Epilogue: The Challenge of Sustainability: Lessons from an Evolutionary Perspective

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Abstract The greatest challenge our generation faces is creating a sustainable future. At the core is maintaining the services ecosystems provide humanity, but our ability to achieve that objective is made more difficult because ecosystems, the biosphere, and the socio-economic system with which they are linked are complex adaptive systems, in which individual agendas translate into global consequences. For management, that introduces problems of the Commons, and of how to achieve cooperation in attaining the best possible solutions for the collective good. At the core are issues of equity, of prosociality, and of the management of public goods and common-pool resources. Progress has been made in addressing these issues, but realism argues that new institutional frameworks will be necessary to create a sustainable future for the global biosphere.

Keywords Sustainability • Equity • Discounting • Prosociality • Public goods • Common pool resources • Commons • Complex adaptive systems

As the chapters in this volume make clear, achieving a sustainable future for our children and their children is the central problem facing our societies. Can we grow economically without unfairly compromising the options for future generations to make choices about their lives (United Nations 1987)? Developing a comprehensive framework for answering that question is the first order of business in assessing and achieving sustainability. How do we measure and aggregate utilities to assess intertemporal social welfare (Arrow et al. 2004)? Are current patterns of consumption consistent with sustainability by this criterion, and if not what must we do differently?

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Sustainability means many things, with different emphases for different people. It includes the stability of financial markets and economic systems, of reliable sources of energy, as well as of biological and cultural diversity. At the core, though, it must mean the preservation of the services that we derive from ecosystems, and this raises a suite of scientific challenges. What are those services? How do they depend upon the features of ecosystems? What aspects of biodiversity and ecosystem organization maintain those features? What are the threats to those aspects, and how do we protect them, within our coupled human–environmental dynamic?

All ecosystems exhibit characteristic regularities in such features as the diversity and distribution of species, the spectrum of sizes of organisms, the balance of nutrients and stoichiometric ratios, and the flow of energy through the levels of the trophic web. If these are preserved, the ecosystem can continue to provide the services on which humanity depends, even if the identities of the component species change; when these are lost, the ecosystem is no longer the same in terms of the services it provides. This has led naturally to a focus on the robustness and resilience of coupled human–environmental systems, and on a search for indicators that systems are nearing qualitative shifts in character; that is, that they are at risk of transition into new basins of attraction, for example, from oligotrophic to eutrophic states (Holling 1973; Levin et al. 1998; Scheffer 2008). Addressing this crucial challenge is only in its infancy, but it represents an extremely promising and exciting area of investigation (Scheffer et al. 2009). The unique features of the challenge arise from the fact that ecosystems and the biosphere, as well as the socioeconomic systems with which they are interlinked, are complex adaptive systems (CAS), made up of individual agents that interact with one another locally, changing behaviors over ecological and evolutionary time, with macroscopic consequences that feed back to influence individual behaviors (Levin 1998). Sustainability science must extract the signal from the noise, focusing on those macroscopic features, and in how they arise and are sustained as the collective consequences of large numbers of interactions at microscopic scales.

The research agenda for sustainability is by nature interdisciplinary and multidisciplinary, leaving no discipline out, from physics and chemistry, biology and mathematics, to psychology, sociology and economics, to the humanities. How do we measure the services we derive from ecosystems, and how do we value those services and aggregate individual utilities to derive measures of social welfare? How do we assess and maintain the robustness of these services? CAS exhibit a range of features that pose special challenges; these have been well studied within individual disciplines, and more recently across disciplines because of the complementarity of insights that can emerge from interdisciplinary studies (Levin 1998, 2003). Independent of the context, CAS exhibit self-organization; the potential for multiple stable basins of attraction, with attendant path dependence and hysteresis; and contagious spread and risk of systemic collapse. Dynamics are played out on multiple scales of space, time and complexity, with the potential for destabilization through the dynamics of slow variables. Robustness in such systems depends on fluctuation and variation, and on a delicate balance of heterogeneity, redundancy, and modularity. For coupled human–environmental systems, therefore, a suite of research challenges present themselves: How do these systems self-organize over time? What features underlie their robustness and resilience, as well as resistance to changes that would improve human welfare? Does robustness normally increase over time, or does system evolution carry with it the seeds of its own collapse? What are appropriate indicators of the erosion of robustness, and increasing vulnerability to shocks? The research agenda to address such questions must include the development of agent-based and hierarchical models of self-organization, the elucidation of a statistical mechanics of ensembles of heterogeneous agents, and the description of emergent macroscopic dynamics.

The challenges already laid out are daunting, but have been at the center of research in ecology for decades. They will surely occupy the attention of ecologists for decades to come; but even if we could resolve them completely tomorrow, our work would have only just begun. Our ability to achieve a sustainable future is limited not primarily by our lack of understanding of biology or physics or chemistry or geology, but rather by a suite of obstacles that relate to psychology, sociology, economics, behavior and culture. They involve issues of intergenerational and intragenerational equity, and of the management of public goods and common pool resources. They inspire a quest to design mechanisms for achieving cooperation in the Global Commons, for example through the establishment and maintenance of social norms and more formal institutions and forms of government (Levin 2009).

At the core of issues of equity is discounting. We discount our own futures, and we discount the interests of others. Much of the inaction on environmental issues like climate change is because of discounting, and associated problems of managing public goods and the Commons. We need to develop theoretical and empirical approaches to problems of public goods and common pool resources, combining game theory and dynamical systems theory on networks to ask how cooperation can arise among independent agents, and how the emergence of groups, norms, customs and traditions depends upon and helps maintain prosocial behavior (Levin 2010). We need also to understand more generally how cooperation arises in natural systems, and to elucidate the role of leadership and the dynamics of collective decision-making (Couzin et al. 2005); and then we need to learn how to apply the insights we derive from other natural systems to human decision-making and the central questions of sustainability.

One of the greatest achievements of human societies has been the capacity to overcome competitive inefficiencies, and to find ways to avoid the "tragedy of the commons" (Hardin 1968). Through these advances, humans have organized themselves into cooperative groups, finding common purpose and laying the foundations for cultures, nations, and to a limited extent a global society. Hardin's solution to the tragedy of the commons was "mutual coercion, mutually agreed upon." Ostrom (1990, 2009) has led in explicating a framework and related theory of self-organization that helps diagnose whether small-scale fisheries will engage in such mutual agreements to improve their long-run capabilities and the sustainability of their fishery, and her work is inspiring other such studies in a wide range of systems. Such solutions involve some degree of prosociality toward other contemporary individuals as well as future generations. How are individual strategies shaped by prosociality, and how does such prosociality arise?

Intergenerational Equity

A fundamental problem in evolutionary theory is to understand how an organism allocates resources over its lifetime, balancing growth and reproduction, and trading off current needs against discounted expected future needs. Since evolution is about genetic combinations that are most successful in reproducing themselves in future generations, the problem of intergenerational allocation of resources is a natural extension—for example how many offspring an individual should have, when she should have them, and what fraction of resources to invest in each. In evolutionary theory, it is natural therefore to derive an implied prosociality, measured in terms of how much an individual values each offspring, and discounted in relation to the growth rate of the population. Other relatives will be valued as well, at lower levels of "prosociality".

This core problem in evolutionary theory has obvious analogues in economics. Parents plan their expenditures over their lifetimes not only to balance their own immediate comforts, but also to leave a legacy for their heirs, as extensions of themselves. This is known in the literature as the "dynasty problem" (Becker 1976), and has been the subject of a broad research literature. For the most part, however, this literature has not dealt adequately with the issue of uncertainty, which is a core topic in the evolutionary literature, or with the implications of individual allocation decisions for the expanding inequity of wealth within and among societies. For example, Arrow and Levin (2009) investigate these issues, determining the optimal (wealth) consumption strategy for an individual in relation to the probability distribution of offspring, the discount rate, and the effective "prosociality" assigned to each offspring. In our simple model, uncertainty can either increase or decrease current consumption, depending upon the shape of the utility curve. Furthermore, once the optimal strategy is implemented, the result will be a logarithmic distribution of wealth, with a variance (inequity) that grows over time at a rate proportional to the variance in the offspring probability distribution.

Work of this sort is a beginning, but much remains to be done. Data show that the distribution of wealth is not lognormal, but has a fatter tail. Possible explanations lie in the increased access wealthy individuals have to high returns on their investments, in the fact that the number of offspring one has is dependent on wealth, and in the shape of the utility curve. Certainly, the next decade must see considerable work in depth on the factors that are contributing to the increasing inequity in the distribution of wealth within and among populations if we are to make progress in achieving a sustainable future.

Intragenerational Equity: Public Goods and Common Pool Resources

Understanding why individuals forgo consumption in order to benefit their children, or more generally their kin, is not difficult. The greater challenge, with hope for humanity, relates to prosociality toward unrelated individuals. What are the consequences of such prosociality, and how has it arisen? Under what circumstances is prosociality sufficient to achieve the collective good, and how may it be enhanced otherwise to avoid defection from socially desirable behaviors? Avinash Dixit and I have explored one approach to these questions, beginning from the basic assumption that every individual can allocate resources selfishly or to a common pool or public good, and receives a payoff that is a nonlinear function of investment in self and the total community investment in the common pool/public good:

$$v_i = y(x_i, Z) - F(x_i + z_i) \tag{1}$$

Here v is individual utility, x is investment in self, z is investment in the public good, and Z is the total (or average) community investment in the public good. F represents a cost function, dependent on the total investment.

Such a representation treats individuals as totally selfish, whereas there is considerable evidence that humans exhibit prosocial behavior toward other individuals, including nonkin. Therefore, as a second step, we modify (1) to account for that prosociality, replacing (1) by

$$v_i = y(x_i, Z) - F(x_i + z_i) + \gamma \sum_j y(x_j, Z) \tag{2}$$

where γ is "prosociality," the value an individual places on other individuals in its group. In this simple formulation, all individuals are valued equally, but we modify this to consider a variety of topologies in which an individual i has a specific prosociality γ_{ij} for each other individual j. Of particular interest is the situation in which individuals exhibit prosociality only (or more strongly) toward other individuals within their own groups; in this case, the model is modified yet again to allow leakage of benefits, namely the incidental collateral benefits one might receive from actions intended to benefit others. In this model framework, one then computes the Nash equilibrium, which allows computation of the game-theoretic optimal strategies for all individuals in the population.

This is a powerful theoretical framework, but the test of its usefulness is in the application and testing of it in particular systems. We have therefore begun to apply the approach to the sharing of grazing lands among Maasai herdsmen, in collaboration with Dan Rubenstein. The sharing of grazing land is an effective strategy for dealing with uncorrelated variations in rainfall, and hence uncorrelated variations in land quality. However, the maintenance of sharing arrangements can be difficult to sustain without agreements (or top–down control), and the robustness of those agreements to defection is a topic of central interest.

Evolution and Emergence of Prosociality

The approaches described above all assume that prosociality exists, and ask what its consequences are. This is reasonable, because as already mentioned there is considerable evidence, in human and nonhuman populations alike, of prosocial behavior. It remains a puzzle, however, to understand why prosociality exists. Some of the explanations are undoubtedly rooted in genetics and in kinship, but prosociality also arises culturally, among unrelated individuals. Understanding this phenomenon is a rich area of investigation, including the concomitant emergence and cultural evolution of groups and institutions that foster prosociality (Axelrod and Hamilton 1981; Gintis and Bowles 2004; Nowak et al. 2004; Boyd and Richerson 2009; Levin 2009). Prosociality can emerge as a norm of behavior (Fehr 1999; Durrett and Levin 2005; Ehrlich and Levin 2005; Akçay et al. 2009), for example in which individuals change behavior based on homophilous imitation and other information gained from neighbors on a social network, and in which rewards and punishments coevolve with prosociality to stabilize those behaviors.

Ecological systems and socioeconomic systems alike are CASs, and it is their nature as such that poses unique challenges for management. Just as Adam Smith's Invisible Hand does not guarantee a collectively optimal system for the dynamics of economic resources, nor does a purely free-market approach assure a healthy future for our environmental systems and the services they provide us. Indeed, it is clear that the selfish agendas of individuals and nations too often trump the collective good, leading us to discount disagreeable futures (Levin 1999). Just as for economic systems, sound stewardship requires a mix of free market and top-down regulation. New institutions are needed that are flexible and adaptive, like the human immune system, and polycentric (Ostrom 2009). Finding the pathway to sustainable management of these CAS is the greatest interdisciplinary challenge of our generation.

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