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Policy Forum

Introduction: Resilience and sustainability

One of the most interesting and potentially useful outcomes of recent collaboration between natural and social scientists concerned with the sustainability of jointly determined ecological-economic systems is the application of the ecological concept of resilience. In its broadest sense, resilience is a measure of the ability of a system to withstand stresses and shocks – its ability to persist in an uncertain world. For many policy-makers, however, the concern that desirable states or processes may not be 'sustainable' is balanced by the concern that individuals and societies may get 'locked-in' to undesirable states or processes. Many low-income countries, for example, are thought to have been caught in poverty traps, and poverty traps have since been seen as a major cause of environmental degradation (Dasgupta, 1993). Other examples of 'lock-in' include our dependence on hydrocarbon-based technologies, or the institutional and cultural rigidities that stand in the way of change (Hanna, Folke, and Mäler, 1996). Such states or processes are too persistent.

The sustainability debate focuses on the other side of the coin. In this case the concern is that the positive process of economic development and improvement in human well-being is too easily disrupted by external shocks. Increasingly, this is related to the degree to which the system is stressed. Economic growth involving resource depletion or emissions beyond the carrying or assimilative capacity of the environment is argued to make societies progressively more sensitive to external shocks (Arrow *et al.*, 1995). Collaborative work between ecologists and economists has used the concept of resilience to explore the relative persistence of different states of nature. The paper that is the focus of this policy forum argues that the concept of resilience offers a useful way of thinking about the sustainability not just of environmental processes, but of social and economic processes as well.

The paper itself is the product of collaboration between ecologists and economists. It is an outcome of the Beijer Institutes annual Askö seminars. It argues that the sustainability of a social system depends on the resilience of that system, and that the resilience of social systems in turn depends on a range of institutional and other properties. The implications are far-reaching. If the argument is right then a strategy of sustainable development has much less to do with the satisfaction of various efficiency criteria than with institutional design, property rights, communication, and trust.

What are the implications of this? The forum comprises invited

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responses to this question from a number of people. Some of these have themselves contributed to the literature, whilst others have a more direct concern with development theory and policy. It is hoped that their contributions will help to bring the concept more directly into the debate about development strategy.

Charles Perrings
Editor

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Resilience in natural and socioeconomic systems

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Introduction

We, as a society, find ourselves confronted with a spectrum of potentially catastrophic and irreversible environmental problems, for which conventional approaches will not suffice in providing solutions. These problems are characterized, above all, by their unpredictability. This means that surprise is to be expected, and that sudden qualitative shifts in dynamics present serious problems for management. In general, it is difficult to detect strong signals of change early enough to motivate effective solutions, or even to develop scientific consensus on a time scale rapid enough to allow effective solution. Furthermore, such signals, even when detected, are likely to be displaced in space or sector from the source, so that the motivation for action is small. Conventional market mechanisms thus will be inadequate to address these challenges.

To deal with such problems, one needs a response system that is flexible and adaptive. What principles might underlie the development of such a system? In drawing from experience, it is useful to examine patterns in how systems or institutions respond to stress. What are the success stories and failures, and what can we learn from them? Is there a thread that connects the response of the human immune system to infectious agents, sociological dynamics that lead to the collapses of regimes and forms of government, or ecological phenomena such as responses to the depletion of stratospheric ozone or the desertification of productive savannas? All exhibit the characteristic behaviours of non-linear dynamical systems, interacting across different scales. Hence all exhibit the potential for thresholds, for multiple domains of stability, and for path dependency. Thus, none can be treated by traditional markets, or regulatory policies. All require the development of flexibility and the capacity for adaptive response.

In ecological and socioeconomic systems alike, human activities can lead to qualitative shifts in structure and function, evidence that the system concerned has lost resilience: that it is no longer capable of absorbing the stresses and shocks imposed by human activity without undergoing a fundamental change involving loss of function and, often, loss of productivity. Resilience, the ability to experience change and disturbance without catastrophic qualitative change in the basic functional organization, is a measure of the system's integrity (Holling, 1973).

Ecological and economic systems are non-linear and adaptive, exhibiting complex and far-from-equilibrium dynamics. Much classical theory in both disciplines, however, relies heavily on locally linear methods to estimate stability and times of return to equilibria, thereby ignoring many phenomena of overriding importance such as the potential for catastrophes and domain shifts.

Most economic analyses of resource management schemes,[1] for example, begin by estimating exploitation costs in relation to the quantity exploited and the existing stock, and then calculating the social benefits from exploitation as a function of the amount exploited and possibly the

[1] There are of course exceptions, for example in fishery economics where even chaotic behaviour of fish stocks have been taken into account.

remaining stock of the resource. From this, one can compute the desired time profile of exploitation as simply the time profile that maximizes the (expected) present value of (future) net benefits, i.e. the difference between costs and benefits. For non-renewable resources, with relatively simple dynamics, this works well; for living resources, however, far greater non-linearities intrude, complicating analysis immensely. In particular, simply quantifying local balances in the neighbourhood of a steady state may be profoundly misleading.

Complex non-linear systems, in general, typically are characterized by multiple domains of attraction; hence historical contingency has a large influence on their behaviours. Evolutionary change through natural selection and speciation, for example, is profoundly influenced by historical accident, so that evolutionary theory is far more powerful as a retrospective tool than for purposes of detailed prediction (Jacob, 1977; Slobodkin, 1964). Similarly, the dynamics of biological communities over ecological time scales are highly non-linear, and the existence of multiple stable states both influences our understanding of current configurations, and raises concerns about possible qualitative shifts in the face of large human-induced or natural perturbations (Holling *et al.*, 1995).

Overgrazing can, for example, lead to desertification; and overexploitation, to the collapse of fisheries and other resource systems. Another example is provided by changing land-use patterns and consequent habitat fragmentation, leading to dramatic species losses with serious consequences for the maintenance of ecological services. Similarly, increased human population size, consumption of resources, technological innovation and mobility can engender pest outbreaks, including the spread of devastating human diseases, linking ecological and health factors intimately.

In socioeconomic systems, war and civil unrest, representing the breakdown of a balance of peace and security, present striking examples of qualitative shifts in which initially small disturbances may become magnified through non-linear feedbacks. The Great Depression of 1929 provides another example of a sudden collapse from one ‘basin of attraction’ into another; furthermore, even more puzzling than the initial collapse of the markets was why the economy remained trapped at low levels until a new perturbation, the Second World War, stimulated markets and initiated recovery.[2] Ecological and socioeconomic systems that are persistent and stable in the face of historical patterns of disturbance may lack the resilience to withstand such novel disturbances, especially those of large magnitude, and the potential consequences become matters of deep concern to the conservation of our ecological and socioeconomic environment.

Resilience thus makes no distinctions, preserving ecologically or socially undesirable situations as well as desirable ones. It helps maintain our environments, sometimes leading to a too-cavalier attitude about the robustness of our life support systems; it similarly translates into resistance to change when such change is mandated. The existence of multiple stable regions of attractions further implies that such regions will be separated by less ‘attractive’ dynamical regimes, both in a dynamical sense

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and often in the sense of public policy. Consider, for example, the familiar but illustrative metaphor of the system state as represented by a ball that becomes pushed from one valley to another, necessarily passing along the way over a ridge that is higher than either valley. The resilience of systems is governed by both the height of such ridges and the distances between them. The transition between zones of attraction is often a painful one; a good example is the dislocation caused by efforts to shift economic systems, such as in the former Soviet Union, from one zone to another.[2]

Not all resilient phenomena are desirable. For example, discriminatory class systems have proved resilient. Similarly, racism has proved stubbornly resistant to policies aimed at wrecking its foundations. Though some social systems are too fragile, others are too hardy. A similar phenomenon may be observed at the level of the household. High rates of fertility in the third world, for example, are caused in part by the absence of effective capital markets, which make it difficult or impossible for households to obtain social security except by having more children. In turn, increases in population density facilitate the transmission of disease; and as families become more vulnerable to disease they may respond by having yet more children, so as to be sure of having more surviving members. This can be a vicious feedback, and one requiring effective public action, not just in terms of immunization and disease control but also in providing for the security of citizens in their old age (Dasgupta, 1995).

There are, however, many new threats to the resilience of human institutions and the ecological systems on which they depend. Examples include global climate change, the loss of biodiversity, and the emergence of new infectious diseases. If the climate, certain natural environments, and the human immune system were resilient to all perturbations, changes in the atmospheric concentration of greenhouse gases or biodiversity loss or the incidence of disease would have small consequences for human well-being, except for the often-important time delays that would be involved in recovery. But since these systems are non-linear, the sum total of our actions may cause them to lurch to quite different, and potentially unwelcome, stability domains. Thus, small changes in global mean temperature could lead to a shift in the Gulf Stream; extinction of certain keystone species may magnify into losses of ecosystem function (Levin, 1997); and the increased and inappropriate use of antibiotics and the presence of more immune-compromised people because of malnutrition, exposure to harmful pollutants, and the HIV virus may erode the capacity of human beings to resist disease.

Similarly, in economic systems, small or medium sized disturbances may be beneficial for the growth of productivity. Schumpeter (1912) created a theory of economic development based on this observation. His famous term *creative destruction* was coined to describe the window for novelty and creation that was generated by the failures of existing plants with their old technologies. Thus, according to Schumpeter, it is all these disturbances that in the long run, through the creative entrepreneurs,

[2] This example was provided by K. Arrow, personal communication.

create economic growth and an ability to survive major changes such as economic depressions. Similarly, the concept of *X*-efficiency (Leibenstein, 1966) introduced by Leibenstein can be interpreted in a similar way. Companies that live in a very stable, protected environment will not have incentives to develop the flexibility and competitiveness that would be needed if a major shock were to hit the market. Companies that always have to fight for survival develop resilience much more fully, partly by the necessity to increase productivity. It is striking the degree to which such theories of economic resilience parallel concepts in evolutionary biology, in which similar tradeoffs have been deeply explored.

The nature of resilience

One of the central features of non-linear systems, and one that confounds management, is that small perturbations can become magnified and lead to qualitatively unexpected behaviours at more macroscopic levels; this becomes increasingly true as system complexity increases. In the case of forest fires, for example, the gradual build-up of fuel during periods without fires can provide the ingredients that can lead to major conflagrations. Classical management regimes endeavoured to suppress fires entirely, apparently preserving the status quo in terms of the most evident variables. Yet total fire suppression increases both the stock of timber, and thus the stock of combustible litter, creating accidents waiting to happen. Through simplistic management regimes, robustness and resilience are lost, and the predisposition to catastrophic fires is increased. Such fires would spread farther and burn longer and at higher temperature than otherwise, leading not just to the destruction of trees and seeds, but also to soil erosion and a deterioration in the capability of the system to recover. It was for example the myopic success of earlier fire control that made the recent fires in Yellowstone National Park so devastating. Enlightened forest management now recognizes the value of letting small fires burn in order to maintain the resilience of systems. Similarly, profligate use of antibiotics to treat individuals provides short-term gains, but increases overall susceptibility of populations to catastrophic disease outbreaks because of selection for more resistant pathogens (Lederberg *et al.*, 1992; Daily and Ehrlich, 1996).

Domain shifts may be virtually permanent, as in desertification or fisheries (Steele, 1996), or periodic, as for example in the recurrent outbreaks of forest pests or diseases such as influenza. In evolutionary theory, attention to punctuated equilibria recognizes the potential importance of permanent domain shifts on even larger time scales.

In the case of AIDS, one theory (e.g., Nowak *et al.*, 1991; but see Wolinsky *et al.*, 1996) argues that a domain shift occurs (an infected individual proceeds to full-blown AIDS) when the capacity of the immune system to repel new mutants is overcome by the diversification of strains through mutation. An analogous phenomenon perhaps underlay the sudden collapse of communism in Central and Eastern Europe. In those nations, although there had always existed a small fringe of political dissidents, persistent and growing economic difficulties strengthened and diversified the voice of opposition. Importantly, the larger is the opposition to any social system, the less likely it is that any one dissident will be singled out. So as the outer fringe of the population began to express their opposition to communism, this in turn gave strength to their ‘neighbours’ to become vocal, which in turn gave their ‘neighbours’ the strength to become vocal, . . . and so forth; until a sufficiently large proportion of people were ‘out on the streets’, as it were, forcing a change in political regime. (This is an example of ‘tipping’. For a readable account, see Schelling, 1978.) In democracies, political institutions have the broad consent of the people they represent, and elected officials are periodically held to account at the polls. This makes governments responsive to stresses and shock and hence more resilient, which also enhances the potential for gradual rather than catastrophic change.

The important destabilizing consequences of global change will be felt locally; but only after they have been processed through changes at the scale of ecosystems, and landscape groupings of ecosystems, where a history of inappropriate resource development and exploitation has already eroded resilience. This, combined with the unavoidable delays in relating effects to causes, will lead to an even greater loss in local resilience. At the same time, because global environmental change is caused by the actions of a large number of parties, most of which are far removed from any one locality, local institutions are rendered even less capable of rebuilding resilience.

What this suggests is that policy should be concerned with more than the immediate consequences of incremental actions. It should recognize the potential for an accumulation of small actions, each on their own perhaps quite harmless, to destabilize important natural and social systems. The difficulty is that, while we can predict with reasonable confidence the immediate consequences of an incremental action, we cannot predict the consequences of an entire sequence of actions without understanding the systems potentially being affected by them.

Every natural system is subject to regular disturbances; those that have survived indeed must have built up some degree of resilience. Ironically, however, the mechanisms that provide short-term resilience may also impose a rigidity of structure that erodes the capacity to respond to disturbances over longer time scales, leading to punctuated changes through an increasing loss of buffering capacity. Resilience comes from flexibility, and the ability to change adaptively. From an evolutionary point of view, we can take lessons from the prototypical adaptive management system, the human immune system, which has evolved to deal with a wide variety of unanticipated challenges by effectively training itself to respond to threats. In somewhat the same spirit, biospherists have become enamoured with GAIA, the notion that the biosphere has its own self-regulatory mechanisms that will protect it against new threats. There is an attractiveness in this notion, since as already argued the very existence of the biosphere as we know it means that it must be to some extent buffered against the environmental challenge that might have destroyed lesser systems. Yet the theory in its boldest form is flawed in that the biosphere is a unique realization of its evolutionary history, not the result of selection among multiple candidates for the capability to respond to stress. It is self-organized rather than selected, the result of the evolution of its components. Much of its buffering capacity in the face of perturbations is encoded in part in its biodiversity, but we have very little understanding of what the quantitative relationships are between loss of species and loss of ecosystem function (Levin, 1997).

Any complex system will exhibit hierarchical organization, in which dynamics at one level, including especially stability and resilience, emerge from phenomena taking place at lower levels of organization. Social systems are no exception. At the level of the household, adaptability has come from the way in which members of the household integrate with the wider community. A household may insure itself against the risk of an illness or accident befalling any of its members by means of the extended-family system. Engaging in transactions outside the family can enhance resilience even further. Most obviously, where risks are household specific, pooling risks across households can reduce substantially the risk any one household faces. Trade between regions can also be welfare-improving, not only because it can allow regions to exploit their comparative advantage and thus increase incomes, but also because it allows for further risk spreading. For example, cattle in India are sold in regional rather than village markets, allowing households to smooth their consumption against village-specific risks such as drought or floods or disease (Dasgupta, 1993). It also can reduce resilience, i.e., by reducing food security in some nations. The potential for risk spreading through trade is also dependent on ecosystem resilience to secure the capacity of the environment to generate a flow of essential natural resources and ecosystem services. This capacity is rarely reflected in the price signals of international trade.

Government also can supply goods and services that individuals would or could not provide themselves in sufficient quantities. Immunization is a good example. If a child is immunized against measles, the population as a whole become more protected. Parents, however, have little or no incentive to take this benefit into account when immunizing their own child, with the result that all families may be better off with state-sponsored mandatory immunization.

What makes for a resilient system in general? Ecological systems typically can be thought of in terms of a hierarchy of responses (Slobodkin, 1964). Small perturbations can be accommodated through the behavioural or physiological responses of individuals; stronger stresses lead to reduced reproduction or death and changes at the population level. Ultimately, over generations, natural selection and other forces will change the genetics of populations. The hierarchy of responses may also be seen in organizational responses to perturbation. When effective, they buffer the system against qualitative changes; but all negative feedback systems, most notably the human immune system, may fail. The lessons are obvious for a broad class of environmental and socioeconomic systems. The critical features are a hierarchy of feedback mechanisms; the maintenance of diversity; options for selection to act upon; and the coupling of stimulus and response in terms of space, time, and organizational scales. These are necessary conditions, but do not guarantee success.

In economic systems, resilience depends on comparable mechanisms: effective feedback mechanisms; the coupling of stimulus and response; and a diversity of resources. Three ingredients are important to the first two: competition, effective government, and other effective institutions (North, 1990). The third depends on the social investment portfolio and on the treatment of risk and uncertainty. It depends on the effectiveness of mechanisms both to spread and to contain risks, and to maintain options to respond constructively and creatively to shocks. An essential element in all three is trust.

The challenge for management

In managing such complex systems, it is important to realize the potential and limitations for resilience, and to design complementary mechanisms that increase resilience in systems such as the biosphere that are essential to human survival and welfare. To some extent, competition can help build resilience in such systems by means of the feedback mechanism provided by the market. This coordinates the activities of millions of people such that, after an economy is subjected to a parameter change (and assuming certain conditions hold; see below), resources are reallocated until all possibilities for mutual gain have been exhausted. In the event of climate change, for example, market forces would compel farmers to alter their use of inputs and provide incentives for firms to develop new seed varieties, such that the extent of damage from climate change is reduced.

This view that market forces are sufficient to maintain systems as we need them is, however, as naive as assuming that the biosphere's self-regulating potential assures its robustness. Market forces will not function well if unsupported by effective institutions. The market allocates resources guided by prices. If the institutional framework for markets does not account for the increasingly scarce capacity of the environmental resource base to provide support to the socioeconomy, the allocation by markets will be suboptimal, and may even enhance ecosystem deterioration. A self-organized system will achieve its own asymptotic behaviour, not one that need correspond to optimization in any desirable way. Despite theories to the contrary, ecosystems achieve patterns that emerge from selection at lower levels of organization, not that optimize aspects of ecosystem function. It has, furthermore, often been observed by evolutionary theorists that optimality is a state, while adaptation is a process (Lewontin, 1977) and that one need not lead to the other. In the elegant metaphor of Jacob (1977), evolution is the result of tinkering, not of grand design. If we hope to use market forces to achieve broader goals, we must change the institutional framework, the norms and rules to steer the process. We must, in short, tighten feedback loops. Unless firms are given the property rights to their intellectual achievements (such as the new seed varieties noted above) in the form of patent protection, for example, the market will fail to exploit all opportunities for mutual gain. This is not to recommend private property as a cure-all. For example, a substantial portion of the wealth of poor people in developing countries is in shared or common property resources (Ostrom, 1990; Hanna *et al.*, 1996). If they are privatized the people who depend on them may suffer a loss in wealth, and this loss may in turn deprive these people of the wherewithal to participate meaningfully in economic life; they become destitutes (Dasgupta, 1993). The result may not only be inequitable but also slow the rate and change the content of economic growth and impair resilience. By 'effective' institutions we mean instead a wide variety of institutions that sustain, by diverse mechanisms, multiple outcomes.

Where competitive markets do not function well the problem typically lies in inappropriate prices or missing markets, and these in turn are often the consequence of inappropriate property rights and badly designed institutions. Whenever anthropogenic emissions cause greenhouse gas concentrations in the atmosphere to increase, for example, the climate can be modified in ways that are deleterious to the human exercise. But the individuals who emit these gases do not presently pay for this damage at a level correlated with their influence; to them, the emission of greenhouse gases is free (prices are 'wrong', the importance of the environmental resource base is not captured in the prices).

The prices are wrong because there are no institutions providing the preconditions for market atmospheric concentrations (the market is 'missing'). Correcting the 'market failure' is not so easy in this case. The atmosphere cannot be nationalized, and countries collectively have not thus far succeeded in devising an international regime for regulating the emission of greenhouse gases.

Plainly, then, the reach of markets and governments does not always extend as far as is necessary to build the desired resilience in social systems. This is why trust, too, is needed. Evolutionary biologists understand that the simplest form of cooperation is reciprocal altruism, in which individuals achieve a fragile trust with one another. The same applies to the mechanisms needed for environmental protection. Trust is a mechanism for widening the basic unit of self-interest, and thus tightening diffuse feedback loops. One party will not contract with another unless it can trust this party to fulfil its obligations. Though government institutions can enforce contracts, contracts cannot account for every possible contingency, and the contracting parties must then trust each other if they are to sustain a mutually desirable outcome in the wake of some shock. Trust in these instances can work through the reciprocal nature of the relationship. Your neighbour may help you today, in the belief that if he does so you will assist him tomorrow if he is in need, and so on. Reciprocal altruism is an important stabilizing force, and its evolution and maintenance are enhanced by the local nature of interactions.

Similar risk-sharing rules are needed to manage the global commons. There is no world government, and so trust between nations is particularly important to making cooperative regimes for managing the global commons resilient. It is remarkable that, despite the absence of a central authority, states comply with their treaty obligations in the vast majority of cases (Chayes and Chayes, 1995). What seems to sustain cooperation is that failure to do so can have system-wide consequences. This restrains states from behaving contrary to established norms, and this in turn builds a degree of trust.

But trust is not likely to be enough to protect the global environment.

Though customary law obligates nations to comply with the international agreements they endorse, it does not obligate nations to endorse any particular agreement. As a consequence, treaties that would be mutually beneficial may fail to attract any support. Alternatively, they may attract universal support but at the cost of requiring that the parties to it do little more than they would have done in the absence of the agreement, or they may require greater sacrifices but accordingly succeed in attracting only a small number of participants. Of course, international cooperation is not always hard to sustain. But it can be expected to be so for problems like global climate change where the benefits of, say, a stabilization of atmospheric concentrations of greenhouse gases would be shared by all nations and where the costs of effecting such a stabilization would be high for each nation. There will then be a temptation to free-ride.

Admittedly, the failure of cooperation need not be disastrous, because some feedback loops are closed locally. Countries will almost always have an incentive to take some actions unilaterally. In the case of global climate change, for example, a number of countries have introduced a carbon tax. This has created incentives not only for individuals and firms to reduce their carbon emissions but also for industry to innovate—to fund research into the alternatives to fossil fuels and to develop the technologies that will reduce the costs of abatement over time. Subsidies to R&D would of course have a similar effect. Governments can also reduce the local consequences of global climate change by providing local public goods like barriers to rising sea levels. All of these unilateral responses can be important. But they can also fall far short of what all nations would prefer was actually done about the problem.

An important exception is the Montreal Protocol, the international treaty governing the use of ozone-depleting substances like CFCs. The agreement is remarkable, not least because it is phasing out these substances in a relatively short time, and with the participation of nearly every country in the world. The agreement has also adapted to changing circumstances. It has been renegotiated on several occasions, prompted by changes in either the science or economics of ozone depletion. And it has been designed to be stable with respect to possible free-riders. It appears that, because of the trade sanctions allowed by the treaty, defection by even a number of parties would not trigger an unravelling of the agreement. Having the assurance that the treaty will not dissolve reinforces the incentives which countries have to measure up to the obligations of the treaty. This in turn creates a situation in which renegotiation can take place, as changing circumstances warrant.

Unfortunately, the Montreal Protocol is a rarity in this regard. International agreements have not proved as successful in other areas, like the management of international fisheries and the global climate (Barrett, 1990). Similarly, while the eradication of smallpox stands out as one of the greatest achievements of this century, we have made comparatively little progress in controlling malaria, cholera, tuberculosis, polio, and measles, especially in developing countries. There is no reason to believe that the appropriate resilience will arise ‘spontaneously’.

In general, resilient systems typically have a hierarchy of feedback mechanisms, and the maintenance of heterogeneity and diversity for selection to act upon. Heterogeneity in space or in sector has a number of implications. It implies, first of all, that there is the requisite diversity, and the potential for change. It also means that responses initially will be localized both in cause and effect, so that concern must exist for providing the motivation for local responses in a global commons in ways that benefit the common good, and for the spread of socially desirable innovations.

The implications of any action need to be examined carefully before we become committed to its consequences. Particular attention needs to be devoted to indirect effects. It was the indirect effect of fire control making available a larger stock of biomass for burning that rendered that policy harmful. In the case of global climate change, much discussion has centred on mean global temperature rise and not the effects that may be triggered by this warming, such as a sudden change in the course of the Gulf Stream. Linkages between resilience in natural and social systems also demands more research. As an example, local control over the Mudialy wetlands near Calcutta appears to have restored the productivity of the fishery and produced a harvest of wood in addition (Pye-Smith and Feyerabend, 1994). A diversity of such ecologically adapted management practices and linked social mechanisms behind these practices for building resilience are found in both local and regional systems of traditional and contemporary societies (Berkes and Folke, 1997).

Research needs to address whether or not our vital systems have sufficient capacity for resilience. Building resilience into our natural systems means maintaining crucial ecosystem elements, such as the soils. The scale of the human enterprise is important, but it is not the level of economic activity itself that determines resilience. Equally important is the nature of this activity: it matters whether profligate consumption of fossil fuels continues or innovative steps are taken to develop fossil fuel substitutes. At the institutional level, resilience requires a competitive economy, effective government, and trust. The global environment is especially in need of resilience, and yet it is precisely at this level that government institutions are least effective and trust most delicate.

Critical scientific and economic conclusions about resilience need to be made available to decision-makers and the public at large in a way that aids understanding. The institutional apparatus that exists now is not always well suited to this. Lobbying groups convey information, but none has an incentive to do so in a balanced way, and it is not clear that having different lobbyists arguing opposite positions contributes to understanding; often this arrangement only polarizes opinion. This is the value in conservative organizations like the Intergovernmental Panel on Climate Change. The IPCC is made up mostly of university-based natural and social scientists, nominated by their governments. Its aim has been to clarify the issues and find a consensus among the global scientific community; and it is noteworthy that the IPCC has sought to involve as many countries as possible in this process. Having a common understanding of a shared problem is a vital ingredient of trust, which is itself a basic building block of resilient social systems, and these will help humanity to interact with natural systems without degrading them.

Most importantly, we must appreciate better the degree to which ecological and socioeconomic systems are linked, across a range of scales of space, time, and complexity. They must be viewed as one single system. We can only ultimately slow the rate of change and the appearance of surprises by slowing population growth, energy use, and the rate at which we are changing our environment. We must rise above parochial interests and tribalism, developing a new order and new mechanisms for providing local, regional, and global incentives that will allow our life support systems to persist for future generations.

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The concept of resilience: retrospect and prospect

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1. Introduction

The modern study of stability in ecology can be said to have begun with the appearance of 'Fluctuations of Animal Populations and a Measure of Community Stability', by R.H. MacArthur in 1955. Since the publication of this influential paper, ecologists have investigated the properties of a number of different stability and stability-related concepts; the concepts of persistence, resilience, resistance, and variability readily come to mind. Of these various concepts, the concept of resilience itself appears to have been rather resilient. Indeed, as Neubert and Caswell (1997) and others have noted, today there is a vast literature on resilience. However, it is important to note that this literature—to the best of my knowledge—has been primarily ecological in nature. In other words, the concept of resilience originated in ecology, and this concept has been applied and studied primarily in the context of ecosystems.

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This paper by Levin *et al.* breaks with this tradition in a significant way. The paper enters uncharted waters by claiming that the concept of resilience is applicable not only to ecosystems, but to socioeconomic systems as well. Consequently, in analyzing the behavior—particularly the desired behavior—of ecological and socioeconomic systems, it is important to understand the notion of resilience. This is a bold claim and the research agenda which accompanies this claim is ambitious. Consequently, this paper is cause for both excitement and reflection. Despite the allure of excitement, in what follows I shall focus largely on the latter of these two states. In particular, I shall argue that while this paper's call for an enlargement of the scope of resilience is welcome, in order for this call to be useful, two features of socioeconomic resilience will have to be addressed at some length. These features concern the measurement of resilience, and the apposite implementation of the lessons learned from this new focus on socioeconomic resilience.

2. The measurement of resilience

If we agree that resilience is a useful concept even in the context of socioeconomic systems, then we must be able to answer the question 'How resilient is a given socioeconomic system?' There is no way to answer this question without measuring resilience; hence the salience of this measurement issue. Although they do not address this issue explicitly, Levin *et al.* refer to this issue tangentially at several points in their paper. They talk of understanding systems affected by a sequence of policy actions, of judging alternative states of a system, and of the linkages between natural and social systems. Measurement is an essential aspect of all these issues. However, measurement itself is a multifaceted concept, with more and less important aspects to it. In the remainder of this section, I shall focus on four of the more important aspects of measuring resilience.

The first aspect concerns the concept that is to be measured. While Levin *et al.* focus exclusively on resilience, it seems to me that the related concepts of persistence and resistance (see Pimm, 1991, pp. 13–14) can be just as important to our understanding of the behavior of socioeconomic systems. For instance, consider the paper's AIDS example. In understanding the behavior of a socioeconomic system that is vulnerable to the AIDS virus, should we not be interested in measuring how long it takes people who have contracted the virus to develop the full blown disease? In other words, should we not be interested in measuring the persistence of the socioeconomic system? Similarly, once the domain has shifted, i.e., once infected individuals have developed the full-blown disease, should we not be interested in measuring the consequences of this shift on other related variables? Put differently, should we not be interested in measuring resistance? I submit that the answer to both these questions is, yes. Consequently, when discussing measurement issues, it is important to note two things. First, because the concepts of persistence, resistance, and resilience are related, it is important to have a clear idea of exactly what it is that one is measuring. Second, to improve our understanding of complex socioeconomic systems, we should not put all our measurement eggs in the resilience basket. Other baskets are also important and measurement issues pertaining to these baskets should not be neglected.

The second aspect also concerns the concept that is to be measured. However, now I want to focus on the definition of resilience. From the ecology literature we know that there is the Holling (1973) definition and the Pimm (1984, 1991) definition of resilience, and that these two definitions are distinct. Although Levin *et al.* claim that they are interested in Holling resilience, some of their discussion—for instance, issues related to fire management in Yellowstone National Park—suggests to me that on occasion, the Pimm definition might be more relevant. There is nothing problematic about this as long as one recognizes that the same concept can have many meanings and that what one can measure may be quite different from what one wants to measure. I say this because my sense is that for many socioeconomic systems, Pimm resilience may be easier to measure than Holling resilience.

The third aspect of measurement that I wish to discuss concerns the distinction between deterministic and stochastic socioeconomic systems. From the ecology literature (see Ives, 1995) we know that the measurement of resilience in deterministic systems is simpler because resilience can be computed directly from the equations describing the relevant population dynamics. While this result should also hold in the case of socioeconomic systems, there is no gainsaying the fact that the socioeconomic systems that are the subject of Levin *et al.* are stochastic in nature. This should alert us to two things when pondering the measurement of resilience in socioeconomic systems. First, definitions of resilience which make sense in a deterministic context may not do so in a stochastic context; consequently, the very definition of socioeconomic resilience may need to be altered. Second, because it is problematic to compare resilience across deterministic and stochastic systems, information about the measured resilience of the deterministic counterpart of a truly stochastic system may tell us very little about the resilience of the stochastic system. This suggests that in measuring the resilience of socioeconomic systems, one should, to the extent possible, follow the lead of the various stochastic measures of resilience (see Batabyal, 1997a, 1997b; and Ives, 1995) that have been proposed in the ecology literature.

The final measurement issue that I wish to address concerns the distinction between the transient and the asymptotic behavior of a socioeconomic system. Levin *et al.* note that from the standpoint of resource management, the analysis of system behavior in the neighborhood of a steady state may be completely misleading. To this, I must add that most of the ecological literature (see Batabyal, 1997b; Cottingham and Carpenter, 1994; and DeAngelis, 1980) has focussed on measuring resilience when resilience has been defined as an asymptotic property. For socioeconomic systems, we presumably are not interested in measuring system resilience when time approaches infinity. Indeed, to paraphrase John Maynard Keynes, in the long run, we are all dead! If anything, we are interested in the short term, i.e., in the transient behavior of a system following some perturbation. This makes the problem of measuring socioeconomic resilience a rather difficult one. Not only can we not draw on the relevant literature in ecology, but work in progress by myself suggests that when transient system behavior is what is of interest, one may not be able to do much more than obtain bounds on resilience.

3. The implementation of policies

The current and the future study of socioeconomic resilience is likely to yield a number of insights about various aspects of socioeconomic systems. If humankind is to benefit from this resilience-based study of socioeconomic systems, then it is important that the lessons that are learned from the adoption of this approach be implemented. This implementation task is actually a two-part task. In the rest of this section I shall attempt to flesh out some of the details of the two constituent parts.

At various points in their paper, Levin *et al.* note that a focus on ecological and socioeconomic resilience often yields rather surprising lessons for the management of such systems. The first part of my two-part implementation task involves the translation of these lessons into concrete policies. After all, most policy makers are not interested in resilience *per se*, but in what this concept means for policy. To give an example of what I mean by policy translation, consider the paper's discussion of forest fire management. The paper notes that instead of attempting to suppress forest fires completely, managers should let small fires burn. This increases the resilience of the underlying forest ecosystem and makes it less likely that this ecosystem will be subjected to catastrophic fires at some later date. Unfortunately, the paper is not always as clear in informing the reader about the policy implications of a resilience-based approach to the study of socioeconomic systems. However, it seems to me that if the concept of resilience is to be an important part of future policy discussions about the management of socioeconomic systems, then we will need to move beyond calls for 'public action', and beyond calls for the creation of institutions which sustain 'multiple outcomes'.

The second part of my two-part implementation task involves the *actual* implementation of the policies that have been identified to follow from a study of socioeconomic resilience, as discussed above. There are two things to note here. First, past experience with the implementation of new ideas and policies—particularly in developing countries—tells us that it is often very difficult to change ways of doing things without running into vested interests with a stake in preserving the *status quo*. This resistance to change must be addressed directly if the benefits of new knowledge are to reach people in a timely manner. Second, the heterogeneity of environmental problems must be recognized. As Levin *et al.* correctly note, this means that the policies that we implement to manage various aspects of socioeconomic systems need to be flexible and adaptive. These twin features of our policies will ensure that we are able to respond effectively to environmental problems whose distinguishing feature is their unpredictability.

4. Conclusions

In this interesting paper, Levin *et al.* have argued that the concept of resilience can be used to effectively describe and study ecological *and* socioeconomic systems, and that we should view these systems as one system. This may well be the way to go. However, before we move further along this route, perhaps we should stop and ponder the ramifications of the measurement and policy issues that I have discussed in this paper.

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Ideas on quantification of resilience-based management

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Levin *et al*. give us a sweeping vision of the notion of resilience and the response of management. In these comments I wish to discuss the daunting task of quantification of the resilience-based management issues raised by Levin *et al*. I also wish to suggest directions of future research.

Start with an ideal benchmark for managing the entire economic/ecological system set by an infinite horizon optimal social welfare planning problem which sets a sequence of dynamically state contingent controls which determine the stochastic process of a state vector. Let social welfare payoffs each period depend upon the state vector and the control vector

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and let management's objective be the maximization of the expectation of the discounted sum of period payoffs.

Let the uncertainty in this problem be represented by commonly understood and accurate objective probability distributions. Then, under a generalized notion of multidimensional diminishing returns, the Russian and Western literatures (see, for example, Arkin and Evstigneev (1987) for the Russian literature and Marimon (1989) for the Western literature) show that zero discounting of the future (and small enough discounting by 'continuity') leads to a type of generalized resilience principle where the optimal controls are set so that the system as a whole evolves to a stochastic steady state. At this steady state the expectation of stationary state welfare is maximized over the set of stationary stochastic processes subject to general material balance and technological constraints. Furthermore if the system starts at any initial state, optimal management controls it so that it goes to the same limiting steady state stochastic process. Hence the focus of attraction of this optimal steady state stochastic process is the whole space. The strong intertemporal smoothing force induced by zero discounting social welfare optimal management is a powerful force.

Marimon discusses how an infinite horizon decentralized economic system of far-sighted individuals with rational expectations under a complete set of markets (including a complete set of futures markets) can (in theory) implement the global welfare optimum in a decentralized manner under an appropriate supporting set of ideal institutions. This setup generates infinite Holling resilience because the basin of attraction of the optimal stochastic steady state is the whole space.

Things change, even in this ideal benchmark, when discounting is introduced (Brock's article in Anderson, Arrow, and Pines, 1988). Here we may have cycles and chaos due to the internal dynamics not being forced to the same stochastic steady state because the discounting of the future breaks the value loss argument of the above literature.

Things get worse when we join the typically strongly non-linear dynamics of ecological systems with the economic dynamics and interact them in a proper treatment of ecological economics. Nevertheless, in many cases, the potential stabilizing effects of very light to zero discounting of the future still may appear in settings which do not possess the generalized convexity/concavity properties of the literature discussed by Arkin and Evstigneev (1987) and Marimon (1989) (see, for example, Becker and Boyd, 1997; and Carlson, Haurie, and Leizarowitz, 1991).

Maintain the assumption of objective commonly understood and accurate probabilistic depiction of the uncertainty but consider the breakdown of resilience due to, for example, channels such as externalities, missing markets, social interactions, expectational dynamics, etc., listed as sources of complex dynamics in Brock's paper in Anderson, Arrow, and Pines (1988).

This raises the issue of appropriate institutional design to fix these problems and to restore some modicum of efficiency in the broad sense of social welfare. Standard remedies such as user charges, Coasian contracts, intertemporal linkages through self-enforcing mechanisms such as reciprocal trust and altruism may be difficult to implement because of transactions costs problems such as negotiation, measurement, risk borne by regulatees induced by behavior and implementation uncertainty of regulators, rent seeking and other directly nonproductive behavior on the part of regulators and regulatees, holes in the fabric of the property rights system, large effective discount rates on the future, asymmetry of discount rates across the actors (leading to some departures from self-enforcing agreements, leading to unravelling overall), etc. Some of the literature on optimal regulation of externalities may be useful.

For example, for many pollution problems there may be a scaling law such as log-normality of the distribution of problem causers (e.g., a small number of autos may be responsible for the bulk of auto pollution problems, a small number of operators may be responsible for the bulk of run-off problems into catch basins of lakes and rivers, etc.). This suggests desirability of regulatory tiering. This regulatory mode avoids 'one size fits all' type of regulation by introducing progressive mitigation burden as a function of measured size of the problem causer see, e.g., Brock and Evans, 1986).

Regulatory tiering not only avoids creation of 'artificial' economies of scale due to averaging down the fixed costs of compliance and of interpretation of the regulations, but also avoids much political backlash in a one person, one vote society by progressively concentrating more of the burden of mitigation upon the bigger polluters.

One can also design flexible regulations which incentivate privately beneficial cost saving technological innovations by always imposing a cost at the margin for socially undesirable spillovers such as polluting. While there is a large literature in economics on optimal design of regulatory mechanisms, we could use more research on optimal design in a framework that couples the economic tradeoffs with implementation tradeoffs embedded in the political sector.

The overall objective could be the design of institutions to eliminate what Garrett Hardin (1993) calls 'CC–PP' games (Commonize the Costs—Privatize the Profits). A slogan for public instruction through the media might be: 'Tax what our society does not want people to do rather than tax what our society does want people to do.' This slogan might induce, for example, suggestions for replacing some income taxes (our society wants people to work) by gasoline taxes (our society does not want pollution and road congestion) after adjustment for hardship on the driving poor by, perhaps, tax relief gasoline coupons based upon the income tax return which could be sold on a white market. Indeed some of the proceeds of the gas tax could be earmarked for redistribution to the poor.

One could be especially alert for 'Flat-of-the-Curve' games where the private sector pushes out the use of an unpriced environmental resource to the point where the social damages are huge but the incremental private benefit is tiny. Even a slight explicit or implicit tax on this kind of activity can bring large benefits to us all.

Turn now to more extreme departures from the benchmark of ideal management conditions discussed above. Let the uncertainty and scientific understanding be genuinely cloudy. In a Bayesian setting, Nyarko and Olson (1996) show, in the context of managing a single resource which is extremely painful to do without should it go extinct, that one should manage the resource as if you always expect the worst-case scenario as assessed by your prior. Depending upon your prior, this management posture can lead to an even stronger precautionary principle than, for example, Ludwig (1995). Even if we endow the scientific community of expertise with an 'objective prior' the Nyarko–Olson precautionary principle still holds.

In the Nyarko and Olson (1996) setting the presence of available signals that tighten the support of the prior still lead to a strong precautionary principle but the narrowing of the support of the prior may increase social welfare.

Pizer (1996) shows that, even in the context of a conventional Nordhaus–Cline climate control setting coupled with a classical stochastic optimal management model, we obtain a strong case for a precautionary principle due to the difficulty of reversing a climate change once it occurs. If one adds to Pizer's model, the multiple basins and hysteresis effects stressed by Levin *et al.*, we could learn a lot about what matters quantitatively to social welfare and what does not.

However, negative externality management rigidities or errors due to, for example, sluggish, inflexible government (or positive probability of a bad policy rule being chosen by government and then left in place even after new information comes in suggesting change) can turn a precautionary principle into an argument for inaction until better information is present. The possibility of damage due to increasing the possibility of bad government policies may turn the precautionary principle on its head. Pizer (1996) discusses work on this issue.

Recent advances in computational economics (cf. Ammam *et al.*, 1996, especially chapter 12 by Judd) now make it possible for us to rapidly compute solutions to complicated management models under various management regimes. This should allow us to prepare posterior welfare distributions for more realistic stochastic management problems, even under potential multiple basins of attraction and partial or total irreversibility to give to policy makers.

I have argued that discounting the future plays a dramatic role in the behavior of general stochastic optimal management models including the loss of a type of resilience due to the stabilizing forces imposed by near-zero discounting of social welfare optimization. Near-zero discounting plays a big role in stimulating the collection of information signals and stimulating research on increasing the precision of these signals. This kind of effort by near-zero discounting social welfare management helps avoid the 'surprises' discussed by Levin *et al.*

This discussion raises the issue whether government and other policy makers are discounting the future too heavily in conventional benefit–cost policy analysis. I gave an early argument (Brock, 1977) that use of market generated discount rates in benefit–cost analysis may lead to excessive discounting from the optimal social welfare point of view if natural services are overused (because, for example, they are not correctly priced or there are 'holes' in the property rights structure) and if the marginal product of capital is an increasing function of natural services. While later work has been done on this question, more work needs to be done in ecological economics settings.

Levin *et al.* (1997) discuss imbalances in lobbying, misinformation campaigns, and in other parts of the political sector. A basic difficulty of democracy concerns the problem of differential ability across interest groups to solve their internal collective action problems in organizing political pressure per unit of gain. Concentrated potential gains groups tend to be able to apply more pressure causing government to end up extracting more resources from the diffuse groups (the citizens at large) to be transferred to the concentrated groups. The same logic applies to the organization of dis-information campaigns. Individuals of the public at large face their own collective action problem in motivating each member to do the difficult cognitive activity of extracting the truth out of misinformation. This collectively irrational but individually rational ignorance can be exploited by concentrated gains groups.

We need more research on the design of institutions to reduce the reward to such activity by concentrated gains groups. We need to understand how to design institutions to equalize the difficulties of social action organizing across all stakeholders in the polity. Colander (1984) gives a nice entry point to this literature. Return now to optimal resilience-based management in a different model of the economy.

The two Santa Fe Institute Volumes, Anderson, Arrow, and Pines (1988) and Arthur, Durlauf, and Lane, (1997), as well as the paper by Brock and Hommes (1997) put forth a rather different vision of the economy than the optimal planning or equilibrium vision laid out above. This raises the issue how to formulate and how to do optimal policy and optimal regulation in these more 'evolutionary' types of models of the economy.

For example, homoclinic bifurcations can appear in the Brock and Hommes (1997) model due to equilibrium dynamics which arise from individually costly information collection borne by each firm in order to plan accurately further into the future and gain a net profit by so doing over a cheaper myopic method of planning. In principle this kind of wasteful duplication of information collection with resulting complicated dynamics (which may lead to dynamical 'surprises' of the type discussed by Levin *et al.*) might be eliminated by a government program to subsidize production of information at the individual operator level so they each have a self incentive to peer further into the future. Investigation of linkages between information gathering, individual operator incentives, and the role of government in bearing the cost of better information, using some of the recent efforts at economic modelling, might be a fruitful topic for future research.

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Resilience in social and economic systems: a concept that fails the cost–benefit test?

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One of the first lessons that students of cost–benefit analysis (CBA) learn is to ask whether projects or policies which they are studying generate *additional* benefits or costs, relative to the status quo. They are also told to be very careful in defining the project/policy which is the subject of their analysis. In my view, the ecological concept of resilience fails the CBA test, when applied to the study of economic and social systems, because it offers no additional insights to those we have already, and appears to be poorly defined. In what follows, I first briefly summarize the paper by Levin *et al.*, and then explain why I feel that the concept of resilience fails

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to deliver in the way they suggest. I shall also try to point out how the authors fail to produce a tight definition of resilience, and how this weakens their argument. Overall, I feel that their paper falls between two stools, of outlining well-known weaknesses in current mainstream approaches to environmental economics (defined in its widest sense), and of trying to make out that there is a common thread which runs though many important problems which uniquely points us to the best solution. In this latter regard, I believe the authors are guilty of over extending a metaphor: from forest fire management to the collapse of communism, for example.

Levin *et al.* argue that the ecological concept of resilience can help us understand and respond to a wide variety of important problems. These include AIDS, civil unrest, biodiversity loss, and global warming. Understanding comes through realizing that these phenomena have one thing in common: they represent the breakdown of a system (the human body, for example, or the global climate) in response to some exogenous change. These phenomena tend to be sudden, unexpected, and irreversible, due to the dynamic non-linear and co-evolutionary nature of the total economic-environmental system. How can we best respond, in a anticipatory management sense, to the prospect of such changes? By encouraging the ability of the system to be able to handle change in a way which retains the essential functioning of the system; in other words, by encouraging its resilience. This analysis is extended to economic problems too. Encouraging resilience in social and economic systems is argued to involve encouraging competition, flexible institutions, and trust (although resilience may not always be a 'good thing' as the authors note: the system could be resiliently stuck in war mode, whilst we could also face, as the authors point out, a trade-off between short- and long-term resilience in natural systems). Let us now consider this argument in more detail and see what, if anything, the concept of resilience adds to our understanding.

The limitations of neoclassical resource economics, with its overwhelming emphasis on the steady state, are well known. It is absolutely correct to say that we need to broaden our analysis to consider far-from-equilibrium effects, possibly chaotic dynamics and non-linearities, but we do not need the concept of resilience to tell us this. The limitations of mainstream approaches arise from features of the systems they are used to model (non-linearities, surprises, discontinuities, chaotic dynamics, co-evolution . . .). We can understand these features, and appreciate their significance, without appealing to the idea of resilience. The authors cite the example of the great depression and the failure of governments to be able to get out of it until war broke out; but this is just the old argument of whether governments can and should intervene in macro cycles, which Keynes based his general theory around (Keynes, 1936). Similarly, the importance of feedback loops in socioeconomic systems is widely recognized. The authors use the example of the links between failings in the welfare state, poverty, and the number of children parents wish to have in developing countries. This example also highlights the problems over defining what functions/states we wish to preserve in socioeconomic systems: clearly stasis is not always preferable (the examples given are racism and the class system), but here the argument is that change to the self-perpetuating status quo is sometimes desirable, which might be an argument against resilience as a desirable property of such systems. But unless we know what it is we wish to preserve, it is hard to say (see below).

The idea of a system moving between different basins of attraction, once some threshold is past, has also been applied independently of the concept of resilience. Perhaps a more fruitful development is to think of transactions costs as reasons why systems either stick or move, in the tradition of Coase and Williamson (Coase, 1988; Williamson and Winters, 1991; Casson, 1991). Disciplines can also get stuck: for example, macroeconomics was stuck in Keynsian mode (on the whole) until the Monetarist revolution came along. It is true that such transitions seem to share features with non-linear ecological systems: no effect is felt despite a gradual build-up of pressure, until one more violation/harvest trips the system into a new state. In the theory of scientific method, this process has already been neatly described by Kuhn (1970) in terms of paradigm shifts. Again, what does this paper add to this?

That households and villages in India find it in their self-interest to risk pool, risk share, and trade is explicable using our understanding of rational attitudes to risk, so that appealing to a new idea (resilience) is unnecessary. That trade could itself increase environmental damages (especially in resource dependent indebted countries), though, begs the question as to whether there are trade-offs between environmental and economic resilience. Again, an argument in favour of publicly funded immunization programmes can be made on public goods/merit good ground: we do not need resilience to do this. In both of these examples, resilience fails the additionality test. Again, noting that the market system, via prices, will fail to generate either an efficient or a sustainable allocation of resources in the presence of environmental linkages is hardly new: does resilience *add* anything here?

One also wonders whether *X*-efficiency and the theory of creative destruction are best described as ‘theories of economic resilience’, and whether describing them in this way furthers our understanding. Both are suggestive of learning-by-doing: in the former case, due to competitiveness pressures, and in the latter due to economic depressions, which create the opportunities for entrepreneurs to develop new ideas. Certainly both theories imply that firms/economies/agents who develop greater fitness and adaptability can achieve greater long-term profitability, but how does resilience add to understanding here? Being rather mischievous, one could say that if *X*-efficiency and creative destruction are synonymous with resilience, then change is better than (as distinct from as good as) a rest. If change also implies learning, and if information has a positive value, then this almost suggests that we should favour some global warming now because that will help us cope with greater warming levels in the future. More seriously, this does point our efforts towards the value of information and the optimal timing of actions in the face of uncertain, irreversible environmental threats, especially when global responses are subject to strategic behaviour (see Ulph, 1998).

In general, then, one could argue that the examples given in the paper are essentially about concepts other than resilience, namely the implications of non-linear systems, feedback effects, policy and market failure, and paradigm shifts. In a sense the paper is also concerned with a classic aggregation problem in macroeconomics: that the sum of individual actions do not always add up to an overall effect (the fallacy of composition: Dow, 1996).[1]

The paper does contain much of merit, most interestingly in the espousal of trust in international agreements. However, one might note here that international agreements on, say, protection of the ozone layer, that cannot be enforced by a supranational government do not necessarily depend on altruism (as the paper goes some way to point out in the specific context of the Montreal protocol). It can be in the selfish interest of countries to abide by agreements which are costly, especially when joint implementation agreements are in place (Botteon and Carraro, 1998; Kroeze-Gil and Folmer, 1998). Where this is not the case, it does appear that self-enforcing international agreements are only likely where the net benefits of cooperating (relative to the Nash bargaining outcome) are rather small (Barrett, 1994).

Finally, one has to note that the introduction of some new metaphor, or underlying explanatory concept, always has a cost. This consists of the costs of knowledge previously held which now becomes irrelevant; and the transactions cost of learning a new language. In this latter regard, the paper is currently guilty of imposing higher costs than are necessary, by being written in a language designed for insiders in the ecological economics literature. Thus, we find many instances of undefined jargon, for example domain shifts, attractors, punctuated equilibria, speciation, and self-organizing systems. One would also like to see a more careful definition of the term non-linear: what exactly are the authors thinking of in terms of the dynamics of such systems?

On definitions

The concept of resilience was developed in regard to ecological systems (Holling, 1973), and refers to the preservation of ecosystem functioning (its organizational structure) in the presence of exogenous change. One problem with this paper, I would argue, is that the authors never define exactly what we want to preserve in economic and social systems. The authors speak of maintaining the structure and function of socioeconomic systems. What does this mean exactly? For the economy, we presumably are not talking about the industrial structure, in terms of the distribution of output or employment across sectors such as manufacture and farming, since we know this has and always will change over time as the economy grows. Presumably we are not advocating no change in this aspect of

[1] It is interesting to note that, in an earlier paper, Common and Perrings (1992) have already referred to this problem: 'it is not possible to derive the properties of the ecosystem as a whole from a study of one population within the ecosystem.... This is in marked contrast to Walrasian economic theory ... [and is] a fundamental point of dispute between an ecological and a neoclassical approach to the economics of the environment.'

structure. Perhaps, then we should look to the parameters of behavioural functions in the economy: utility and demand functions. But on what grounds do we want to preserve these unchanged? Alternatively, we could focus on total output or total income, but is advocating zero growth in these macro variables what one is interested in? One reasonable assumption might be that we are interested in preserving some minimum capacities in the economic system, such as some minimum level of income per capita over time, or some level of the capital stock. But if so (and there are clearly strong links with the economics of sustainability here), it is highly desirable that we are more precise about exactly what we want to preserve in the face of exogenous changes. A similar lack of clarity exists with respect to the social system. In contrast, what we are interested in preserving for environmental systems (ecosystems) for which the concept of resilience was developed, is much clearer: namely, the functions that describe the processing of matter-energy within the system (see, for example, Common and Perrings, 1992). This is also true in the study of resistance and immunity, where again what we wish to preserve is clearer (see Munro, 1997). For the human body, in respect of AIDS, what we wish to preserve is also clear, namely a given state of health. The key question for future research in applying the concept of resilience to economic and social systems is thus: how should the 'health' of such systems be defined?

If the functions and structures/variables of the economic system which we wish to preserve can be identified, then the next step is to determine the role of diversity in such systems in maintaining resilience. As one understands it (and the paper could perhaps summarize the arguments/evidence here), greater diversity equates with greater resilience in ecosystems. If this is so, then the questions are whether diversity is also desirable in socioeconomic systems, and what we wish to maintain as diverse. The authors state that competitiveness and flexibility are desirable in such systems from a resilience point of view, but this at present is a rather untested assertion.

Finally, it may be that resilience is currently too vague a concept to be useful for analysing socioeconomic systems. This is particularly so when trying to establish the necessary conditions for a resilient economic system to exist. For example, consider the following statement from the paper: 'In economic systems, resilience depends on . . . effective government and other effective institutions . . . by effective, we mean . . . a wide variety of institutions that sustain, by diverse mechanisms, multiple outcomes.' This is hardly the language of either detailed policy advice or refutable theoretical hypotheses. Similarly, without some precise definition of resilience, it would be hard to prove that perfect competition improves its prospects, or that the scale of economic activity does not affect it. Daly (1990) has suggested, on the contrary, that reducing scale is vitally important to achieving sustainability, which is what one suspects the advocates of resilience are primarily concerned with.

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Resilience, sustainability, and environmentalism

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Resilience is turning out to be a resilient concept. First proposed way back in the 1970s in the context of ecosystem dynamics, it was then dissected and elaborated—spawning terms such as malleability, elasticity,

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hysterisis, inertia, resistance, amplitude—as ecologists struggled to make it into something measurable, usable, and distinct from its notoriously slippery predecessor 'stability'. But in the post-Brundtland era, the focus appeared to have shifted to the umbrella concepts of 'sustainability' (Brown *et al.*, 1987; Lubchenco *et al.*, 1991, Levin, 1993), 'ecosystem health' (Schaeffer *et al.*, 1988; Costanza *et al.*, 1992) or 'ecosystem integrity' (Regier, 1993; Angermeier and Karr, 1994). The article by Levin *et al.*, however, is a strong pitch for reviving the concept of resilience and even for applying it in social contexts. Why has resilience been resuscitated? How can it be operationalized? How does it relate to sustainability? And can either resilience or sustainability be considered sufficient for environmental soundness?

Resilience, 'the ability to recover from [presumably severe shocks or stress]' as the dictionary puts it, is a flag to draw attention to the need to incorporate non-linearities in models of socio-ecological systems. Superficially, it might seem surprising that it should take so much effort to get us to recognize the importance of non-linearities. After all, we experience non-linearities and irreversibilities on a daily basis: plants die of too much watering as well as too little, children falter with too little guidance but rebel at too much. Non-linearities are well-recognized in traditional philosophies and knowledge systems, be they those of Indian sages, Amazonian hunters, dialectical Marxists or even nineteenth century natural historians. Nevertheless, those branches of natural science (agriculture, fisheries, forestry, even medicine) and of social science (essentially economics) that most directly inform public policy today appear to be oblivious of such phenomena, sticking to their linear mechanistic mindsets. That such approaches continue to hold sway in face of everyday experience, traditional philosophy, and also recent developments in non-linear systems theory speaks of their hegemony over the policy-making process (Holling *et al.*, 1995; Norgaard, 1987). Any attempt to break these mindsets and hegemonies is therefore to be vigorously applauded.

Once we accept the basic thrust of the argument, however, we can proceed in the traditional manner of science, viz., developing a clear taxonomy and hypotheses. How then should resilience be defined? Here, I found Levin *et al.*'s treatment inadequate and had to take recourse to Holling (1973), who states that resilience is *the size of the stability domain* around stable time-invariant equilibria (point attractors) or stable oscillations (periodic attractors). From this definition, a number of points follow. First, resilience should not be measured in terms of the distance of the current state of the system from the edge of the stability domain, which is a constantly changing parameter. This in turn implies that reductions in the *magnitude of the excursion* away from equilibrium should not be termed as increases in resilience. Second, reductions in the *perturbing force* or in the *deviation per unit perturbing force* (the latter being the inverse of 'robustness' or 'inertia'—Westman, 1986) should not be confused with increases in resilience. They are complementary ways of ensuring the same end result (viz., system stays within the stability domain) as increasing resilience (increasing the size of the domain). Third, resilience must refer to a situation where the perturbation applied to the system is significant (to cause it to move far away from equilibrium) but *temporary* (a shock or a period of stress—Westman, 1986), because a continuously applied perturbation will eventually drive any system out of its stability domain, regardless of the size of the domain.

In the absence of sufficient resilience, i.e., if the perturbation drives the system out of a stability domain, the system may either collapse (when there is no other stable equilibrium) or may enter another stability domain, characterized by a different system structure, such as a reversed Gulf Stream. Intuitively, this seems to be the situation in which one should use the term *adaptability*: the ability of a system to keep some 'ultimate' desired state variables (say net food production) at the desired level in the face of *domain shifts* in 'underlying' ecosystems (say the agro-climatic system). Again, one can talk about the time required to adapt, the extent of recovery to the old level of the desired variable, etc. as different aspects of adaptability. But it is clearly useful to distinguish adaptability from resilience. For instance, an agricultural system may be resilient to (able to recover from) occasional severe droughts, but it may not be able to adapt to a shift to a significantly drier climatic regime.

Using the above framework, one can begin to evaluate various hypotheses about the resilience of socio-ecological systems tossed out by Levin *et al.*, and propose a few others. First, if the perturbation is anthropogenic (such as net CO_2 emissions) and clearly of significant magnitude, then, regardless of the exact nature of the system and one's distance from equilibrium or the edge of the stability domain, reducing the perturbing force (stopping the burning of fossil fuels) is clearly one (and probably the best) means of reducing the chances of a disastrous domain shift (say in the climate system), even though this does not really constitute an increase in system resilience. And a careful distinction between resilience and adaptability would, for instance, prevent the climate change debate being hijacked by the adaptationists.

Second, a key result of resilience research (mentioned in passing by Levin *et al.*) is that one should attempt to work with natural variations. Small perturbations should be utilized to build resilience rather than be suppressed in order to reduce variability of the state variable. For instance, it is better to leave mild illnesses untreated so as to build immunity rather than ingest antibiotics at the mildest sneeze. It follows that Levin *et al.*'s general statement that 'effective feedback is necessary for resilience' needs to be qualified, because taking medicines at the mildest sneeze is in fact a sign of a system with a very effective negative feedback! Normal negative feedbacks reduce short-term variability, what resilience needs is a nonlinear negative feedback: nil at low values of deviation and high at values close to the edge of the stability domain.

Third, competition—and the *positive* feedback it provides—may lead to greater efficiency, but it is not necessary for resilience: most traditional resource management systems, now seen as being resilient and ecologically well-adapted (Berkes *et al.*, 1994), have evolved in non-competitive communitarian settings. Fourth, the link between risk-spreading and resilience is complex. If risk is adaptively internalized, by say a person developing multiple skills, the results are different than if it is externalized, by the person continuing to specialize but hooking up with a much larger system: the regional or national job market. The latter approach increases the connectance of the overall system. It has been shown in a number of cases, ranging from food webs (May, 1973; Siljak, 1978, who worked on 'connective stability') to trade networks (Siljak, 1978), electrical systems (Fink, 1991), and (qualitatively) even stock markets (Rochlin, 1991), that indiscriminately increasing connectance may increase efficiency and even asymptotic stability, but it reduces resilience to structural perturbations in the system. Furthermore, 'dynamical systems composed of interconnected subsystems are stable [with respect to disruptions in connectance] if the subsystems are self-contained and the interdependence between the subsystems is properly limited' (Siljak, 1978, p. 2): something for us to ponder over in this era of indiscriminate globalization, free trade, and networking.

Fifth, resilience may in fact require some 'slack capacity' (Rochlin, 1997) that is relatively 'unplugged' from the larger system (such as a stash of gold jewellery at home as against simply a diversification of one's stock-market investment portfolios), so that this capacity is unaffected by shocks in the larger system. 'Exploiting all opportunities for mutual gain' (Levin *et al.*) may in fact reduce resilience by leaving no such 'slack'. On the other hand, adaptability may require a different kind of slack: a store of as yet unexplored, unvalued resources (such as biodiversity), and of course the ability to learn.

Clearly, since resilience and adaptability are defined with respect to a stability domain, the notions of equilibrium and stability continue to be relevant even after incorporating non-linearity. In general, for a system to be able to persist (in some desired form or with some desired properties) over time, i.e., to *sustain*, requires that it be at or around some equilibrium, have some stability in the face of small ('normal') perturbations, some resilience in the face of large ('abnormal') perturbations, and some adaptability to domain shifts. Thus, rather than stretch and pull the concept of resilience (sometimes beyond all recognition) or cast the debate in terms of short-term stability versus long-term resilience, it would be more appropriate to think of these properties as different attributes of *sustainability*—a concept general enough to serve in most discourses as one of society's meta-objectives (Lélé, 1988, 1993).

Particular situations would require more emphasis on particular attributes: systems characterized by high degrees of environmental variability (such as semi-arid regions or turbulent business conditions) must give primacy to resilience (hence the domination of *r*-selected grasses or small, loosely structured, opportunistic firms), while those characterized by low environmental variability (such as moist tropical regions or stable economies) permit the neglect of resilience (hence the domination of *k*-selected trees and complex rain forests or large, complex firms). Each specialization comes at the cost of some other qualities, and has an associated productivity gain under certain conditions. Research may no doubt have hitherto focussed disproportionately on stable ecosystems. But to insist that resilience is somehow more 'fundamental' would be akin to insisting that *k*-selected species are unfit to survive.

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Finally, it needs to be pointed out that the critique of conventional socio-environmental science is much broader than just the problem of not incorporating non-linearities. From a scientific perspective, the study of complex socio-ecological systems also suffers from the problem of reductionism—the tendency to look at tree growth only as a function of age rather than thinking of succession, disease and pollination in modelling forest stands (Holling *et al.*, 1995)—and the lack of methodological pluralism (Norgaard, 1989).

From a social perspective, conventional, primarily Western, environmental science is also characterized by narrow value systems. Both resilience as a goal in itself and sustainability as an overarching goal essentially pertain to the *temporal* dimension of human well-being. There is, however, also a simultaneously or primarily *spatial* dimension to many environmental problems, where current actions of one group affect the current well-being of another group. Typically, these spatial externalities (and the political power of the involved actors) are asymmetrical, if not entirely unidirectional. Unless one takes a clear position that in addition to our concern for the future, *intra-generational justice* is also a fundamental value, these environmental problems will get short shrift. For instance, when upstream factories pollute rivers that are the primary source of drinking water for downstream communities, the argument that the pollution is reducing 'long-term river ecosystem resilience' or 'water use sustainability' will not cut much ice with the factory owners: one has to invoke the notion of intra-generational justice. Similarly, a concern for the climate we may pass on to our future generations will not *in itself* prevent unfair arm-twisting by the North. The North would prefer to increase the resilience of the global climate system by buying up forest lands and emission rights from the South at historically biased exchange rates, rather than reduce its own level of fossil fuel consumption. The lessons from the history of environmental policy are unambiguous: no amount of 'trust', 'clever institutional design' (a la the already faltering Montreal Protocol), or 'epistemic consensus' (a la the IPCC: but see Jasanoff, 1992) can compensate for major asymmetries in the interests and powers of the different actors. And no amount of concern for long-term resilience of the human ecosystem can by itself ensure a fair environmentalism or a just development. Levin *et al.* do not claim that it does, but in a world of limited attention spans and paltry environmental budgets, we must ensure that resilience does not knock more pressing but politically inconvenient matters off the agenda.

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Into the wilderness within

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Levin *et al.* deliver a sweeping lecture on the state of nature and society. They point out that economic and ecological systems are linked, this linkage is complex, and that in the litany of environmental disasters that awaits us 'none can be treated by traditional markets, or regulatory policies.' Markets fail because they do not aggregate information accurately; corrective policies fail too because lobbying efforts serve to polarize rather than galvanize public debate. Policymakers, social planners, and researchers are asked to rethink their typical conduct, and instead focus on the construction of flexible and adaptive institutions that can accommodate the uncertain future in a way that maintains human welfare. Trust and intellectual guidance are the ties that bind a better world to these undefined, but resilient new institutions.

It is hard to argue with a general idea that a forward-looking society should be nimble enough to bounce back and handle the problems it creates. In fact, the goal of establishing well-constructed institutions has occupied the minds of political economists for centuries. Adam Smith, Edmund Burke, and other individualist writers stressed the need for rules and principles that can reconcile conflicts without empowering one group to always prevail through exclusion or coercion. Hayek (1948, p. 23) neatly summarizes their concern—'quite as important for the functioning of an individualist society . . . are the traditions and conventions which evolve in a free society and which, without being enforceable, establish flexible but normally observed rules that make the behavior of other people predictable in a high degree.' But operating at general levels runs the risk of reiterating common knowledge or worse, and Levin *et al.* are hazy on exactly how these new resilient institutions will evolve and how their performance will be evaluated. It is left unclear whether existing institutions will be modified or scrapped for new international environmental institutions (Levy *et al.*, 1993). It is also left unclear how these new resilient institutions will improve on the information aggregation properties of market prices without falling prey to the chimera of authoritarianism.

General edicts about a better world can tempt one to think about big science for guidance (e.g., Vitousek *et al.*, 1997). I take this opportunity, however, to stress that big questions do not always need big science. Big questions can be stripped down and addressed systematically in the laboratory of experimental economics. The lab has and continues to reveal how alternative institutions affect the wilderness within. If institutional

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resilience is an idea worth pursuing in detail, the lab is a well-suited tool because that has been its purpose for nearly four decades—explorations into the nature of institutions and behavior (Smith, 1982). By choosing what phenomena to explore, institution to evaluate, theory to test, response to measure, a researcher constructs the environment and rules of exchange that affect the flexibility of an institution and thus the behavior of people. Failure to meet expectations of resilience and rational behavior will trigger more experiments to better understand what traits created the unintended, but influential signals that create a brittle institution.

The lab provides the control, repetition, and feedback needed to understand the behavioral underpinnings of economic phenomena. By supplying information on the behavioral links between incentives, preferences, beliefs, and choice, experiments can be used to explore the nature of behavior in alternative institutions, complementing both field and simulation data (e.g., Arthur, 1988). Economists have use experiments to test the specific predictions of alternative stylized models, and as a testbed to measure the performance of new institutions too complex to be modeled note-for-note (Plott, 1994). For example, experimental methods were used to understand the workings of a new ascending-bid, multi-good auction for spectrum rights before the actual field implementation, which eventually generated over a billion dollars for the United States (McAffee and McMillan, 1996).

Ecologists promoting resilience should be open to the idea of using experimental economics to test their ideas. Given that the primary mechanism of research in ecology has been observation-based lab and field experiments often aimed at pattern recognition and the cause–effect relationship, they should be promoting the lab-mindset in economics to get a handle on institutional resilience (Shogren and Nowell, 1991). They may still complain that resilience is too complex to be captured adequately in the lab. But complexity is not an argument against resilience experiments, rather it makes the case for a research program in which the complexity of the lab increases gradually to isolate and control the factors that might influence the resilience of an institution (Plott, 1989). The lab can assist the best guesses guiding how institutional resilience can rectify environmental policy. By identifying how such complexities as trust and cooperation, intellectual guidance, transaction costs, strategic behavior, risk reduction mechanisms, and information affect resilience, the lab provides the testbed for new institutions before they are promoted at a grander scale.

A basic triad grounds all lab work, including any tests of institutional resilience (Mount and Reiter, 1974). The triad captures the main components underlying an economic experiment—the environment, human, and natural (E); the institution (I); and actual performance (A). The environment includes the preferences, endowments, technology, physical constraints, property rights, indigenous knowledge, and information structure (e.g., exchange value and starting quantity of a commodity). The institution specifies the rules that aggregate and generate information and coordinate actions. It outlines the rules of interaction and consequences: possible actions and messages, allocation rules conditional on messages and actions, and transition rules which may also be conditioned on actions

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and messages. Given the environment, people send messages (e.g., bids or prices) that the institution uses to allocate resources and costs. Given performance criteria (*P*) and a set of behavioral models (*B*), the experimenter can evaluate the efficiency and rationality of the actual behavior of the people under these alternative institutional structures. Experiments evaluating the effectiveness of alternative institutions control the environment (*E*) and then explore how alternative market and non-market mechanisms (*I*) affect the allocation of scarce resources.

How can experiments help define Levin *et al*.'s resilient institution to address a potential issue like global climate change? Consider three lines of experimental research already on-going and readily adaptable to climate change policy. First, climate change is a public good—non-rival and non-exclusive in consumption. Received theory says that rational people will free-ride off the emission reductions of others, and thus markets will fail to provide optimal levels of the public good and new institutions will be needed. Public good provision remains an active and fertile area of experimental research, one readily adaptable to address additional questions about why cooperation is brittle (see Ledyard, 1995). Suppose one thousand people are endowed with $5 each. They can privately contribute either $0 or $5 to a collective program to reduce global climate change. Assume every $1 contribution returns $500 to the group—$0.50 to the contributor and $499.50 to the other members ($0.50 each). The efficient outcome is when each person contributes $5, but his or her dominant strategy is to contribute $0 since the private net return is negative. Evidence from the lab reveals that neither complete self-interest ($0) nor cooperation ($5) dominates behavior. The evidence also reveals that the environment and institutional rules such as marginal payoffs, group size, and communication can be manipulated to get more cooperative behavior.[1] Extensions of this basic lab design could accommodate Levin *et al*.'s theme about maintaining resilient cooperation in the face of non-linear environmental shocks.

A second climate change issue is the effective design of a tradable emission permit system to increase the flexibility of finding low-cost carbon emissions around the globe. The lab is well-suited to examine what conditions are necessary to create and evaluate the performance of an emission trading program. For example, the efficiency of emission trading can be enhanced by providing so-called 'when' flexibility—firms can bank and borrow emission permits by either carrying permits forward to or drawing permits from a future compliance period. Using a series of testbed double auction experiments, Godby *et al*. (1997) show that banking had strong positive impacts on the efficiency of the emissions market. Two reasons drive this finding: firms can mitigate the distortion caused by an initial allocation of permits that is suboptimal over time; and firms planning to bank some permit have less incentive to hoard additional permits as a hedge against bad states of nature. Godby *et al*. also show that the introduction of a futures market also increased efficiency.

[1] Also see the work on common property regimes (e.g., Ostrom *et al*., 1994), and coordination games (e.g. Cooper *et al*., 1992).

Finally, Levin *et al.* also refer to the global climate change treaty, and the importance of cooperation and trust in institutions. Again the lab can evaluate how alternative institutions promote or debase the trust needed for cooperative agreements. Experimental economics has to consider the robustness or resilience of bargaining to different forms of economic friction (Kagel and Roth, 1995). The basic lab design has a bargaining dyad, payoff schedules, perfect information, zero transaction costs, perfect contract enforcement, and no wealth effects. While initial experiments observed efficient bargaining (Hoffman and Spitzer, 1982), other treatments suggest that economic friction such as imperfectly enforced contract or delay costs can reduce cooperation (Shogren, 1998). Again if Levin *et al.* have some specific elements of bargaining protocol that they believe would increase the resilience of cooperative institutions, the lab can be useful.

Complexity triggers adaptation which builds more complexity and more adaptation that disperses unique pieces of information throughout the economy (Holland, 1995). The market has aggregated this information with such success that many of us have the luxury and freedom to challenge the role of the market. But before social theorists begin experimenting with society, they should consider taking the new rules of organization into the lab for a test drive.

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Resilience, instability, and disturbance in ecosystem dynamics

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I am in agreement with the main thesis of the paper by Levin *et al*., namely that complex, non-linear systems, whether ecological or socioeconomic, do not lend themselves to management protocols based on assumptions of linear, globally stable, single equilibrium systems. As the authors point out, policy makers need a better understanding of the concept of resilience. Furthermore, it is especially important for them to understand the crucial elements for maintaining resilience in the integrated ecological-socioeconomic resource use systems (the forests, rangelands, and agro-ecosystems) on which most human welfare depends.

Three points arise out of this paper that deserve some elaboration or comment. The first, a point of confusion for many applied ecologists, has to do with the nature of the so-called 'stability domain'. The other two are particular aspects relating to the use of resilience theory. I'll deal with them in turn.

While I am aware that the authors of the paper fully appreciate the complexity of a stability domain in a natural ecosystem the statement that ecosystems have one or more stable states needs qualifying. The implication of the term 'stable state' for many applied ecologists is that each state is a stable point, a particular combination (particular amounts) of the variables making up the system. For simplified one- or two-variable systems, e.g. forest fuel as the variable, or grass and trees as the variables in a savanna, it is easy to conceptualize such stable equilibria. Indeed, the

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initial hypothesis for savanna dynamics proposed just such a two-variable two-state system, each with a stable equilibrium point. However, to continue with the savanna system as an example, subsequent testing of the hypothesis revealed that savannas are in fact essentially non-equilibrium systems (Scholes and Walker, 1993). The 'state' of savannas preferred by most managers—an open vegetation with a mixture of grass and trees—is an unstable region in the grass–tree phase plane, kept within some bounds of grass–tree ratios by variations in rainfall, grazing and fire. There is no particular combination of grass and trees towards which the system tends to change. If we add a few more variables, e.g. palatable and unpalatable grass and grazers and browsers, then the notion of any single equilibrium combination of these five variables becomes very difficult to sustain. But a constrained region of the state space of these five variables is entirely plausible, and is in fact what is most likely. Considering just three variables (grass, trees, and fuel load), the dynamics of the savanna closely resemble those portrayed in Ludwig *et al.* (1997), driven by rainfall, grazing, and fire. The pattern is one of a constantly changing system within a defined region of grass—tree biomass, with occasional 'flips' into a woody dominated system, and long periods of recovery to the open system.

The difference between the notion of a stability domain as an equilibrium point and as a bounded region (best visualized as a basin of attraction with a flat bottom) has important implications for management. The former could induce managers to attempt to force the system into one particular configuration—the supposed equilibrium state. Doing this could well create just what the manager does not want, namely a reduction in the size of the region of attraction. Realising that the system must vary in composition within the region of bounded dynamics leads to an appropriate management response.

Turning now to the two particular points referred to at the start, from the perspective of a resource manager the critical thing about understanding resilience is to know how to use the understanding. How does one apply it in managing particular ecosystems?

In many ecosystems, particularly those in very variable climates, significant changes in state are very often related to particular events: very wet years, major droughts, hurricanes, extreme temperature conditions (frost in the tropics, lack of frost in high latitudes), particular sequences of climatic conditions, and so on. Such event-dominated systems need to be event managed (Walker *et al.*, 1986). El-Niño years followed by a La-Nina in Australia offer an opportunity for re-establishing perennial grasses on the Mitchell grass plains, an opportunity that only arises every few decades. The El-Niño year involves a strong mid-season drought which causes mortality of many grasses, especially the competitors of the Mitchell grasses. The La-Nina year involves above average rainfall extending the growing season into late autumn, allowing newly germinated seedlings (in the spaces vacated by the dead plants) to become sufficiently established to survive the dry season. Austin and Williams (1988) showed that management during the establishment phase of these grasses was critical. Poor management at that time could lead to a lost opportunity, while attempting to improve species composition through de-stocking or other means in between these events achieved very little. Maintaining species composition under grazing in these grasslands depends on careful management during the establishment events. Considering ecosystems in general, the important thing to know is the extent to which the dynamics of an ecosystem in question are event driven, and if so, how to recognize the critical events. The first step in this is to appreciate that such critical events are likely to occur, and therefore that it is important to develop, in an iterative way, a model of the system's dynamics that pays particular attention to thresholds for change in relation to possible events. There are, of course, gradual ecosystem changes that do not depend on particular events and focussing on only event-driven change would be wrong, and could lead to unwanted outcomes.

The second issue concerns the emphasis in the paper on the role of frequent, small disturbances in maintaining resilience, in both ecological and social systems. The management of forest fires is given as an example. If frequent small fires are prevented, then the system begins to change. Fire-adapted species begin to decline in abundance, fuel accumulates, and the system loses resilience with respect to the impact of fire, becoming prone to an eventual and inevitable devastating fire that results in major undesirable change. The implied lesson is that what is needed is frequent small fires. But this can also be too prescriptive, and it is likely that neither option on its own is 'desirable'. In southeast Australia, for example, regular, small fires over a long time (used to pre-empt life-threatening major bush fires) lead to changes in species composition and forest structure. Every now and then a major, very hot fire is required to initiate germination and establishment of a suite of ground cover species (Catling, 1991). In the absence of this, the ground cover becomes dominated by grasses. A resilient forest, maintaining a diverse ground cover of shrubs and herbaceous species, requires a mixed fire regime. Constant applications of only frequent small fires or only infrequent major fires, both lead to changes in species composition and in resilience. Prescribed disturbance regimes for maintaining resilience require a deep and thorough understanding of the system's dynamics. In most cases, a prescribed management regime based on a particular pattern of disturbance is unlikely to achieve the resilience it is intended to produce.

The final paragraph in the Levin *et al.* paper emphasizes the need to view linked ecological and socioeconomic systems as one single system. From an ecologist's perspective, a quick scan of current papers in applied ecology journals confirms that we have a way to go in this regard. We may determine from some biophysical research that a particular rangeland has the composition to make it resilient in the face of a drought, assuming normal management. We may also determine from some socioeconomic research that the long-term economic viability of the farmer is resilient in the face of a market shock, assuming normal rangeland dynamics. The important question is whether the whole ranch system is resilient in the face of a simultaneous drought and a change in the market.

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