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Resilience and sustainable development

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1. Resilience

This special issue results from a call for papers to address the connection between resilience and sustainability, and stems from the fact that the ecological concept of resilience has been exercising an increasing influence on the economics of development. Resilience is interpreted in two different ways by ecologists: one capturing the speed of return to equilibrium following perturbation (Pimm, 1984), the other capturing the size of a disturbance needed to dislodge a system from its stability domain (Holling, 1973). The latter may be interpreted as the conditional probability that a system in one stability domain will flip into another stability domain given its current state and the disturbance regime (Perrings, 1998). The relevance of this concept for the problem of sustainable economic development has been recognized for at least fifteen years (Common and Perrings, 1992). Indeed, Levin *et al.* (1998) claimed that resilience is the preferred way to think about sustainability in social as well as natural systems, and a research network – the Resilience Alliance – has subsequently developed around the idea.[1]

The economic literature has since tended to focus on the non-convexity properties of the general system implied by the existence of multiple stable states, and the related problems of irreversibility and hysteresis (Brock *et al.*, 2002; Brock and Starrett, 2003; Brock and Xepapadeas, 2004; Dasgupta and Mäler, 2004; Carpenter and Brock, 2004). Researchers in the Resilience Alliance and others writing from an ecological perspective have, by contrast, concentrated on the ecological properties that correlate with system resilience. They generally argue that two attributes of a system affect its resilience. One is its adaptive capacity, which is generally related to the heterogeneity of a system (Carpenter *et al.*, 2001, Bengtsson *et al.*, 2003) – broadly equivalent to the diversity amongst the institutions and assets available in social systems (Scheffer *et al.*, 2001; Folke *et al.*, 2002). A

[1] The Resilience Alliance data base currently offers 276 papers on the application of the principles of resilience. http://www.resalliance.org/index

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second is its robustness, which refers to the properties of a system that allow it to accommodate perturbations without additional adaptation (Webb and Levin, 2005). Both robustness and resilience relate to the capacity of a system to accommodate perturbations without losing functionality. In economic systems, these bear on the ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently (the functionality of the market and supporting institutions), or to deliver essential services (the functionality of the production system.

Both concepts are related to the vulnerability of the system. The resilience of an ecological system in any given state depends on its position in what Holling refers to as the adaptive cycle. They are argued to be least resilient in the K phase of the adaptive cycle, i.e. when they are characterized by high biomass and complex structure. Recent developments in ecology have identified four aspects to resilience (Gunderson and Holling, 2002; Walker *et al.*, 2004). The first is 'latitude' or the degree to which a system can be altered before losing the ability to recover. The second is 'resistance', or the capacity of the system to prevent itself from being altered. These correspond loosely to adaptive capacity and robustness. The third is 'precariousness', or its position relative to the thresholds – the unstable manifolds between stability domains. The fourth is 'panarchy', or the convergence or divergence of cross-scale effects within the system. The vulnerability of a system involves both precariousness and panarchy. The latter captures the idea that the resilience of a system made up of many sub-systems, such as an economy, depends on the degree to which the adaptive cycle of each sub-system is synchronized. The whole system is most vulnerable when all sub-systems at a particular scale, say all firms in an economy, are at the same (least resilient) point in their cycle. This is referred to as hypercoherence (Stepp *et al.*, 2003).

Two aspects of the problem turn out to be particularly problematic for the sustainability of economic development. The first is the importance of thresholds, irreversibility and hysteresis associated with the transition from one state to another. A loss of resilience in an ecological-economic system in some state implies a change in the range of socio-economic or environmental conditions over which the system can maintain the flow of services. It is economically interesting if it changes the risks associated with particular development strategies, and if the value of the system varies across states. A development strategy is not sustainable if it is not resilient: i.e. if it involves a significant risk that the economy can be flipped from a desirable state (path) into an undesirable state (path), and if that change is either irreversible or only slowly reversible.

A second aspect is the role of heterogeneity or diversity in the resilience of the system in any particular state. A number of ecological systems are known to exist in multiple stable states, their resilience in each state being dependent on the economic use of the system. In terrestrial systems, boreal forests (Ludwig *et al.*, 1978), rangelands (Walker and Abel, 2002), and shallow lakes (Ludwig *et al.*, 2003) have all been analyzed in these terms. In all these cases, the connection between economic usage and resilience lies in

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the impact of either extraction (habitat destruction, harvesting, pest control) or waste disposal (pollution of air, soils and water) on the composition of the species that support ecosystem functioning and processes. There has been less work on resilience in marine systems, but the link between the functional diversity of species and resilience that has been observed in terrestrial ecosystems also applies to all aquatic systems dominated by substrate (e.g. near-shore ecosystems, coral reefs or the benthic communities of the open oceans). Changes in species diversity simultaneously change both the ecological dynamics and the economic value of the system. While the importance of the portfolio of assets is perfectly understood in the management of financial risk, the importance of the mix of biotic (species) and abiotic environmental assets in the management of the sustainability of resource-based economic development is not.

From an economic perspective it is important to understand the role of the price system in either signaling impending changes in the state of a system, or inducing changes of state. The significance of missing markets for economic efficiency is, of course, very well understood. The problem here is that markets may be missing for properties of the system that may affect its resilience, and hence its sustainability. Hence prices can induce decisions that push the system closer to unseen thresholds. There has been relatively little work on this problem to date. Perrings and Stern (2000) modeled the resilience of semi-arid rangelands with respect to both offtake prices and the cost of livestock holdings, and found evidence that price shocks led to changes in the long run productivity of the range through (perverse) impacts on offtake decisions, but that productivity changes induced by environmental shocks could not be anticipated from prices. In a different context, Mäler *et al.* (2003) and Carpenter *et al.* (1999) explored the existence of hysteresis effects in the responsiveness of the physical system to changes in prices. They show, in the case of shallow lakes subject to nutrient run-off from agricultural land, that the fertilizer price that induces a change of state of the lake is very different from the fertilizer price that induces a return to the original state. Once an oligotrophic lake has flipped into a eutrophic state, fertilizer prices need to be maintained at a much higher level than the price that induced the flip if the condition is to be reversed. In agroecosystems generally the impact of price shifts on crop choices, pesticide and fertilizer regimes all have the potential to induce a change of state, and to involve hysteresis, but are unable to signal the change in advances.

The problem this poses for management is that where events can trigger a change of state in a joint system, it is hard for a regulatory agency to observe the signals of impending change – since the dynamics of the system are revealed only through the response of the state variables to the controls. The less resilient the system is (the closer it is to the boundaries of the stability domain), the greater is the risk of irreversible or only slowly reversible loss. This also makes it difficult to develop appropriate taxes or charges to resist a change of state. Economic instruments can be used to induce the restoration of a state if the position is not irreversible, however their force is significantly weakened by the effects of hysteresis (Brock *et al.*, 2002).

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2. The special issue

The six papers in this special issue consider the existence of threshold effects, the importance of diversity or heterogeneity and the role of prices. A number of the papers concern agroecosystems: coupled ecological-economic systems in which the dominant economic activity is agriculture, including both crop and livestock production. This reflects the fact that employment, output and exports in many low-income countries are still dominated by agriculture. Although the percentage of the population engaged in agriculture has declined in every region due to the continuing movement of people from rural to urban areas, rural population growth remains positive in many low-income countries. It is highest in South Asia and Sub-Saharan Africa, where agriculture and forestry account for a higher proportion of the labour force than elsewhere (World Bank, 2005). Moreover, agriculture is one of the main proximate causes of biodiversity loss precisely because it is extremely sensitive to the effects of predation and competition. The elimination of existing pests, predators and competitors is generally a necessary condition for agriculture to take place, and invasive exotic pests and pathogens primarily affect agriculture, forestry and fisheries.

Within the focus on agroecosystems, there are two distinct problems addressed: the importance of knowledge about system dynamics and the implications these have for output and income where there are threshold effects; and the importance of diversity as a mechanism for assuring system resilience. The importance of knowledge about system dynamics is addressed in papers by Albers *et al.* (2006), Skonhoft *et al.* (2006), Antle *et al.* (2006) and Wirl (2006). The importance of diversity is addressed in papers by Sengupta (2006) and Garmestani *et al.* (2006).

Albers *et al.* (2006) consider farmer decisions in a shifting cultivation system that contains a critical threshold for the regeneration of soils. Once the threshold is crossed there is an irreversible regime from forest to grassland. They consider the role of prices in inducing such a regime shift. If farmers are encouraged to crop land for extended periods, the system's capacity to regenerate is reduced enough for invasive grasses to establish, hence reducing both the ecological and economic output of the system. More importantly, they consider the combined effect of foresight (information as to the significance of the regime shift) and incentives. They show that policies that subsidize the cost of production or that enhance producer prices can have opposite effects on the farmers' welfare, depending on the information available to them. Farmers who are not aware of the potential for regime shifts may be induced to take actions that cause the shift. Conversely, policies that improve productivity or the rate of forest regeneration reduce the risk of a regime shift.

Skonhoft *et al.* consider a problem that is, at one level, quite distinct from the more general questions addressed in this special issue. It is the problem of the optimal control of a particular agricultural pest: multimammate rats. As in the paper by Albers *et al.*, the key to the result is an understanding of the ecology of the problem. Intervention at a particular moment in the growth of rat populations rather than as a result of observed damage is shown to be much more effective in avoiding major losses. The authors find that the most cost-effective control is in the period prior to the

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planting season, rather than current practice of symptomatic treatment when damage is observed. This is essentially a management problem, but it also reflects the fact that farmers currently have no economic incentive to change their management practices, and so indicates the existence of an externality. This is because forward grain prices do not reflect the beneficial effect of an ecologically informed management strategy.

Antle *et al.* (2006) are similarly interested in a transition between states in an agroecosystem, and similarly focus on the role of prices in inducing that transition. In their case, the determinant of the transition between states is the level of investment in soil conservation, and this is driven by the return to that investment. They argue that the system has two equilibria: a high-productivity equilibrium maintained by investment in soil conservation and a low-productivity equilibrium where there is no investment in soil conservation. The threshold level of soil degradation is the point at which returns to investment in soil conservation become negative. In this case there is nothing in the physical system that is irreversible – in the sense that investment in soil conservation could bring the system back up to the high productivity state. However, they argue that it is 'economically irreversible' in that, at the expected prices, a rational farmer has no incentive to change their decision not to invest. This reflects a classic problem of externality, in which the transition between states is the unintended consequence of decisions based on prices that do not reflect the forward costs/benefits of soil conservation.

The last paper on the importance of knowledge about system dynamics does not consider an agroecosystem. Nevertheless, the paper by Wirl (2006) does address an analogous problem: how does information about the future consequences of pollution affect the choices between accepting, stopping or delaying pollution activities. Once again, it is motivated by the fact that there exist thresholds beyond which the costs of making the wrong decision are either irreversible or long-lasting. Using the real options approach that has already been applied to emissions of greenhouse gases by Conrad (1997, 2000), Pindyck (2000, 2002) and Saphores and Carr (2000), he identifies the conditions in which it will be optimal to stop polluting activities, or when and for how long to call a moratorium on such activities when the decision-maker is aware that the system exhibits both path dependence and hysteresis.

The remaining two papers in the special issue address the link between resilience and diversity in ecological-economic systems. One of these, Sengupta (2006), is also concerned with agroecosystems. The other, by Garmestani *et al.* (2006), considers a completely different problem. In the second of these two papers the authors attempt to use developments in ecology relating to the link between functional diversity and resilience to explore the role of industrial diversity in the resilience and hence sustainability of the economy. The proposition that is considered is that just as the functional richness of species in an ecological system enhances its resilience, so does the functional richness of firms enhance the capacity of an economic system to function in the face of economic and environmental shocks. The authors propose that functional richness is increasing in the number of firm – that functional richness across size classes indicates

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lower entry barriers for firms and greater opportunities for product diversification. Their proxy for resilience is a measure of variation in employment levels, and so is closer to Pimm than Holling. They find, using data on the location, Standard Industrial Classification (SIC) code, number of employees, and years of operation of firms in South Carolina, that greater functional richness enhanced the capacity of the manufacturing sector to maintain employment levels in the face of exogenous shocks.

The paper by Sengupta (2006) addresses a question originally considered by Sporrong (1998), who shows that the partial inheritance system of central Sweden led to a fragmented pattern of landholdings that created much greater diversity than would otherwise have been the case, and that enhanced the resilience of the agroecosystem. Sengupta considers the role of fragmentation in irrigated agriculture in south Bihar, India, from a similar perspective. In this case fragmentation is not the result of inheritance laws, but reflects 'farmers' creative participation' in irrigation schemes. He finds that diversity of management strategies increases the resilience of the system, and concludes that while it is difficult to design diversity precisely because it reflects the adaptive response of many different farmers, a policy that is intended to promote sustainability should do nothing to discourage it.

3. Implications for sustainable development strategies

Since research into the economics of resilience and sustainability is at a relatively early stage of development, there are few hard and fast lessons for sustainable development policy. However, we can at least point to two general conclusions reached by the papers in this special issue that are both consistent with the wider literature on the subject and that have clear implications for sustainability strategies.

The first of these is obvious, but it bears repetition. It is that a necessary condition for the sustainable management of dynamical systems is that the system dynamics be understood. If they are not, then any feedback control mechanism – like the market or the economic policy process – may be misdirected. That is, both the system measures and the controls applied may be inconsistent with the control objectives. The papers in this special issue support the conclusions of a much wider literature that uncertainty about the dynamics of most real ecological-economic systems extends well beyond Gaussian measurement errors, and includes basic misspecifications of system dynamics. The implication of this is that decision-makers are simply unable to form realistic expectations about the consequences of their actions.

To a large extent this uncertainty is inescapable. Because ecological-economic systems are evolutionary there is always the potential for current decisions to have novel and entirely surprising outcomes. Nevertheless, the first challenge to both sustainability science and policy is to improve knowledge of the system dynamics, whether through a passive Bayesian learning process or a policy of adaptive management – in which the system is perturbed in order to uncover information about its dynamics. As the papers by Albers *et al.* and Skonhoft *et al.* show, awareness of system dynamics changes decisions even if the current system measures (prices) do

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not reflect the range of possible outcomes. This is an extremely important point, and underlines the value of developing appropriate models of system dynamics. Even where there are externalities – where markets fail to provide good approximations of the true value, the social opportunity cost, of resource use – there is a payoff to improving understanding of system dynamics.

This does not detract from the importance of 'getting the prices right'. Since uncertainty about systems dynamics stems either from measurement error or misspecification of system dynamics, it is always desirable to improve the quality of measurements. Moreover, in a world of decentralized decision-makers where individual users of environmental resources have limited access to information about system dynamics, if prices reflect true social opportunity cost then decision-makers will still behave as if they understood those dynamics.

At a more fundamental level, understanding system dynamics is important to sustainability because it enables decision-makers to choose between actions that involve adaptation to future changes, and actions that mitigate those changes. Once again, this is implicit in the papers in this special issue. Adaptation involves actions that alter the cost or benefits of change without altering the likelihood of that change, and is the only potential response for most decision-makers. Indeed, it is built into the assumptions generally made about atomistic competition or openness in international markets. Mitigation, on the other hand, is a viable response where actions by some decision-maker have the potential to affect the probabilities attaching to future outcomes, and where those probabilities are known. It follows that mitigation is a viable response only where the decision-maker has an appropriate model of the system dynamics that link current decisions with future outcomes: i.e. that enables the decision-maker to predict the consequences of their actions. So mitigation of the effects on climate of carbon emissions depends on the quality of the predictions made by the general circulation models. But at a much finer grain, mitigation of the effects of localized uses of a range of environmental resources depends on the quality of partial models of local dynamics. The papers in this special issue give examples of such partial models.

They show that it is important to be able to identify the existence of thresholds, and the dynamic implications of crossing thresholds – especially the implications for either irreversibility or hysteresis. In ecological systems, for example, threshold values exist for species diversity. While there may be a range of population sizes for the different species in an ecosystem over which the system remains stable, if any one population falls below its critical threshold level the self-organization of the whole system may be irreversibly compromised. Threshold values also exist for overall regressive succession; standing crop biomass; energy flows to grazing and decomposer food chains; mineral micro-nutrient stocks and so on. But as Antle *et al.* (2006) point out, there are also economic thresholds – prices beyond which activities that have important dynamical consequences are either triggered or are stopped. If resource prices correctly measure the discounted stream of services deriving from the allocation of those resources, given the dynamics of the system, this is not an issue. If they do not, then it is important to

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understand the nature of price thresholds and the physical consequences of crossing those thresholds.

The second general conclusion reached by the papers here is consistent with the ecological literature on resilience (Levin, 1999). It is that one critical indicator of the resilience of systems is their diversity. Since this also meshes with the understanding that economists have of the role of asset portfolios in the management of financial risk it is not surprising, but importantly the notion of diversity extends well beyond asset portfolios. From an ecological standpoint, biodiversity guarantees ecological functioning and hence the provision of valuable ecosystem services by building in functional redundancy. So, for example, several species will typically perform nitrogen fixation functions, but each will perform those functions differently depending upon climatic conditions. In the same way as the financial risk properties of an asset portfolio might be evaluated in terms of the covariance in the returns on the different assets in the portfolio over a range of market conditions, so might the nitrogen fixation risks of the set of species in an ecosystem be evaluated in terms of the covariance in the nitrogen fixed by each of the species in the set over a range of climatic conditions.

It follows that the capacity of an ecological-economic system to function over a range of both social and environmental conditions depends on the mix of assets in the system, where assets includes not just financial and produced assets, but also natural assets. The paper by Sengupta (2006) attempts to capture the diversity of an agroecosystem through its fragmentation – the heterogeneity of farming assets and management strategies. Garmestani *et al.* (2006) attempt to capture the diversity of an industrial system through differences in firm size. Others have argued the importance of institutional, political and cultural diversity.

As in portfolio theory, there may be a trade-off between productivity and resilience. The most resilient systems in the long term are not necessarily the most productive in the short term. This trade-off exists at every spatial scale. Systems that are resilient at one spatial scale may not be resilient at another spatial scale. A strategy that satisfactorily manages the trade-off for a multinational corporation, for example, may be inconsistent with a strategy that manages the trade-off within a single state, or within a company that operates within a single state. Moreover, the globalization of the world economic system is changing the nature of the trade-offs, precisely because it is reducing the heterogeneity of the global system. Risk pooling strategies that were effective in the past because the risks in each sector or region were largely uncorrelated, are becoming less effective as the risks have become more highly correlated. The growth of world trade and travel, the development of global industries and the global diffusion of technologies have all had the same effect.

For a small nation state this makes the design of a strategy for sustainable economic development increasingly problematic, but it does not change the value of the general conclusions reached by the papers in this special issue. It is still important to be able to understand the dynamics of the ecological-economic system in order to predict the consequences of current actions. It is important to be able to identify thresholds and the

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consequences of crossing thresholds. It is important to understand the role of heterogeneity – diversity – in the ability of the coupled system to support human well-being over a range of social and environmental conditions. The evolution of a theory of economic development that captures these things has only just begun, but its central properties are already reasonably clear. Sustainable development, however it is defined, requires that the value of the asset base available to the relevant population does not decline over time. A resilience perspective implies that the composition of the asset base is critically important. A strategy that seeks to concentrate assets in those areas of activity that yield the highest short-term returns will almost certainly reduce the resilience of the system as a whole. More particularly, a strategy that runs down critical elements of the natural environment will reduce the capacity of the coupled system to function over a range of environmental conditions. The important choice for a national development strategy is to identify the appropriate spatial scale at which to ensure that the portfolio of produced and natural assets is balanced.

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