability of carriers of some genomes to use a certain resource to best advantage may make other resources more efficient for those with different genomes to use. Or it may lead to selection for mechanisms like nitrogen fixation that provides a selective advantage against those with other genomes. Viral strains that take advantage of the lack of resistance of host cells to their stereochemistries are replaced by other strains that exploit host cells in different ways, ways that previously were competitively inferior.

All of these considerations emphasize that adaptation does not necessarily lead to optimization (Lewontin 1977; Gould and Lewontin 1979). As useful as it is to study biological adaptation from the viewpoint of optimization, we must recognize that evolution is a process that is first of all strongly path dependent (Jacob 1977), historically constrained within a landscape that at any one time has multiple peaks, and secondly that the evolution of any lineage cannot be uncoupled dynamically from the evolutionary and demographic responses of other lineages. When those lineages are within the same species, this phenomenon is called frequency-dependence; when other species are involved, it is termed coevolution (Janzen 1980; Ehrlich and Raven 1964). Within this context, the notion of optimization must be replaced by perspectives from game theory (Lewontin 1961; Slobodkin 1964), which led John Maynard Smith to borrow from economic theory (Nash 1950, 1951) and introduce the concept of the evolutionarily stable strategy—a type that, once established, cannot be displaced from the population (Maynard Smith and Price 1973; Maynard Smith 1982). Dynamically, the situation is even more complicated, since evolutionarily stable strategies may not be reachable within an evolutionary dynamic, and since, conversely, the evolutionary process may lead not to stable strategies but to bifurcations and speciation (Eshel and Motro 1981; Dieckmann and Law 1996; Geritz et al. 1998)

Within this framework, the evolution of cooperation was a puzzle even to Darwin. Cooperation is evident throughout the natural world, including at the extreme the evolution of multicellularity, the ultimate form of cooperation. Our own bodies are consortia of genes and organelles of diverse origins, that each benefited by evolving together into a collective. Early explanations of some extreme forms of cooperation within species relied on genetic relatedness, and the benefits of helping one's kin; but genetic relatedness clearly is not required for cooperation, and there are multiple explanations, from reciprocal altruism and bilateral partnerships, to the more complex arrangements like social norms that sustain large societies (Axelrod 1984).

Here then is the critical nexus between ecological theory and economic theory. What can we learn from evolutionary theory about how cooperation has arisen and been maintained, and what are its limitations as the sizes of groups become larger? William Forster Lloyd elegantly called our attention to the problems associated with common-pool resources, like the grazing commons that are found in most cultures. Garrett Hardin rediscovered Lloyd, and introduced the term that has had such resonance, the "Tragedy of the Commons," in which the collapse of common resource systems can result from a lack of incentive of individual agents to modify their own acquisitive and exploitative behaviors. The problems are reminiscent of those well known to Adam Smith, Walras, and Marshall. The only solution, according to Hardin, was to achieve "mutual coercion, mutually agreed upon" (Hardin 1968: 1245).

Quite simply, this is why the biosphere is in the mess it is today. Whether the agents are individuals or collectives or nations, the interests of the one and the interests of the many can diverge. There are many lessons to learn in dealing with global environmental problems concerning how evolution has resolved, or failed to resolve, these conflicts. Most centrally, we can look at the exquisite functioning of natural systems and feel comfort in the multi-species partnerships that keep nutrients and energy flowing; but that would be misleading, because it ignores the many genotypes and indeed species that disappeared along the way. The biosphere will resolve today's conflicts and find new balance, but there is no guarantee that we, or components we cherish and value, will be part of that balance.

4. Linkages and Parallels Between Socio-Economic and Ecological Systems

The social complex adaptive system is embedded within the CAS of the biosphere—collectively all the world's ecosystems (Levin 1999). The latter is of even greater complexity, and the social CAS is in continual, but often little recognized, interaction with it. For instance, the world market system requires huge amounts of energy, some twenty-fold more than humanity used in 1850, and the signs for rapidly finding a cheap abundant replacement for fossil fuels are not good. There are no obvious new sources of energy, the equivalent of the coal that replaced wood and the oil that added to coal permitted today's degree of global "development," waiting in the wings as fossil fuels are (necessarily) phased out.

While, for example, there is pressure from the social CAS for perpetual growth in GDP and population, that pressure alters the ecosystem CAS and could trigger emergence of nasty consequences from climate disruption that devastates agriculture to epidemics much more severe than those suffered before modern medicine. As mentioned earlier, Gaia theory has often assumed there is a similar invisible hand guiding the evolution of the biosphere (Lovelock 2001), but the flaws in this metaphor are at least as great as they are for the social CAS.

Understanding the properties of complex adaptive systems helps one think about the world, but it will not tell us what will occur. Most of their aspects have not even yet been satisfactorily modeled mathematically, although considerable progress has been made recently at least in identifying early warning indicators of system collapse, like critical slowing down or increasing variance (Scheffer 2008; Scheffer et al. 2009). But understanding the properties that lead to robustness and resilience, of desirable and undesirable states alike, does suggest some lessons that we might internalize as we try to struggle with increasingly dangerous threats to the persistence of civilization (Levin 1999). For example, because a complex adaptive system is prone to emergence of unpredictable phenomena, from AIDS to market meltdowns, policies should be designed with more attention to flexibility and adaptability in response. Resisting change often will not work, but flexibility and adaptability may foster recovery and hence enhance robustness. Similarly, despite the great popularity of large-scale solutions and "globalization," ways should be sought to find small-scale solutions and find an optimal degree of modularity of the world, increasing robustness of desirable large-scale states and patterns. Modularity, of course, just as heterogeneity, has advantages and disadvantages both for human welfare, and for the robustness of systems. Giant electric grids are vulnerable to properties of both the ecosystem CAS (storms, earthquakes, solar storms), and the social CAS (error, terrorism, overloading); housetop solar-electric panels are not, and hence collectively increase the robustness of the entire power grid. More generally, systems that are too interconnected carry systemic risk, the potential for contagious spread of disturbances like bank collapses, infectious diseases and forest fires. On the other hand, interconnectedness, like the ability to trade goods or provide insurance arrangements, confers benefits both to system performance and robustness. The goal should be to find an intermediate level of modularity that does a satisfactory job of balancing costs and benefits. Indeed, the advantages of some degree of modularity is reinforced by the fact that modularity has been selected for through natural selection, enhancing the process of adaptation and preserving its advances.

As world leaders have belatedly realized that the world's economic system may have flipped into a new basin of attraction, one where we would rather not be, they have attempted unprecedented cooperation, for example in propping up the Euro, reducing modularity as much as feasible. This is a sensible short-term response, since the goal has been to overcome the robustness of the undesirable state. By the same token, these must be short-term efforts at synchrony; once the system is back in a more desirable state, additional independence and modularity are essential to provide the adaptive capacity needed to sustain the system. Theories of robustness of complex adaptive systems have much to contribute. Economists should be doing more to understand the relationship between markets, culture, and different definitions of freedom (e.g., the freedom we all have to be street people). They should be looking at ways that markets can be restrained from taking us even further from sustainability, and see if their allocative efficiency could be preserved with a goal of individuals seeking adequacy rather than maximizing utility. They should be looking at ways to modularize markets to some degree, so that unfortunate emergent properties can be more readily isolated (e.g., could packaging poor mortgages into Structured Investment Vehicles have been better segregated from the rest of the financial system?) so as to reduce the vulnerability of networks to the propagation of local disaster (Haldane and May 2011). Ben S. Bernanke, addressing this in comments to the Council on Foreign Relations in 2009, expressed what many believe in stating that "First, we must address the problem of financial institutions that are deemed too big--or perhaps too interconnected--to fail." Again, trade offers obvious advantages in spreading benefits and providing insurance against local failures, but these benefits must be balanced against the risks associated with overconnectedness. The recent problems in banking and in sovereign debt illustrate the delicate balancing that must be performed.

Modularity, redundancy and heterogeneity, in balanced proportions, are all essential aspects of a system's capacity to maintain its functioning in the face of stressors. Redundancy can compensate for the loss of key elements; modularity can contain contagion and systemic risk, and provide building blocks for improvement; and heterogeneity embodies the adaptive capacity of the system to deal with threats (Levin 1999). In ecological and evolutionary systems alike, diversity and heterogeneity are often enhanced by fluctuations (Hutchinson 1961), and hence efforts to suppress short-term fluctuations, like controlled fires or small-scale market corrections, may be misguided. The optimal pathway requires some balance between exploration and exploitation, and this is a lesson that should be heeded by governments, companies and funding agencies alike.

So it is clear both empirically and theoretically that markets alone cannot create a society that is both just and sustainable. In the rest of this essay we look more closely at the intertwined social and ecosystem complex adaptive systems, Partha Dasgupta's domain, to seek directions in which humanity might proceed toward the goal of such a society. We also suggest and explore that, because of the similar complex adaptive natures of the two systems and their coupled combination, an evolutionary perspective can be a guide in addressing problems of sustainability. Indeed, an attractive, oft-cited metaphor and model in this regard is the vertebrate immune system, which has evolved to deal with the certainty of unpredictable threats. The immune system combines generalized and immediate responses with longer-term and adaptive ones, illustrating the balance that must be found in the linked social-ecosystem systems between the implementation of known solutions and the adaptive capacity that allows for exploration of new solutions.

Intragenerational and Intergenerational Equity

The great challenge facing society – achieving a sustainable future for our children and our grandchildren – is inherently interdisciplinary. Ecology must meet economics in issues such as the valuation of Earth's biotic resources, and obviously bio-physico-chemical constraints must be addressed as well. At the core, however, ethical issues loom. How should we discount the future (Dasgupta 2008; Arrow and Dasgupta 2009)? How much can we consume now, while heeding the Brundtland Commission mandate to leave for future generations the same options we enjoy today? How should we take account of the inevitable uncertainties necessarily associated with the future (e.g., Arrow 2009)? And of course, intergenerational equity does not stand alone, but must be coupled with its dual, intragenerational equity, and the associated problems of the Global Commons. Both of these issues have been addressed in parallel research in the economic and ecological/evolutionary literature.

The problem of intergenerational transfer of resources is a natural dynastic extension of the problem of optimal resource utililization during one's lifetime (Arrow and Levin 2009). In the ecological literature, this falls under the rubric of life history theory, which addresses issues such as when a plant should switch from growth (consumption) into reproduction (investment), how to allocate reproduction over one's lifetime, and what resources to transfer from parent to children. Life history theory is also largely about the adaptations of organisms to uncertainty, the relative benefits of specialization versus generalization and risk-spreading, and the tradeoffs between exploitation and exploration/innovation. The parallels between the ecological and economic issues are obvious, and should not be surprising because of the parallel nature of ecosystems and socio-economic systems as self-organizing complex adaptive systems, in which individual agents compete for resources.

Optimal Utilization of Multiple Resources

The issue of uncertainty as it relates to the utilization of a single resource extends obviously to the issue of specialization versus generalization in a heterogeneous environment, especially when there is uncertainty regarding which kind of environment will be available. Good and bad environments for growth represent one kind of heterogeneity, but organisms and economic agents alike can modify what "good" and "bad" mean through adaptation and plasticity. Richard Levins (1968) introduced the notion of "grain" into ecology and elegantly demonstrated how temporal correlations in the patterns of environmental variation shaped optimal utilization strategies. In a "fine-grained" environment, an individual's utility or fitness is averaged arithmetically over many different experiences, as if one had picked up a handful of sand on the beach. In contrast, in a coarse-grained environment, utility or fitness emerges from one or a small number of events. Again, there is a strong parallel between ecological and economic systems. For example, plants utilize multiple environmental nutrients, like nitrogen and phosphorus; herbivores feed on multiple plant species; and businesses not only must exploit multiple markets, but also must allocate resources to capital versus labor. In all these cases, the allocation problems are similar, and the optimal patterns of use depend upon predictability and grain.

A central issue in all such determinations is the balance between exploration and exploitation, in ecology the domain of optimal foraging theory (Pyke 1984). The theory deals with the utilization of a known good or a known technology versus investment in less certain alternatives that might have a higher payoff. Animals leave patches where they are feeding to forage for potentially more valuable resource items, paying an immediate price in order to gain information that is not otherwise available. Similarly companies and funding agencies must balance investment in known quantities with speculative forays into research and development of new ideas. Such exploration is key to persistence, especially in a competitive environment, be it ecological or economic.

Exploration is also a way to spread the risks in an uncertain environment, as opposed to investing fully in a pure strategy. Plants disperse seeds, or place them in dormancy, in order to spread them over a variety of environments; investors diversify their investments for the same reasons.

Information, Conflict, Cooperation, and Collective Action

If generalization and risk-spreading are ways individuals deal with heterogeneity and uncertainty, so too is cooperation. Indeed, cooperation is a first step in the evolutionary transition to the formation of complexes, modules that provide building blocks for higher-level evolution. The emergence of multicellularity is a classic evolutionary extension of such transformations, but more generally genetic and phenotypic modules are receiving increasing attention in the evolutionary literature (Hartwell 1999). In socio-economic systems, modularity is ubiquitous, represented by entities such as tribes, religions, professions, and nations. However, too often, cooperation has arisen as a means to allow groups of individuals to compete more effectively against other groups. For the sustainability of our life-support systems, we must find ways to extend such cooperation to broader scales, raising the unit of focus to the biosphere as a whole. Most likely, that will require an hierarchical approach, for example building cooperation up from polycentric foci (Ostrom 2010; Levin 2011).

Backcasting

Backcasting is a tool that tends to be underutilized in the study of the conjoined complex adaptive systems. Backcasting consists of postulating some desired future state and then working backwards to determine programs and policies, and the timing of their implementation that would be required to reach the proposed goal. Backcasting has an advantage over forecasting in that it allows one at first to largely ignore the potentially disruptive emergent properties (chaotic behavior) of complex adaptive systems, and provides a multi-stage set of concrete targets that need to be met.

A recent example of backcasting was the exercise of the World Business Council for Sustainable development (WBCSD) examining what would be required to reach a sustainable society by 2050. One of the things not included in the WBCSD exercise was the issue of diminishing margin product, which is rarely considered in demographic analyses (Ehrlich and Holdren 1971) and has been deeply implicated in the collapse of complex societies, as documented by Tainter (1988). But more important from our viewpoint was that the WBCSD, having done the backcast with the appropriate assumption that the conjoined complex adaptive systems would not generate negative emergent properties that could drastically alter the requirements, did not go further. We believe the exercise should have been extended to develop ways to add robustness and resilience to those requirements, while not neglecting the possibility that trajectories could also be altered by emergence of unexpected positive factors (e.g, a dramatic breakthrough in solar energy technology, or the generation of a mass "shrink your ecological footprint" or "population control movement"). There is a long historical record of both rapid technological change (e.g., following the invention of the internal combustion engine) and social change (American Revolution, civil rights in the U.S., collapse of the Soviet Union).

Finding reasonable ways to work emergence into backcasting is a major challenge for those wishing to plan for a sustainable future.

It is, of course, the interactions of the ecosystem and social complex adaptive systems that determine the carrying capacity of Earth for human beings, and how far (at any given time) the joint system is from that capacity. Here the issue becomes especially difficult because of the problems of factoring emergent properties into both elements. Should the social CAS quickly transition to a state where individuals accept adequacy rather than maximizing consumption became the norm, the carrying capacity would increase. Should the climate shift into a basin of attraction that made many grain-growing regions warm dramatically, carrying capacity would plummet.

Carrying Capacity, Sustainability and Ecosystem Services

Perhaps the most crucial question facing scholars today is how to create a global society that gives a decent life to all people without doing it at a serious cost to future generation (that is, a society that is "sustainable"). This obviously involves some broad agreement not just on how to define "decent," but also on the distribution above a floor of "decency." Some peoples' standards of living will inevitably be more decent than others. And since the intertwined CASs make predicting the future with great accuracy impossible, societies must consider probabilistic issues when trying to decide on courses of action that might impose costs on our descendants who would violate the sustainability criterion. In short, there is a need for broad social agreement on what is decent, sustainable, and serious—and, most critically, on what is possible or likely. The latter is an issue of the carrying capacity of Earth for human beings (Daily and Ehrlich 1996), where widely disparate guesses have been catalogued (Cohen 1996). But serious estimates under different assumptions are largely lacking (MacKellar 1996), with the outstanding exception of the work of Rees (2001) and Wackernagel (Wackernagel and Rees 1996) on "ecological footprints."

For instance, at the moment there is much discussion of the "need" to increase food production by seventy percent by 2050 in order to provide adequate nourishment to an expected population of some nine billion people. But the demographic projection only represents a population increase by some thirty percent, so that a more realistic (and environmentally cautious) goal might be to attempt to increase production by fifty percent to be used in feeding the newcomers and in improving the diets of the poorest of the poor. Market mechanisms have not developed for adequately feeding seven billion people, as a result of the persistent inability of a billion or so people to command nourishment and thereby generate sufficient demand. If they are to be adequately nourished, it seems a less ambitious and more targeted goal, to strive to increase production by fifty percent and to work hard to institute new policies within the social CAS to increase the demand generated by those now under- or malnourished might have a better chance of success. A related and more limited goal would be to establish the basic investigative apparatus that is required to estimate the long-term carrying capacities of Earth for societies under different assumptions of life style and the robustness and resilience of the ecosystem services required to maintain that lifestyle. The absence of such information, widely shared, is an enormous barrier to the making appropriate policy interventions.

5. Conclusions and Recommendations

Our most basic conclusion is that policy makers fail to give adequate consideration to some of the most fundamental aspects of the complex adaptive global system they are charged with influencing.

There are a series of evolutionarily-inspired topics that badly need a public airing in humanity's attempts to deal with the two intertwined complex adaptive systems. They include their unpredictability —people as a whole must begin to substitute probabilistic thinking for the notion that science can "prove" things or that supernatural forces can supply certainty about ethical issues or the trajectory to the future. Such probabilistic thinking is, of course, central to all standard evolutionary thought, genetic or cultural. In discussions of infrastructure or institutions, much more attention needs to be paid to the issues of robustness and resilience. Considering robustness—how desired aspects of the social CAS can resist change or return to desired states following perturbation—is one of the most ignored aspects of the human predicament. For example, rich nations designed and deployed electric grids that originally were sensible and, with the invention of alternating current, relatively efficient. Now, for economic and political reasons, they are tending toward unreliability and with their great expansion are vulnerable to propagating disaster. In the extreme, a solar storm of the magnitude that occurs every century or so could destroy all the transformers in the North American grid, essentially crippling the civilization of the continent. Without electricity, gasoline and oil could not be pumped; food could not be harvested, dried, or transported; the subways of New York would flood and the skyscrapers would topple; many water systems would collapse; most medical aid would be unavailable; and new transformers could not be manufactured. It would be a catastrophe absolutely unprecedented in scale and death rate, and yet no serious steps have been taken to make the electrical system robust (e.g., modularizing it to one degree or another in the process of transitioning away from fossil-fuel based generation).

Similarly, it now appears that precipitation patterns will be changing dramatically for at least the next millennium (Solomon et al. 2009), but as yet there is not even broad discussion as to how to convert humanity's water-handling infrastructure so that it is more robust to those relatively unpredictable shifts. Here, as in the evolution of development patterns in organisms, the issue of buffering would necessarily enter the analysis. Just as in development the gene-environment system is buffered in order that that minor changes in genes, gene regulation, or environmental impacts do not change the number of heads on an animal, so water systems need to be redesigned so that storage is sufficient and ducting adequate that critical amounts will be available to agriculture where it is essential.

All of this implies that economists should pay much more attention to the allocation of opportunity costs of dealing with the most likely threats embodied in the little-understood instabilities of the linked complex adaptive systems. It suggests that more consideration should be given to establishment and reestablishment of foresight institutions in all nations—for example, in the U.S. replacing the excellent Office of Technology Assessment of the Congress that was foolishly disbanded in 1995, and expanding its mandate. Foresight institutions could provide needed estimates of carrying capacities, capital requirements for revising water-handling infrastructure under different scenarios of climate disruption, necessary revisions of global governance mechanisms, and the like. They could help attack an aspect of the social CAS that demographer Nathan Keyfitz described accurately two decades ago: "If we have one piece of empirically-backed knowledge, it is that bad policies are widespread and persistent. Social science has to take account of them" (Keyfitz 1991: 15).

We also believe that at this time of crisis the world desperately needs to start a dialogue on the big issues, since the natural sciences have clearly shown that the ecosystem CAS upon which humanity depends has been significantly degraded. There are numerous and diverse attempts to start organizing the necessary discourse. One example is the MAHB (Millennium

Alliance for Humanity and the Biosphere – http://mahb.stanford.edu/), which is bringing together natural and social scientists and scholars from the humanities to try to catalyze needed developments throughout society. Another is the Pachacuti movement (http://pachacuti.com/), trying to build an online community that would help to shift human cultures and institutions towards environmentally sustainable practices and an equitable and satisfying future. Unless how people perceive and use ecological capital and services changes, the continuity of today's societies, an unchallenged assumption of past thinking, is seriously in question. In any case, special emphasis now should be given to making it clear to people that the issues of human well-being that have been central to Partha Dasgupta's work are also central to creating the required dialogue, however generated.

Any programs or movements trying to rapidly move society toward sustainability, will need to emphasize that many old ideas—such as that infinite growth of the physical economy is possible, that people are rational utility maximizers, that plagues are a phenomenon of the past, that nation states are the final stage of evolution of large political entities—can no longer be solid anchors for thinking about the future. Overall we would also recommend the "precautionary principle" needs to move into the forefront of both policy analysis and the thinking of the general public. This principle states, loosely, that we should avoid following any policy for which there is credible, even though not conclusive, evidence that it may lead to a very serious negative effect. In theory it should be prominent in any properly done cost-benefit analysis, but it normally is not—indeed many of the interactions of the human system with the ecosystem-environmental system (e.g., depletion of natural capital) are classically ignored. It's a big order to apply the principle broadly to the really major issues facing society, but doing so would greatly improve society's ability to buffer the serious threats embodied in the evolution of the two intertwined complex adaptive systems, which have been so central to Partha Dasgupta's research agenda.

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