Environmental and Resource Economics **11(3–4):** 503–520, 1998.

Resilience in the Dynamics of Economy-Environment Systems

CHARLES PERRINGS
Environment Department, University of York, York YO1 5DD, UK (email: cap8@york.ac.uk)

Abstract. The ecological concept of resilience has begun to inform analysis of change in economy-environment systems. The linkages between resilience and the stability of dynamical systems are discussed, along with its role in understanding of the evolution of such systems. Particular linkages discussed include those between resilience, biodiversity and the sustainability of alternative states. Recent developments in modelling the resilience of joint economy-environment systems suggest the advantages of analysing change in the system as a Markov process, the transition probabilities between states offering a natural measure of the resilience of the system in such states. It is argued that this 'emergent property' of the collaboration between ecology and economics has far-reaching implications for the way we think about, model and manage the environmental sustainability of economic development.

Key words: biodiversity, dynamics, resilience, stability

JEL classification: Q30, D80

1. Introduction

Two rather different concerns dominate analysis of the environmental consequences of economic change. 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. Both concerns reflect a perception that there are many possible states of the economy and its environment, and that not all states are equally valued or equally persistent. The 'underdeveloped' state of many low income countries in the post-war years, for example, was interpreted as evidence of the strongly stabilizing effect of population growth at low levels of productivity. Low income economies were conceptualised as being at a locally stable equilibrium in which any increase in per capita income above subsistence level induced income-depressing population growth. They were caught in a poverty trap by Malthusian forces (Leibenstein 1957; Myrdal 1957). Such poverty traps have since been seen as a major cause of environmental degradation (Dasgupta 1993). Other frequently cited examples of 'lock-in' with significant environmental implications include dependence on hydrocarbon-based technologies and institutional and cultural rigidities that stand in the way of change (Hanna, Folke and Mäler 1997).

On the other side of the coin, the whole of the sustainability debate has been driven by a concern that economic growth and the pattern of consumption in high income countries may be both unstable and unsustainable. It has been argued that economic growth that increases both resource use and the waste emissions beyond the carrying or assimilative capacity of the environment may make societies more not less sensitive to external shocks (Arrow et al. 1995), and the irreversible environmental consequences of consumption may mean that future states may offer fewer opportunities to society than present states (Meadows et al. 1992).

Collaborative work between ecologists and economists has used the ecological concept of resilience to explore the relative persistence of different states of nature. The concept of resilience has two main variants. One is concerned with the time taken for a disturbed system to return to some initial state and is due to Pimm (1984). A second is concerned with the magnitude of disturbance that can be absorbed before a system flips from one state to another and is due to Holling (1973). Both variants deal with aspects of the stability of system equilibria, offering alternative measures of the capacity of a system to retain productivity following disturbance. Most work in the area has concentrated on the Holling version and its application to the management of joint economy-environment systems. But given the interest in lock-in and sustainability, both have a rather natural appeal. More recently, it has been argued that the concept of resilience offers a useful way of thinking about the sustainability of non-environmental dynamical systems (Levin et al. 1998).

This paper reviews the concept of resilience and its introduction into the analysis of economy-environment systems. It identifies the linkages between resilience and stability of dynamical systems generally and considers its contribution to our understanding of the evolution of such systems. Particular linkages discussed include those between resilience, biodiversity and the sustainability of alternative states. The paper summarises recent developments in modelling the resilience of joint economy-environment systems, and indicates the approaches that seem to have greatest potential. In addition, it discusses key methodological and substantive research questions that remain to be addressed.

2. Resilience and Stability

The concept of resilience in the ecological literature was developed in response to three widely observed characteristics of the behaviour of ecological systems. The first is that observed change in ecological systems tends not to be continuous or gradual, but involves more or less sudden alteration in the stock resources. This may occur after long periods of ‘stability’, and may be stimulated by quite small perturbations of the system. The second is that functionally different states of a system involve different equilibria. That is, systems tend to ‘evolve’ by switching between system equilibria. The third is that the dynamics and stability of ecological systems tend to vary non-linearly with the scale of those systems.

As has already been remarked, the concept of resilience has been defined in two rather different ways. One refers to the properties of the system near some stable equilibrium (i.e. in the neighbourhood of a stable focus or node). This definition, due to Pimm (1984), takes the resilience of a system to be a measure of the speed of its return to equilibrium. The second definition refers to the perturbation that can be absorbed before the system is displaced from one state to another. This definition, due to Holling (1973, 1986, 1992), does not depend on whether a system is at or near some equilibrium. It assumes that ecological systems are characterised by multiple locally stable equilibria, and the measure of a system's resilience in any one local stability domain is the extent of the shocks it can absorb before being displaced into some other local stability domain. Perturbation may induce the system to change from one attractor (stability domain) to another, or not. If not, the system may be said to be resilient with respect to that perturbation.

By the Holling definition, the resilience of an ecological system is a measure of its ability to maintain its self-organization without undergoing the 'catastrophic' and possibly irreversible change involved in crossing the threshold between stability domains. As biomass accumulates the system is thought to become more susceptible to shocks, and hence to a change of state. Similarly, an increase in stress or reduction in the resilience of an ecological system makes it more susceptible to exogenous shocks or changes in environmental conditions. In many cases, the link between stress and the loss of resilience is an alteration in the mix of species in the system (Perrings et al. 1995). There is evidence that deletion of some species has minimal effect on at least the short term functioning of ecosystems, whilst the deletion of others triggers a fundamental change from one ecosystem type to another – from forest to grassland, or grassland to a shrubby semi desert, for example (Walker and Noy Meir 1982). Agroecosystems – ecological systems whose species mix is transformed for the purpose of agriculture – are particularly at risk (Conway and Barbier 1987; Conway 1993).

To characterise the resilience of a system in some state, Common and Perrings (1992) and Perrings (1995) relate it to the Liapunov function associated with the corresponding equilibrium. A Liapunov function, if it exists, may be used to estimate the size of the basin of attraction of some equilibrium, and hence the limits within which the state variables may be perturbed before the system switches to some other basin of attraction. This property of Liapunov functions makes them suitable for deriving measures of resilience in the sense of Holling (1973).

It is important, however, that terrestrial and marine systems alike are characterized by a hierarchical structure. While the behaviour of terrestrial and aquatic systems dominated by substrate (near-shore ecosystems with abundant recruitment, coral reefs or shallow fresh water lakes) is recognised to be different from that of open pelagic marine systems, both are hierarchically structured. In a forest system, for example, the structure extends from the leaf/needle at the bottom, through the tree, the stand, the forest to the biome. In marine systems these structures are produced by physical forces that increase in scale from turbulence, to waves, to eddies, to gyres. Not only is the resilience of the system different at different hierarchical levels, but the resilience of the system in one state and at one level may depend upon its ability to cycle through different states at another level. The resilience of forests and semi-arid rangelands, for example, depends on their being burned at regular intervals (Walker and Noy Meir 1982; Westoby et al. 1989).

3. Stochastic Evolutionary Systems: New Directions

The key point is that resilience is a measure of stability in the face of shocks to the system. It assumes a stochastic environment: that the system is subject to a regime of shocks. Indeed, this is the starting point for the most recent developments in the theory of resilience in joint economy-environment systems. Two lines of research appear to be promising, each with its roots in a different area of the theory of stochastic dynamical systems. The first is explicitly related to the survival of populations. Originally due to Reed (1979, 1988, 1989), it focuses on single populations or interactions between populations and models the probability of the collapse of those populations. Specifically, it includes the hazards confronting individual populations as part of the explanation of their dynamics. The approach has more recently been linked to the problem of identification and measurement of the resilience of particular populations (Tinch 1998).

The second approach, discussed in more detail here, treats the evolution of joint economy-environment systems as a Markov process in which the resilience of the system in any given state is measured by the probability of its transition to some other state. This parallels recent developments in macroeconomic modelling (see for example Aoki 1996; Barnett et al. 1996). Deterministic multiple equilibrium systems will necessarily converge on the equilibrium in whose basin they are initially located. Stochastic systems may, however, be driven from one basin of attraction to another by the force of exogenous stresses or shocks. The evolution of joint systems can be analysed as the transition dynamics of stochastic multiple equilibrium systems.

The economic value of a system in some state depends on its ability to maintain the flow of goods and services for which it is valued given the shocks or disturbances it faces. The source of disturbances may be either anthropogenic or ‘natural’. Many environmental systems are valued for the protection they provide against natural events. Mangroves and wetlands, for example, provide storm-buffering services. Their capacity to provide these services depends on their resilience with respect to storm events, and this varies both with the structure and extent of the natural system and with the frequency and severity of storms. Mangroves and wetlands also filter out anthropogenic waterborne pollution, and their value in this respect similarly depends on the level of stress posed by emissions to water and the distribution of pollution events. But the probability that the system will be able to cope with the disturbance regime – whatever that may be – can itself be influenced by anthropogenic change. The construction of dykes and bunds, for example, has generally reduced the capacity of wetlands to respond to stress and shock.

The capacity of most terrestrial ecosystems to accommodate exogenous shocks depends on the number of species that can carry out key functions or support critical processes. The deletion of species in a particular system may compromise its capacity to function if environmental conditions change. That is, it may induce a change of state of the system. A recent example of this approach is given by Batabyal (1997a, b) who uses renewal theory to characterise the resilience of systems in terms of stationary probabilities. He describes the resilience of a system in terms of the probability of survival of some subset of the species in that system – which can be thought about as the minimum set needed if the system is to be able to function over the expected range of environmental conditions. The measure of resilience of the system is then the probability, as time tends to infinity, that the surviving set of species will be the minimum set.

This approach is promising, but it is still focused on the long run equilibrium of the system. From a policy or management perspective, it is just as important to understand the resilience of the system away from equilibrium as at the steady state. Ludwig et al. (1997) and Perrings and Dalmazzone (1997) both make the point that ecological and economic systems alike are typically characterised by both multiple stable states and hysteretic effects. They are path dependent. The theory of the evolution of stochastic multiple equilibrium systems turns out to offer a tractable way of modelling the resilience of an economy in different states of nature, and at different stages in its evolution.

Consider a simple discrete time problem. Let **P** define a (stochastic) matrix of transition probabilities, the elements of which, p_{ij}, denote the probability that a system initially in the ith state will change to the jth state in the next period. The transition probabilities after t periods will be $\mathbf{P}^t$: i.e. $\mathbf{P}(t)$ evolves recursively according to

$$\mathbf{P}^{t+1} = \mathbf{P}^{\mathbf{t}}\mathbf{P}$$

with

$$\lim_t \rightarrow_\infty \mathbf{P}^t = \mathbf{P}^\infty$$

The matrix $\mathbf{P}^\infty$, if it exists, defines the limiting transition probabilities of the system.

Now let $\mathbf{p}_i(t)$ denote the probability that the system will be in state i at time t. The probability that it is in any one of n possible states at that time is then summarised by the row vector $\mathbf{p}(t) = [\mathbf{p}_1(t), \mathbf{p}_2(t), \ldots, \mathbf{p}_n(t)]$. Since the transition probabilities conditional on the state of the system at time t are given by $\mathbf{P}^t$, $\mathbf{p}(t)$ evolves according to the recursive relation:

$$\mathbf{p}(t) = \mathbf{p}(0)\mathbf{P}^t$$

and the limiting probabilities are defined by

$$\lim_{t} \rightarrow_{\infty} \mathbf{p}^{t} = \mathbf{p}(0)\mathbf{P}^{\infty}$$

This is equivalent to Batabyal's (1997a) measure of resilience. However, transition probabilities of the system may be interpreted as direct measures of its resilience in each state with respect to perturbations towards other possible states at each moment in time. To illustrate this consider the following very simple case. Let the matrix of transition probabilities take the form:

$$\mathbf{P} = \begin{bmatrix} 1 - e^{-\alpha_1\beta} & e^{-\alpha_1\beta} \\ e^{-\alpha_2\beta} & 1 - e^{-\alpha_2\beta} \end{bmatrix}$$

The exponents of the elements in this matrix have two terms. The first term, α_i, may be interpreted as a direct measure of the resilience of the ith state. The second term, β, may be interpreted as an index of the flexibility of the system. Since the probability that the system in one state will change to another state is a decreasing function of both terms, both increase the persistence of the state concerned. If $\alpha_1 > \alpha_2$ then state 1 may be said to be more resilient than state 2. Moreover, as β rises, this increases the probability that the system will, in the limit, be in state 1. The parameter α_i has been interpreted by some as the height of a barrier between the ith and other basins of attraction (Aoki 1996). There are many reasons why the system may be resilient in a given state and the existence of the barrier between basins is certainly one. Indeed, the institutional rigidities that inhibited change in the former Soviet Union can be thought of in these terms. In general, however, resilience is a function of both the properties of the system in a given state, and the disturbance regime.

Now the matrix $\mathbf{P}^{\infty}$ will exist if and only if it is 'proper'. Since **P** is a stochastic matrix it has a dominant eigenvalue equal to one. Denoting this by λ_1, and the remaining eigenvalues by $\lambda_2 \ldots \lambda_n$, **P** may be said to be proper if and only if $\lambda_j < 1$ for j = 2, …, n. If **P** is proper, then

$$\mathbf{P}^{\infty} = \{\lambda_1[\mathbf{I} - \mathbf{P}]^{-1}D(\lambda)\}/D'(\lambda)$$

in which $D(\lambda)$ is the characteristic polynomial of **P**. Each of the columns of $\mathbf{P}^{\infty}$ will then be an eigenvector of **P** corresponding to the eigenvalue λ_1. If λ_1 is a simple root of the characteristic polynomial, **P** is said to be 'regular'.

To see how the resilience of different processes affects the evolution of a stochastic system, consider the limiting transitional probability matrix, $\mathbf{P}^{\infty}$. First, if **P** is regular, then the eigenvector corresponding to λ_1 is the vector [1, 1, …, 1] and all elements in the corresponding column of $\mathbf{P}^{\infty}$ will be the same. The main implication of this is that limiting transition probabilities of the system will be independent of the initial state. The limiting transition probabilities will not be path dependent.

But now consider a second, more general case – where the matrix of transition probabilities is reducible. If **P** is reducible, then it will be possible to write it in the normal form:

$$\mathbf{P} = \left[\begin{array}{ccc|ccc} \mathbf{P}_{11} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{P}_{\mathrm{mm}} & 0 & \cdots & 0 \\ \hline \mathbf{P}_{\mathrm{m+11}} & \cdots & \mathbf{P}_{\mathrm{m+1m}} & \mathbf{P}_{\mathrm{m+1m+1}} & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{P}_{\mathrm{n1}} & \cdots & \mathbf{P}_{\mathrm{nm}} & \mathbf{P}_{\mathrm{nm+1}} & \cdots & \mathbf{P}_{\mathrm{nn}} \end{array}\right]$$

in which each submatrix on the diagonal corresponds to an interlinked group of states. There is an important distinction to be drawn between the groups of states in the two main blocks on the diagonal. The groups of states indexed 1, . . . , m are be said to be ‘essential’ or ‘absorbing’, while the groups indexed m + 1, . . . , n are be said to be ‘inessential’ or ‘transient’. There turns out to be a correlation between essential and resilient states, but it is more helpful to think of absorbing states as ‘limiting’ states: i.e. states which may occur with positive probability in the limit. Transient states are, by contrast, not limiting. Formally, each of the submatrices on the diagonal, $\mathbf{P}_{11}, \ldots, \mathbf{P}_{\mathrm{mm}}$ is positive, irreducible, and has a dominant eigenvalue whose absolute value is equal to one. Each of the submatrices, $\mathbf{P}_{\mathrm{m+1m+1}}, \ldots, \mathbf{P}_{\mathrm{nn}}$ is also irreducible but has a dominant eigenvalue whose absolute value is less than one.

The importance of the distinction between absorbing and transient states lies in its implications for the evolutionary potential of system. This is because only certain transitions are possible. Specifically, it is possible for the system to evolve from one absorbing state to another absorbing state in the same group, but not to another absorbing state in any other group, and not to a transient state. It is also possible for the system to evolve from one transient state to certain other transient states, or from a transient to an absorbing state. Because of the unidirectional nature of the transition probabilities, the limiting probabilities for transition into a transient state are zero. Only absorbing states are possible in the limit. That is, the limit of $\mathbf{P}^{\mathrm{t}}$ as t tends to infinity, $\mathbf{P}^{\infty}$, takes the form:

$$\mathbf{P}^{\infty} = \left[\begin{array}{ccc|ccc} \mathbf{P}^{\infty}_{11} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{P}^{\infty}_{\mathrm{mm}} & 0 & \cdots & 0 \\ \hline \mathbf{P}^{\infty}_{\mathrm{m+11}} & \cdots & \mathbf{P}^{\infty}_{\mathrm{m+1m}} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{P}^{\infty}_{\mathrm{nm}} & \cdots & \mathbf{P}^{\infty}_{\mathrm{nm+1}} & 0 & \cdots & 0 \end{array}\right]$$

The first implication of this is that the limiting transition probabilities of the chain do depend on the initial state. Because the chain does not involve positive limiting transition probabilities between every pair of states, the initial state restricts the future evolution of the system. If the initial state belongs to a particular group of *absorbing* states, the system will be locked-in to that group of states. If the initial state belongs to a particular group of *transient* states its future evolution may involve transition within that group; between that group and groups of transient states indexed above the initial group (i.e. if the initial state is in $\mathbf{P}_{qq}$, $m + 1 < q < n$, it may involve transition to groups $m + 1, \ldots, q - 1$); or between that group and an absorbing group. Transition from a transient state to an absorbing state will be irreversible.

The second implication is that, irrespective of the initial state, the limiting probability that the system will be in a transient state is zero. That is, since $\lim_{t \to \infty} \mathbf{p}^t = \mathbf{p}(0)\mathbf{P}^{\infty}$, if $\mathbf{P}^{\infty}$ has this form, $\mathbf{p}_i^{\infty} = 0$ for $i = m + 1, \ldots, n$.

The elements of **P** may be interpreted as measures of the resilience of the system with respect to the set of exogenous stresses and shocks which explain its stochastic structure. By this interpretation, the greater the probability that the system in one state will change to some other state, the less resilient is the system in the first state. The greater the value of p_{ii}, and the smaller the value of p_{ij}, the more resilient is the system in the ith state. It follows immediately that if **P** is reducible, the groups of states indexed $1, \ldots, m$ are more resilient than the states indexed $m + 1, \ldots, n$. Absorbing states are more resilient than transient states. It also follows that the system will evolve from less resilient transient groups of states to more resilient absorbing groups of states, and that this transition will be irreversible. Another way of describing the same thing is that the system will get locked-in to a particular group of absorbing states. Its future evolution will then involve only transition between states in that group.

I have suggested that it is possible to think about the elements in the transition probabilities matrix as depending on institutional conditions. Some institutions effectively lock people into patterns of behaviour or technologies that preclude particular development or evolutionary options. Open access property rights to scarce environmental resources, for example, lock resource users into strategies that cause the overexploitation of such resources. Institutionally defined environmental public goods, such as the high seas, mean that none can be excluded from the resource despite the fact that the marginal cost of its use is not zero – it is rival in use. Nationally, social rules, structures of rights and obligations, norms and mores all prescribe the set of possible uses of environmental resources. They also structure the feedbacks that determine how people adjust to changing environmental conditions. Internationally, competition and the lack of supranational authorities inhibits cooperation in the provision of global public goods, ensuring that the only possible outcome in many cases is the non-cooperative Nash equilibrium.

On the one side, the elements of **P** depend on the regime of shocks that perturb the system. On the other, they depend on the way in which the resources of the system are used – the pressure placed on its assimilative or carrying capacity – and the effectiveness of the feedback mechanisms that guide resource use. Both are institutionally determined. The privately optimal stock size in fisheries, forests, rangelands and the like all depend on the institutional regime under which they are exploited. The effectiveness of feedback mechanisms, particularly the price mechanism, determines users' ability to respond to and absorb exogenous shocks. The lack of an effective feedback mechanism when an ecosystem is being exploited close to the limit of its carrying or assimilative capacity, for example, increases the probability that shocks will be undetected and induce a change of state. Put another way, the lack of effective feedback mechanisms reduces the resilience of the system in that state.

Whether a change of state significantly affects welfare depends on the nature of the change. The collapse of a particular fish stock, for example, may or may not have significant welfare effects depending on the role of that stock in the ecosystem and the availability of alternative stocks. The evolutionary potential of the system and its resilience or persistence in any given state, together with the set of alternative (reachable) states is at least influenced by these factors. Wherever the transition probabilities matrix decomposes, as it may generally be expected to do, history matters. The limiting transition probabilities of the system do depend on the initial state and structure of the system.

4. The Research Agenda

While the notion of system resilience has its roots in ecology, it is concerned with something that is common to any stochastic evolutionary system – the effect of the stability domain structure on the system's dynamics. These matters are currently attracting attention in a variety of different fields within economics, and in a variety of different disciplines. The questions being addressed are, in many cases, the same. They include the implications of path dependence and discontinuous change, the behaviour of the system away from equilibrium and the nature of uncertainty in evolutionary systems. Ecologists have long been concerned with change in ecological systems that involves an irreversible and rapid alteration in the state of the system at intervals of varying length (cf May 1977). Moreover, this has been formally modelled as a problem of loss of resilience of a system in a given state (Perrings and Walker 1995; Ludwig et al. 1997).

The same phenomenon has since been picked up in other disciplines in both the social and the natural sciences. In organisational theory, for example, organisational dynamics are increasingly seen to be characterised by long periods of relative stability punctuated by short periods of upheaval that involve a change of state (Gersick 1991). In economics, the evolution of stochastic macroeconomic systems has been modelled as a Markov process, in which the transition probabilities depend on the relative sizes of the basins of attraction of distinct equilibria (Aoki 1996). Once again, one of the prime sources for this is earlier work in population biology and genetics (Watterson and Guess 1977; Kingman 1978). More generally, discontinuous change in dynamic economic systems is now recognised to be a widespread phenomenon (Brock and Malliaris 1989; Benhabib 1992).

The agenda for further research on resilience and the sustainability of dynamic economy-environment systems is wide, but there are a small number of issues that stand out as warranting early attention. Methodologically, there are two areas where further research is needed before it will be possible to make much progress in analysing the dynamics of joint systems. One is the problem of aggregation. The other is the problem of measuring loss of resilience. Substantively, the important questions are why societies become locked into undesirable states, and how they may sustain desirable states. Two key issues are worth investigation: the role of the diversity of assets in the resilience of systems; and the related phenomena of density dependence, field effects and endogenous technical change.

4.1. METHODOLOGY

The first of the methodological problems is well recognised by those seeking to model economy-environment systems, but remains quite intractable. The models of joint systems already referred to (Ayres and Kneese 1969; Victor 1972; Mäler 1974; Lipnowski 1976; Van den Bergh 1991; Ruth 1993; Amir 1994; Ayres 1994) tend to incorporate environmental resources directly into the production functions for economically scarce goods, aggregating by sector as is common in macroeconomic and applied general equilibrium modelling. But this seldom satisfies natural scientists as being a reasonable approach. The reason is that most ecological models tend to be highly disaggregated. While this makes them analytically intractable, it improves their ability to simulate the behaviour of the modelled system as parameter values vary. The highly aggregated models developed to describe economy-environment systems necessarily lose the detail that makes them useful for this purpose.

This said, the behaviour of most terrestrial systems appears to be dominated by a few key structuring species and processes (Holling et al. 1995). This offers at least one place to start in developing an alternative approach to the sectoral aggregation of joint economy-environment models. Ecosystems are thought to comprise hierarchies, each level of which involves a different temporal and spatial scale. Small fast-moving systems are embedded in and constrained by large slow-moving systems (Wiens 1989; Levin 1992). The dynamics of each level of the structure can be summarised by the key processes, and are predictable so long they remain within the bounds imposed by higher levels in the hierarchy (Allen and Starr 1982; Norton 1990). While the interaction between scales is still not very well understood (Levin 1992), and while it is possible for 'catastrophic' change in large slow-moving systems to be triggered by change in small fast-moving systems (Rosser 1990; Rosser et al. 1995), this provides a natural way of simplifying models of economy-environment systems.

More particularly, such systems can be modelled at a hierarchical level that reduces their dimensions to manageable proportions. A similar approach has independently been suggested by economists concerned with the aggregation of the activities of firms and households in macroeconomic models. Aocki (1996), for example, proposes an aggregation of agents at a common ultrametric distance from others (analogous to the aggregation of organisms into species on the basis of their phylogenetic distance from others).

If the evolution of the system is modelled as a Markov process, aggregation along these lines reduces the set of alternative states of the system. If, in addition, the transition probability matrix is decomposable there may be even greater scope for simplification. Decomposability of the transition matrix implies that not every state can be reached from all others. That is, there may be few relevant alternatives to the current state. Moreover, the most likely alternatives may differ in only a few respects to the current state. Since the evolution of economy-environment systems is not typically modelled as a Markov process in the literature – still less as a process characterised by decomposability of the probability transition matrix – there are few examples of the approach. The state and transition models developed by ecologists address what is essentially a Markov problem but without using the Markov techniques (Noy-Meir and Walker 1986; see also Starfield 1990; Starfield et al. 1993).

A second methodological problem is how to measure changes in state given (a) imperfections in market measures of the scarcity of environmental resources and (b) the lack of physical measures of relevant changes in environmental variables. Clearly, one of the tasks in applying the approach is to specify the relevant characteristics of each state, and the change in those characteristics induced by a transition to some other state. If preferences over states reflect the yield or productivity of each state, for example, the relevant characteristics of alternative states will include the productivity of the system in those states. One recent approach to the estimation of loss of resilience in semi-arid rangelands identifies a change in the state of semi-arid rangelands as equivalent to a change in the maximum potential carrying capacity of the range, and models it as a process of ‘technological change’ (Perrings and Stern 1997). Specifically, it models the evolution of the agroecosystem as a non-stationary stochastic trend. The approach provides estimates of both the speed of return to equilibrium, and the threshold effects that occur when the system loses the capacity to absorb shocks of a given magnitude. More generally, the characteristics of distinct states will depend on the decision-maker’s object function.

4.2. DIVERSITY AND RESILIENCE

What factors support the resilience of economy-environment systems in particular states? Whether the problem is to sustain the system in a desirable state or to avoid it being locked-into an undesirable state, it is important to understand these factors. Reducing the probability of transition into undesirable states or increasing the probability of transition into desirable states both imply management of the factors underpinning the resilience of the system. The probability of transition from one state to another depends on the capacity of the system to continue to function in the face of stress and shocks. There are many factors contributing to this, including institutions, property rights, the completeness and effectiveness of markets. All are important, but one factor is worth flagging as a key area for research just because the link with system resilience is not well understood, and even where it is understood is often ignored. It is the diversity of natural assets.

Within ecology, the link between the diversity of species and the resilience of ecological systems is still debated. One view holds that more complex systems (e.g. tropical moist forests or coral reefs) are less resilient because of their high level of ‘connectance’ – the degree to which individual processes are interdependent. In highly ‘connected’ systems loss of one species may imply loss of others (May 1972). Against this, it is argued that while resilience is not necessarily an increasing function of the number of species, the resilience of ecosystems does depend upon the range of species capable of supporting the critical structuring processes of those systems under different environmental conditions. Some individual species and some sets of species have greater ecological value under the current state of nature than others, but this does not imply that all other species are redundant (in excess supply) and hence of no value. The importance of the mix or diversity of species for the resilience of ecosystems lies in the fact that species which are passengers under one set of environmental conditions may have a key role to play under other environmental conditions (Holling 1986, 1992; Perrings et al. 1995). Whether the loss of some species affect critical processes depends on the number of alternative species that can ‘take over’ a particular function when an ecosystem is perturbed (Schindler 1990).

In managed ecosystems ‘environmental conditions’ refers to both natural and economic conditions. A change in agricultural prices, for example, can increase the stress on agroecosystems just as much as a change in rainfall or temperature. Hence the resilience of such systems depends on the species supporting key structuring processes over the range of both economic and natural environmental conditions. In agroecosystems this includes the diversity of crops, livestock, pests and pathogens, the soil micro-organisms that support nutrient cycles and so on. The existence of particular pests and pathogens, for example, can either preclude cultivation of certain crops or maintenance of certain livestock – it can lock the system into a particular state. Conversely, the existence of a diverse set of crops or livestock can enable the system to function effectively over a wide range of natural and economic conditions (Heywood 1995).

Conservation of the appropriate level of biodiversity is a necessary condition for the sustainability of any managed system. Nevertheless, a good deal of biodiversity research is still focused on areas characterised by high levels of endemism – the so-called biodiversity hotspots. The scientific research agenda implied by a focus on resilience is different: (a) to establish the role of species in supporting key processes in managed ecological systems over the relevant range of natural and economic conditions; and (b) to estimate the social opportunity cost of species and processes in such systems, and to identify the institutional conditions, the regulatory framework, and the structure of incentives required to assure their conservation.

4.3. DENSITY DEPENDENCE AND FIELD EFFECTS

The second area for research concerns the phenomena known as density dependence (ecology) or field effects (economics). Their impact on transition probabilities are ambiguous, but extremely important. Most population growth functions in biology assume density dependence – the fact that the rate of growth of the stock depends on its size. The Lotka-Volterra models of population growth are classic examples. Similarly, predator prey or epidemiological models generally assume that the impact of predation or infection is a function of the density of the prey or the host (Clark 1990). Nor is density dependence restricted to population growth. Models of ‘stock’ pollution make very similar assumptions (Pethig 1994). The notion of maximum carrying or assimilative capacity is merely the point at which density dependent growth or assimilation falls to zero. The maximum carrying or assimilative capacity in Lotka-Volterra models is a stable equilibrium. In real economy-environment systems, however, it is widely recognised that exceeding the carrying or assimilative capacity of the environment increases the probability of a system ‘collapse’ or transition to a state characterised by lower levels of productivity (Arrow et al. 1995).

A related idea in economics (drawn from physics) is the notion of field effects. Field effects exist if an individual’s decision depends on the proportion of the total population making the same decision. One example is the sensitivity of one consumer’s demand for particular products to the strength of other consumers’ demand for the same products – the importance of being ‘fashionable’. Another is the sensitivity of an individual’s beliefs or expectations to the proportion of the population sharing those same beliefs or expectations. ‘Speculative bubbles’ or ‘bandwagons’ are instances of field effects on expectations. There are many other examples in economics (Aoki 1995, 1996).

The importance of both density dependence and field effects is that they affect the transition rates between states. Aoki (1996) conjectures that the level of uncertainty beyond some threshold is an important aspect of field effects on expectations. He compares such effects to the phase transitions that occur in physical systems when temperatures, pressures or other key variables cross threshold values. It is also analogous to the reorganisation of ecological systems that occurs when critical variables cross threshold values. Field effects cause a concentration of activities, expectations or beliefs that may lock the system into a particular technology or set of preferences. At one level this makes the system more stable in the sense that there is less variation in behaviour. But it also reduces the capacity of that system to absorb shocks.

This is analogous to the point made by Holling (1986) that as terrestrial ecosystems approach the climax state (carrying capacity) they become more ‘brittle’. The system becomes more not less sensitive to exogenous shocks – it becomes what he decribes as ‘an accident waiting to happen’. It is possible to think about the accumulation of produced capital in much the same way. Consider an economy in which a high proportion of assets lie in flood- or erosion-prone coastal zones. Growth of that stock of assets induces increasing investment in flood and coastal protection which in turn encourages development in increasingly sensitive locations. The net effect is that the resilience of the system (its capacity to recover from major storms) falls at the same time as its capacity to withstand minor storm damage rises.[1]

Just as density dependence is due to the interdependence of the growth dynamics of distinct populations, field effects are due to the interdependence of people’s preferences. A very similar phenomenon can be seen in the choice of technology. Such effects influence the future evolution of the system. By concentrating activities in particular states, they weight the transition probabilities from that state. Recent work on reference-dependent preferences captures one very important aspect of this. Preferences are argued to evolve with the income or endowments of individuals. That is, preferences are reformulated or updated on the basis of changes in income and endowments (Tversky and Kahneman 1991; Bateman et al. 1997; Munro and Sugden 1997). Interdependence of preferences also involves updating, but the reference is not so much an individual’s own income or endowments as the preferences of others.

Field effects represent a particular form of density-dependence. Whether expectations, beliefs or demand move in a particular direction depends on some threshold level of acceptance by the community. If that threshold level is exceeded, the proportion of the population accepting the same expectations or beliefs, or demanding the same commodities, rises rapidly. Technological lock-in and social customs are both examples of field effects that tend to retard change. Indeed, customs that are codified into law or reinforced by institutions can prevent societies from responding to small shocks. Many other field effects are much more volatile, and have the effect of accelerating change. Because a high proportion of the population moves to a particular state, the evolution of the system as a whole becomes more sensitive to the transition probabilities from that state. If the accepted state is unstable, as fashions, speculative bubbles or bandwagons may very well be, then the probability of transition to some other state will tend to increase.

Although a good deal of research has considered the environmental effects of institutional rigidities, in particular economies, there is still comparatively little work on field effects. This is partly because few studies have focused on the evolution of economy-environment systems. But it is also because of the persistence of standard assumptions that preferences, technology and environmental conditions are both exogenous and constant. A start has been made in relaxing

---

[1] Thanks are due to Kerry Turner for this example.

such assumptions when dealing with technology, but there is clearly a very long way to go.

5. Concluding Remarks

Has the integration of economics and ecology revealed any emergent properties? I believe that the answer is yes, and that these concern the way that we think about the long-run dynamics of economic systems. The concept of resilience provides a different perspective on economic dynamics than that normally adopted by economists, and a different set of insights into the way in which economic interactions with the environment drives change in the joint system. Instead of focusing on the system equilibria and the properties of the system at equilibrium it focuses on the basins of attraction around those equilibria, and the susceptibility of the joint system to change at different points in the basin. Indeed, one element in the path-dependence of the joint system is precisely that its sensitivity to shocks varies as it converges on the equilibrium state.

Consider the concept of sustainability. Levin et al. (1998) argue that resilience offers a helpful way of thinking about the evolution of social systems partly because it provides a means of analysing, measuring and implementing the sustainability of such systems. This is largely because resilience switches attention away from long-run equilibria, and towards the system's capacity to respond to short-run shocks and stresses in a constructive and creative way. Economists have generally tended to equate sustainability with both equilibrium and the steady state (cf Baldwin 1995). Evaluation of the sustainability of extraction or investment paths tends to be the same as evaluation of the properties of the system at long-run equilibrium, usually in a deterministic framework. Levin et al. (1998) suggest that sustainability is more an issue in stochastic than deterministic systems, and that it is best measured by system resilience whether at or away from equilibrium. In an evolutionary system this makes the notion both more policy relevant and more testable. To be sure, it is just as difficult to devise appropriate experiments in economics as it is in ecology, but the methods of adaptive management devised to test (and manage) the resilience of complex path-dependent ecosystems (Walters 1997) apply a fortiori to economic systems (Anderson et al. 1988; Arthur 1992).

This paper has suggested that further work on the resilience of joint economy-environment systems might use a Markov approach. This is partly because the approach focuses on the transition probabilities between states in a way that captures the essential features of the concept of resilience sensu Holling – that it is a measure of the sensitivity of the system in a given state to exogenous stress and shock. But it is also partly because the approach allows us to think about the transition probabilities as targets of policy. Institutional or property rights reform enables the economy to respond to changing environmental conditions. That is, it influences the transition probabilities between states. Economic development and environmental change are both stochastic evolutionary processes. Analysis, measurement and management of those processes requires an appropriate set of concepts and tools. The concepts and tools developed by ecologists to deal with the evolution of multiple equilibrium ecosystems have the potential to change fundamentally the way we approach the economics of change.

References

Allen, T. F. H. and T. B. Starr (1982), *Hierarchy: Perspectives for Ecological Complexity*. Chicago: University of Chicago Press.

Amir, S. (1994), ‘The Role of Thermodynamics in the Study of Economic and Ecological Systems’, *Ecological Economics* **10**, 125–142.

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

Aoki, M. (1995), ‘Economic Fluctuations with Interactive Agents: Dynamic and Stochastic Externalities’, *Japanese Economic Review* **462**, 148–165.

Aoki, M. (1996), *New Approaches to Macroeconomic Modeling*. Cambridge: Cambridge University Press.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Jansson, S. Levin, K.-G. Maler, C. Perrings and D. Pimentel (1995), ‘Economic Growth, Carrying Capacity, and the Environment’, *Science* **268**, 520–521.

Arthur, B. (1992), *On Learning and Adaptation in the Economy*. Stanford. Food Research Institute, Stanford University.

Ayres, R. U. and A. V. Kneese (1969), ‘Production, Consumption and Externalities’, *American Economic Review* **59**, 282–297.

Ayres, R. U. (1994), *Information, Entropy and Progress: A New Evolutionary Paradigm*. New York: American Institute of Physics.

Baldwin, R. (1995), ‘Does Sustainability Require Growth?’, in I. Goldin and L. A. Winters, eds., *The Economics of Sustainable Development*. Cambridge: Cambridge University Press, pp. 51–77.

Barnett, W. A., G. Gandolfo and C. Hillinger, eds. (1996), *Dynamic Disequilibrium Modelling*. Cambridge: Cambridge University Press.

Batabayal, A. A. (1997a), *On Some Aspects of Resilience and the Conservation of Species*. Department of Economics, University of Utah, mimeo.

Batabayal, A. A. (1997b), *An Ecological Economic Perspective on Resilience and the Conservation of Species*. Department of Economics, University of Utah, mimeo.

Bateman, I., A. Munro, B. Rhodes, C. Starmer and R. Sugden (1997), ‘A Test of the Theory of Reference-Dependent Preferences’, *Quarterly Journal of Economics*, in press.

Benhabib, J., ed. (1992), *Cycles and Chaos in Economic Equilibrium*. Princeton: Princeton University Press.

Brock, W. A. and A. G. Malliaris (1989). *Differential Equations, Stability and Chaos in Dynamic Economics*. Amsterdam: North Holland.

Clark, C. W. (1990), *Mathematical Bioeconomics*. New York: Wiley.

Common, M. and C. Perrings (1992), ‘Towards an Ecological Economics of Sustainability’, *Ecological Economics* **6**, 7–34.

Conway, G. R. and E. B. Barbier (1988), ‘After the Green Revolution: Sustainable and Equitable Agricultural Development’, *Futures*, 651–669.

Conway, G. R. (1993), ‘Sustainable Agriculture: The Trade-Offs with Productivity, Stability and Equitability’, in E. B. Barbier, ed., *Economics and Ecology: New Frontiers and Sustainable Development*. London: Chapman and Hall.

Dasgupta, P. (1993), *An Inquiry into Wellbeing and Poverty*. Oxford: Blackwell.

Gersick, C. J. G. (1991), ‘Revolutionary Change Theories: A Multilevel Exploration of the Punctuated Equilibrium Paradigm’, *Academy of Management Review* **16**, 10–36.

Hanna, S., C. Folke and K.-G. Mäler (1997), *Rights to Nature: Ecological, Economic, Cultural, and Political Principles of Institutions for the Environment*. Washington DC: Island Press.

Heywood, V., ed. (1995), *Global Biodiversity Assessment*. Cambridge: Cambridge University Press.

Holling, C. S. (1973), ‘Resilience and Stability of Ecological Systems’, *Annual Review of Ecological Systems* **4**, 1–24.

Holling, C. S. (1986), ‘The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change’, in W. C. Clark and R. E. Munn, eds., *Sustainable Development of the Biosphere*. Cambridge: Cambridge University Press.

Holling, C. S. (1992), ‘Cross-Scale Morphology Geometry and Dynamics of Ecosystems’, *Ecological Monographs* **62**, 447–502.

Holling, C. S., D. W. Schindler, B. W. Walker and J. Roughgarden (1995), ‘Biodiversity in the Functioning of Ecosystems’, in C. Perrings, K. G. Mäler, C. Folke, C. S. Holling and B. O. Janssen, eds., *Biodiversity Loss: Ecological and Economic Issues*. Cambridge: Cambridge University Press.

Kingman, J. F. C. (1978), ‘Random Partitions in Population Genetics’, *Proceedings of the Royal Society of London Ser. A* **361**, 1–20.

Levin, S. A. (1992), ‘The Problem of Pattern and Scale in Ecology’, *Ecology* **73**(6), 1943–1967.

Levin, S. A., S. Barrett, S. Aniyar, W. Baumol, C. Bliss, B. Bolin, P. Dasgupta, P. Ehrlich, C. Folfe, I.-M. Gren, C. S. Holling, A.-M. Jansson, B.-O. Jansson, D. Martin, K.-G. Mäler, C. Perrings and E. Sheshinsky (1998), ‘Resilience in Natural and Socioeconomic Systems’, *Environment and Development Economics* **3**(2), in press.

Liebenstein, H. (1957), *Economic Backwardness and Economic Growth*. New York: John Wiley.

Lipnowski, I. F. (1976), ‘An Input-Output Analysis of Environmental Preservation’, *Journal of Environmental Economics and Management* **3**, 205–214.

Ludwig, D., B. H. Walker and C. S. Holling (1997), ‘Sustainability, Stability and Resilience’, *Conservation Ecology* **1**(1), 7.

Mäler, K-G. (1974), *Environmental Economics: A Theoretical Enquiry*. Oxford: Blackwell.

May, R. (1972), ‘Will a Large Complex System be Stable’, *Nature* **238**, 413–414.

May, R. (1977), ‘Thresholds and Breakpoints in Ecosystems with a Multiplicity of Stable States’, *Nature* **269**, 471–477.

Meadows, D. H., D. L. Meadows and J. Randers (1992), *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future*. Post Mills, Vermont: Chelsea Green Publishing Co.

Munro, A. and R. Sugden (1997), *A Theory of General Equilibrium with Reference-Dependent Preferences*. School of Economics and Social Studies, University of East Anglia, mimeo.

Myrdal, G. (1957), *Economic Theory and Underdeveloped Regions*. London: Duckworth.

Norton, B. G. (1990), ‘Context and Hierarchy in Aldo Leopold’s Theory of Environmental Management’, *Ecological Economics* **2**, 119–127.

Noy-Meir, I. and B. H. Walker (1986), ‘Stability and Resilience in Rangelands’, in P. J. Joss, P. W. Lynch and O. B. Williams, eds., *Rangelands a Resource Under Siege*. Proceedings of the Second International Rangelands Congress. International Rangelands Congress, Adelaide, pp. 21–25.

Perrings, C. (1987), *Economy and Environment: A Theoretical Essay on the Interdependence of Economic and Environmental Systems*. Cambridge: Cambridge University Press.

Perrings C. A. and B. H. Walker (1995), ‘Biodiversity Loss and the Economics of Discontinuous Change in Semi-Arid Rangelands’, in C. A. Perrings, K.-G. Mäler, C. Folke, C. S. Holling and B.-O. Jansson, eds., *Biodiversity Loss: Ecological and Economic Issues*. Cambridge: Cambridge University Press.

Perrings, C. (1995), ‘Ecological Resilience in the Sustainability of Economic Development’, *Economie Appliquée* **48**(2), 121–142.

Perrings, C., K.-G. Mäler, C. Folke, C. S. Holling and B.-O. Jansson, eds. (1994), *Biodiversity Conservation: Problems and Policies*. Dordrecht: Kluwer Academic Press.

Perrings, C., K.-G. Mäler, C. Folke, C. S. Holling and B.-O. Jansson, eds. (1995), *Biological Diversity: Economic and Ecological Issues*. Cambridge: Cambridge University Press.

Perrings, C. and S. Dalmazzone (1997), *Resilience and Stability in Ecological Economics Systems*. Discussion Papers in Environmental Economics and Environmental Management 9701, University of York.

Perrings, C. and D. Stern (1997), *Modelling the Resilience of Agroecosystems: Rangeland Degradation in Botswana*. Discussion Papers in Environmental Economics and Environmental Management 9704, University of York.

Pethig, R. (1994), *Valuing the Environment: Methodological and Measurement Issues*. Dordrecht: Kluwer Academic Publishers.

Pimm, S. L. (1984), 'The Complexity and Stability of Ecosystems', *Nature* **307**, 321–326.

Reed, W. J. (1979), 'Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models', *Journal of Environmental Economics and Management* **6**, 350–363.

Reed, W. J. (1988), 'Optimal Harvesting of a Fishery Subject to Random Catastrophic Collapse', *IMA Journal of Mathematics Applied in Medicine and Biology* **5**, 215–235.

Reed, W. J. (1989), 'Optimal Investment in the Protection of a Vulnerable Biological Resource', *Natural Resource Modelling* **3**(4), 463–480.

Rosser, J. B. (1991), *From Catastrophe to Chaos, A General Theory of Economic Discontinuities.* Dordrecht: Kluwer Academic Publishers.

Rosser, J. B., C. Folke, F. Günther, H. Isömaki, C. Perrings and T. Puu (1994), 'Discontinuous Change in Multilevel Hierarchical Systems', *Systems Research* **11**(3), 77–94.

Ruth, M. (1993), *Integrating Economics, Ecology and Thermodynamics*. Dordrecht: Kluwer Academic Publishers.

Schindler, D. W. (1990), 'Natural and Anthropogenically Imposed Limitations to Biotic Richness in Freshwaters', in G. Woodwell, ed., *The Earth in Transition: Patterns and Processes of Biotic Impoverishment*. Cambridge: Cambridge University Press, pp. 425–462.

Starfield, A. M. (1990), 'Qualitative Rule-Based Modelling', *Bioscience* **40**, 601–604.

Starfield, A. M., D. H. M. Cumming and M. S. Quadling (1993), 'Frame-Based Dynamic Ecosystem Models', *AI Applications* **7**(2–3), 1–13.

Tinch, R. (1998), *Risk and resilience in Resource Management*. Environment Department, University of York, mimeo.

Tversky, A. and D. Kahneman (1991), 'Loss Aversion in Riskless Choice: A Reference-Dependent Model', *Quarterly Journal of Economics* **106**, 1039–1061.

Van den Bergh, J. C. J. M. (1991), *Dynamic Models for Sustainable Development*. Tinbergen Institute Research Series 21. Amsterdam: Thesis Publishers.

Victor, P. A. (1972), *Pollution, Economy and Environment*. London: George Allen and Unwin.

Walker, B. H. (1988), 'Autecology, Synecology, Climate and Livestock as Agents of Rangelands Dynamics', *Australian Range Journal* **10**, 69–75.

Walker, B. H. and I. Noy-Meir (1982), 'Aspects of the Stability and Resilience of Savanna Ecosystems', in B. J. Huntley and B. H. Walker, eds., *Ecology of Tropical Savannas*. Berlin: Springer, pp. 577–590.

Walters, C. (1997), 'Challenges for Adaptive Management of Riparian and Coastal Ecosystems', *Conservation Ecology* **1**(2), 1.

Watterson, G. A. and H. A. Guess (1977), 'Is the Most Frequent Allele the Oldest?' *Theoretical Population Biology* **ii**, 141–160.

Westoby, M., B. Walker and I. Noy-Meir (1989), 'Opportunistic Management for Rangelands not at Equilibrium', *Journal of Range Management* **42**, 266–274.

Wiens, J. A. (1989), 'Spatial Scaling in Ecology', *Functional Ecology* **3**, 385–397.