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ECOLOGICAL RESILIENCE IN THE SUSTAINABILITY OF ECONOMIC DEVELOPMENT

by

Charles Perrings

Heslington, York, YO1 5DD
Telephone: 44 (0)904 432 999
Telefax: 44 (0)904 432 998

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Charles Perrings
Department of Environmental Economics and Environmental Management
University of York
Heslington
York
YO1 5DD

Abstract

Recent work on the ecology and economics of biodiversity loss has indicated that the main economic costs of species deletion to the present generation are likely to be found in the loss of resilience of ecosystems providing basic life support services. This paper considers how ecological resilience relates to the sustainability of economic development. It is argued that maintenance of ecosystem stability is necessary to satisfy the basic criterion of sustainable economic development - that the value of the capital stock should be non-declining. Since ecological resilience is a measure of ecosystem stability, loss of resilience implies reduced ecosystem stability. Loss of resilience does not necessarily mean that economic development will be unsustainable, but it increases the probability that this will be so. It also increases the burden on environmental management.

1 Sustainable development: economics and ecology

There is a general consensus in the economic literature that economic development may be said to be sustainable only if the value of the aggregate capital stock is non-declining. This is implicit in the Hicks/Lindahl concept of income: the maximum amount which may be spent on consumption in one period without reducing real consumption expenditure in future periods. It admits the possibility that development based on the depletion of natural capital (environmental resources) may be sustainable, so long as (a) there exist substitutes for such natural capital, and (b) investment in those substitutes at least compensates for the loss of the natural capital [Solow, 1974, 1986; Hartwick, 1977, 1978; Dixit, Hammond and Hoel, 1980]. The sense of this investment rule, the Solow-Hartwick rule, is very widely recognised, and the debate about the sustainability of economic development has instead focussed on the degree of substitutability between produced and natural capital [Daly and Cobb, 1989; Daly, 1991; Turner, 1988, 1992]. It is now generally agreed that there are limits to the possibilities for substitution between these two types of capital, though these limits are not very well defined, even for existing technologies. Nevertheless, at the level of principle, it is accepted that sustainable economic development implies the conservation of at least some environmental resources [Pearce, 1987; Pearce and Turner, 1990].

Which environmental resources should be conserved is another matter. There are limits to the possibilities for substitution not just between produced and natural capital, but between different types of natural capital. The historical tendency to assume that environmental resources which are substitutes in terms of human consumption are substitutes in terms of all their ecological functions may have been discarded, but it remains the case that the complementarity between species in many ecosystems is still very imperfectly understood. There is certainly some potential for substitution between species in the performance of ecosystem functions. Indeed, the resilience of ecological functions in terrestrial systems is an increasing function of the number of substitute species that can perform those functions [Schindler, 1990; Holling 1992], but the resilience of ecological functions in many coastal and estuarine systems is not. It depends on the ability of a small number of species to operate over a wide range of conditions [Costanza et al, 1994]. The ecological problem is to determine the minimum combination of resources that will enable ecosystems to function under the expected range of environmental and economic conditions. This is the same as determining the stability of ecosystem functions with respect to perturbation of the relevant environmental and economic parameters.

Conservation of irreplaceable environmental resources implies conservation of the capacity of ecological systems to provide those resources. In different ecosystems, this will have different consequences for the system components. But in all cases, it implies the protection of the stability of the system concerned with respect to potential perturbations. The point has been made elsewhere that economic sustainability and ecological resilience are 'disjoint', in the sense that maximising the sustainable income from the exploitation of produced and natural capital will not simultaneously maximise ecological resilience. Indeed, it has been remarked that most economy-environment systems characterised by a high level of ecological resilience have not satisfied even the minimum conditions for intertemporal economic efficiency [Common and Perrings, 1992]. The question I wish to explore here is related to this. How are ecological resilience, stability and the sustainability of income connected at different levels of development, and what does this signify for the economics and management of environmental resources?

The paper introduces a way of thinking about the problem that brings to centre stage the question of where an economic-ecological system is with respect to the boundaries of local stability. The question is partly motivated by differences that have emerged between ecologists on the nature and properties of ecosystem resilience. These differences are discussed in detail below, but what makes them interesting to the problem of economic development is that they turn on the distinction between systems close to and far from equilibrium. There is a long history of conceptualising economic development as a process characterised by evolution away from a stable equilibrium state [see, for example, Lewis, 1954, Liebenstein, 1957; Myrdal, 1957]. Those ecologists who argue that the relevant concept of resilience is that applicable to systems far from equilibrium, also argue that this is precisely because economic development has driven most major ecological systems away from equilibrium. The linkages between these two lines of inquiry turn out to be highly relevant to the problem of sustainable development.

To address this question the paper looks at three sets of issues. The first of these, considered in section 2, concerns the general problem of economy-environment system dynamics. This section identifies the main characteristics of jointly determined economic-ecological dynamical systems, and discusses the the stability of the equilibria of such systems. A third section addresses the joint dynamics of produced and natural capital more formally, and stability and capital growth may be related. Section 4 focuses on the concept of resilience and its relation to the stability of the jointly determined system. A final section offers a discussion of the implications this has for the theme of this conference: sustainable economic development.

2 Economy-environment system dynamics

There is a sense in which the field of ecological economics has been driven by the perception that as the economic system grows relative to its environment, the dynamics of the jointly determined system are increasingly non-linear and discontinuous. It is this perception, more than any other, that has induced economists interested in the behaviour of the joint system to move beyond the static Walrasian approach. The flow of ideas, it should be said, has been very much from biology to economics. The mathematics of non-linear dynamical systems were applied in biology well before they were applied in economics. In the 1970s, May [1976, 1977] had observed the potential for complex behaviour in Lotka-Volterra predator-prey models. At the same time, examples of mathematical and Riemann-Hugonoit catastrophe were recorded in spruce budworm outbreaks in boreal forests [Jones, 1975]. More recently, it has been shown that change in either the structure of environmental constraints or the biotic potential of a system may lead to complete alteration in the state of the system [O'Neil, Johnson and King, 1989]. Small adaptive moves may trigger 'avalanches' of adaptive responses amongst competitors [Kauffman and Johnsen, 1991]. In economics, applications of the theory of non-linear dynamical systems were late in appearing, but there is now a burgeoning interest in this area [see for example Anderson et al, 1988; Arthur, 1992; Brock and Malliaris, 1989; Puu, 1989; Rosser, 1990; Benhabib, 1992].

There are two characteristics of jointly determined economy-environment system dynamics that are important from the perspective of this paper. The first is that the dynamics of the joint system reflect the structure of the connections between each sub-system. Any change in conditions generates two interlinked sets of 'general equilibrium' effects: a set of ecological effects that work themselves out in the evolution of the ecological systems concerned, and a set of economic effects that work themselves out in the evolution of the economic system. The cross effects depend on the connectnedness of the two systems, to borrow a term from ecology. The more highly connected ecological and economic systems are, the more change in one implies change in the other: the more they 'coevolve' [Norgaard, 1984]. It is, however, important to appreciate that there is both a spatial and a temporal structure to the connections between the economy and its environment. It is, for example, possible for components of the joint system to be entirely unconnected viewed over one temporal or spatial horizon, but highly connected viewed over some other temporal or spatial horizon [Perrings, 1987]. Moreover, the dynamics of the system vary between spatial scales [Holling et al, 1994]. It turns out that the structure of the connections between the economy and its environment has a major effect on both the timing and the impact of economic change on the environment.

The second important characteristic of the dynamics of the joint system is that there exist multiple locally stable equilibria (or basins of attraction), separated by unstable equilibria (or unstable manifolds) that are defined in terms of the level or density of the state variables or components of the system. Moreover, as economic and ecological systems pass from one basin to another, so the central characteristics of the system may undergo a profound change.

The main implications of these characteristics is that the system dynamics may be neither continuous nor gradual. In ecosystems, the slow accumulation of biological capital tends to be broken by sudden shocks, and if this moves the system into another basin of attraction, the result can be irreversible or only slowly reversible. In economic systems, a very similar pattern is observed. If business cycles are the limit cycles of stable (but not asymptotically stable) equilibria; the revolutions, wars, coups and other 'events' that restructure economies are the unstable manifolds separating such equilibria. It follows that the joint system responds very differently to perturbation depending both on where either the economy and the environment are relative to the system equilibria, and the characteristics of those equilibria. So, if a system is in the neigbourhood of a particular unstable equilibrium, or threshold, minor perturbation of its state variables may have 'catastrophic' consequences for its structure and organisation. This has been observed in the management of dryland systems, for example [Walker and Noy -Meir, 1982; Walker, 1986; Westoby et al, 1989]. It has also been observed in unmanaged systems. Conversely, if a system is at or close to a locally stable equilibrium, major perturbation of the same variables may have very little effect on its structure or organisation.

In ecology, this characteristic has induced an approach to the analysis of system dynamics that concentrates on where an ecosystem is relative to the unstable manifolds or thresholds of the general system. This approach requires identification not of the existence and stability of equilibria, but the capacity of a system - whether at or away from equilibrium - to absorb shocks without losing stability. This capacity is captured in the concept of ecosystem resilience. Holling [1973, 1986, 1992] has described the dynamics of ecosystems in terms of the sequential interaction between four system functions. These are exploitation - processes responsible for rapid colonization of disturbed ecosystems; conservation - the accumulation of energy and biomass; creative destruction - abrupt change caused by external disturbance which releases energy and matter; and reorganization - mobilisation of matter for the next exploitive phase.

Reorganisation may be associated with a new cycle involving the same structure, or a switch to a completely different structure. If reorganisation does involve a new structure, this implies that the system has crossed some threshold or unstable equilibrium, and is converging on a different locally stable equilbrium. Threshhold values exist, for example, for the diversity of species in an ecosystem. There may be a range of population sizes for the different species in an ecosystem over which the system remains stable, but if any one population in an ecosystem falls below its critical threshhold level the self-organization of the ecosystem as a whole may be radically and irreversibly altered [Pielou, 1975]. Threshhold 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 [Schaeffer et al, 1988]. The resilience of an ecosystem is related to its ability to maintain its self-organization without undergoing the 'catastrophic' and irreversible change involved in crossing such thresholds.

Holling et al [1994] point out that resilience of a system is defined in two rather different ways in the ecological literature. One definition is concerned with resistance to pertubation of and speed of return to a locally stable equilibrium [Pimm 1984; O'Neill *et al.* 1986]. The second is concerned with the magnitude of disturbance that can be absorbed before the system flips from one basin of attraction to another [Holling 1973]. As we shall see later, the two definitions are in fact very closely related, both being testable in terms of the properties of the Liapunov functions (if such exists) associated with each locally stable equilibrium. In both cases, resilience refers to the capacity of a system to retain its organisational structure following perturbation of some state variable from a given value [Common and Perrings, 1992]. The resilience of a system is therefore conditional on the initial values of the system variables, and is relative to perturbation of one or more of those variables. It is the second definition that is explored in this paper. If the effect of economic development is to increase the pressure on ecological systems, then the management problem is that associated with systems closer to thresholds of instability than to stable equilibria. We shall come back to this in section 4.

3 Sustainability and stability in an economy-environment system

My purpose in this section is to make the relation between development, sustainability, and stability as transparent as possible. Each of these three terms will be given precise meaning momentarily, but it is worth underlining that since they are all the subject of a large multidisciplinary literature it is not possible to capture the nuances of interpretation attaching to each. With respect to 'development', almost the only thing on which everyone agrees is that it is more than the rate of change of GDP or GDP per capita. Pearce and Turner [1990] refer to improvement in a vector of attributes including real income per capita, health and nutritional status, educational achievement, access to resources, the distribution of income and basic 'freedoms' - for which it is simply impossible to find a single index. Sustainability, has been given a bewildering variety of definitions [for some of which see Pearce, Markandya and Barbier, 1989]. On the face of it, stability should be the easiest to handle because there exist precise mathematical definitions, but it has been observed that the term 'ecological stability' has been used to mean the stability of so many different ecological characteristics that it is in fact very difficult to know what it implies [Kay, 1991]. Given the very specific purpose of this paper, it seems reasonable to avoid the confusion surrounding these terms by working with precise definitions.

To proceed, let us denote the vector of assets or capital available to the system at time t by $k = k(t)$. The ith component of this vector, $k_i \geq 0$, denotes the non-negative value of the ith asset or type of capital at time t. To ease discussion, let us identify two components only, which may be called produced capital, $k_p = k_p(t)$, and natural capital, $k_n = k_n(t)$. Hence:

$$k = (k_p, k_n).$$

Without yet specifying the relation between these two types of capital, we may define:

> *Development* : An economy having a stock of produced capital, k_p, will be said to be more developed than an economy having a stock of produced capital, k_p', if $k_p > k_p'$. The process of development is the process of expanding the stock of produced capital, and the level of development is measured by the value of that stock: i.e., the level of development of an economy having a stock of produced capital, k_p, will be said to be approximated by k_p.

'Development' is assumed to be a function of produced capital alone. If the value of produced capital is strictly greater in one economy than another, then the first will be said to be the more developed irrespective of the value of natural capital in each economy. Similarly, if the value of produced capital in an economy is increasing over time, that economy will be said to be developing. Note that population size is not explicitly taken into account here (since I am thinking about the relation between produced and natural capital in a single closed economy), but all definitions might be set in per capita terms without loss of generality.

The main operational difference between these two types of capital, is that the generation of one is controlled, while the generation of the other is not. One might want to object to the exclusion of k_n from the definition of development. The point is that k_n defines the natural endowment of the economy at a particular moment. An economy with very large natural endowments may have considerable potential for development, but it cannot be said to be developing unless that natural endowment is in the process of being converted into produced capital. Moreover, it cannot be said to be developing sustainably unless the conversion of natural capital into produced capital yields an aggregate of both natural and produced capital that is non-declining. That is, we define sustainability in the following terms:

> *Sustainability* : An economy at any level of development, k_p, will be said to be sustainable if $\dot{k}_p + \dot{k}_n \geq 0$ for all t.

This is the Hicks/Lindahl requirement for sustainable income: that the value of the aggregate capital stock is non-declining over time. It does not imply that $\dot{\mathbf{k}} \geq 0$, since it allows individual components of **k** to be declining. However, it is immediate that a sufficient condition for the sustainability of development is that $\dot{k}_p = \dot{k}_n = 0$.
Given our previous definition of development, we now have:

> *Sustainable development*: The development of an economy may be said to be sustainable if $\dot{k}_p \geq 0$ and $\dot{k}_p + \dot{k}_n \geq 0$.

While definition of sustainable development does not restrict the sign of $\dot{k}_n$, since k_n cannot decline indefinitely it follows that in the limit, $\lim_{t\to\infty} \dot{k}_n(t) \geq 0$. Natural capital may be reduced in the development process over some finite time, but in the long run natural capital must be non-declining. This is consistent both with the Hicks-Lindahl concept of income and with the arguments of Turner, Pearce and Daly.

To approach the stability of the joint system let us first identify the equations of motion for produced and natural capital: $\dot{\mathbf{k}} = f(\mathbf{k})$. Specifically, let these be described by the differential equations:

$$\dot{k}_p = f_p(k_p, k_n) \quad f_p: K \to K$$
$$\dot{k}_n = f_n(k_n, k_p) \quad f_n: K \to K$$

in which K, the state space of the system, is an open set, and f_p and f_n are the growth functions of produced and natural capital respectively mapping. In general terms, if $\mathbf{k}^* = (k_p^*, k_n^*)$ is an equilibrium of these equations, it is stable if all solutions close to $\mathbf{k}^*$ remain close, and is asymptotically stable if all solutions close to $\mathbf{k}^*$ tend to $\mathbf{k}^*$. If $\mathbf{k}^*$ is asymptotically stable it is said to be a sink.[1] More particularly:

> *Stability*: An equilibrium of the system, $\mathbf{k}^*$, will be said to be stable if there is a neigbourhood of $\mathbf{k}^*$, K', such that every solution curve, $\mathbf{k}(t)$, with its origin, $\mathbf{k}(0)$, in K' tends to $\mathbf{k}^*$. The union of all solution curves tending towards $\mathbf{k}^*$ as t tends to infinity is its basin, denoted $B(\mathbf{k}^*)$.

Stability in this sense may be characterised in terms of the properties of Liapunov function, $g: K' \to K$. Specifically If $g: K' \to K$ is a continuous function defined on a neigbourhood K' of $\mathbf{k}^*$, differentiable on K' - $\mathbf{k}^*$, then $\mathbf{k}^*$ is stable if

$$g(\mathbf{k}^*) = 0$$

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[1] In this case, the eigenvalues of the derivative $Df(\mathbf{k}^*)$ where $\mathbf{k}^* = (k_p^*, k_n^*)$ will all have negative real parts.

$$g(k) > 0 \qquad k \neq k^*$$

$$\dot{k} \leq 0 \qquad k \in K' - k^*$$

and is asymptotically stable if

$$\dot{k} < 0 \quad k \in K' - k^*$$

$\dot{k} \leq 0$ admits the possibility that k(t) will converge to a limit cycle, whereas $\dot{k} < 0$ ensures that it will converge to k*. If a Liapunov function with these properties exists, the system characteristics it describes will be stable with respect to perturbation of the components of k within the neighbourhood, K'. In ecological-economic systems a natural candidate for a Liapunov function is the self-organisation or structure of those systems, in the sense that one would expect that if the component parts of such systems were at equilbrium or on a limit cycle, there would be no tendency for the self-organisation of the system to change.

For our purposes, the most important property of the stability or asymptotic stability of the equilibria of jointly determined economy-environment systems is that it determines the time path of natural and produced capital only within the basins of those equilibria. Put another way, such equilibria are 'local' only. If perturbation of either produced or natural capital dislodges the system from the basin of any given equilibrium or attractor, that equilibrium will lose influence over the evolution of the system. The Liapunov function obtained for any given equilibrium may be used to estimate the extent of its basin, and so the limits within which the state variables may be perturbed before the system switches to some other basin. It is this property of Liapunov functions that we will find useful in characterising system resilience in section 4. First, however, let me illustrate the relation between development, sustainability and stability in the jointly determined system.

To take things further it is necessary to impose some structure on the system dynamics. It is, however, possible to go quite a long way with minimal structure. I shall suppose the following:

(i) There exists some maximum stock of natural capital fixed by the biotic potential of the system and the finite supply of abiotic resources. That is, there exists a maximum value of k_n, denoted $\bar{k}_n$, such that $\dot{k}_n > 0$ only if $k_n < \bar{k}_n$.
(ii) Natural capital is essential to the creation of produced capital. That is, $k_p > 0$ only if $0 < k_n < \bar{k}_n$, and $f_p(k_p, k_n) = 0$ if $k_n = 0$. It is not possible to substitute produced capital for natural capital completely.
(iii) For any given technology there exists a well defined range of values for k_n and k_p within which accumulation of produced capital does not imply depletion of natural capital. Outside of this range, $\dot{k}_p > 0 \Rightarrow \dot{k}_n < 0$.

These very general assumptions about the relation between produced and natural capital in economy environment systems enable us to say a good deal about the system dynamics. Consider the phase diagrams described in figures 1 - 3. In all three the graphs of the functions $\dot{k}_p = 0$ and $\dot{k}_n = 0$ divide the values of k_p and k_n at produced and natural capital is growing or being depleted. Since a sufficient condition for the sustainability of the system is that $\dot{k}_p = \dot{k}_n = 0$, it follows that equilibria defined by the intersection of the $\dot{k}_p = 0$ and $\dot{k}_n = 0$ curves are sustainable. Each of the three figures reflects a different assumption about the development potential of the economic system. In all cases, the accumulation of capital is positive only if the stock of natural capital is positive. Figure 1 represents the case where the capacity of the economic system (to convert natural to produced capital) is low relative to the capacity of the ecological system (to convert produced to natural capital). Figure 2 represents the opposite case: where the capacity of the economic system (to convert natural to produced capital) is high relative to the capacity of the ecological system (to convert produced to natural capital). Figure 3 represents a median case.

Consider the system equilibria in each of these three cases. In Figures 1 and 2 there are only two equilibria: (0,0) and $(0,\bar{k}_n)$. In Figure 1 there is an asyptotically stable equilibrium at $(0,\bar{k}_n)$, and an unstable equilibrium at (0,0). That is, as $t \to \infty$, $k_n \to \bar{k}_n$ and $k_p \to 0$ for most trajectories of **k**. The development of this economy is manifestly not sustainable. Since the economic system is not large enough to secure its place in the steady state, it is 'swamped' by the ecological system. In Figure 2, on the other hand, both $(0,\bar{k}_n)$ and (0,0) are unstable equilibria. Since the economic system is too large relative to the carrying capacity of the environment, the stock of natural capital will tend to be fully depleted. Since the economic system cannot exist without natural capital, it also collapses. The development of this economy is also not sustainable.

Now take the 'codependent' system described in Figure 3. Aside from the cases representing, respectively, the collapse of the general system and the collapse of the economic system, (0,0) and the $(0,\bar{k}_n)$, there exist equilibria, $\mathbf{k}^*$ and $\mathbf{k}'$, at which both k_p and k_n are strictly positive. Of these, $\mathbf{k}'$ represents a higher level of development than $\mathbf{k}^*$, in that $k_p' > k_p^*$: the level of produced capital at $\mathbf{k}'$ exceeds that at $\mathbf{k}^*$. Both equilibria are sustainable, in that $\dot{k}_p + \dot{k}_n = 0$. However, only one, $\mathbf{k}^*$ is stable (a node). The other, $\mathbf{k}'$, is unstable (a saddlepoint). At the stable equilibrium the level of produced capital is 'low', and the level of natural capital is 'high'. At the unstable equilibrium, the position is the opposite. It follows that from a development perspective the unstable equilibrium will be preferred to the stable equilibrium.

4 Resilience and stability

With this background we are now in a position to consider the relationship between resilience and stability. The concept of resilience derives from the ecological literature. It is, however, relevant to the analysis of any complex dynamical system. The observed properties of ecological systems that have prompted a re-evaluation of resilience by systems ecologists include two important features. First, change in most terrestrial systems is not continuous and gradual, but is punctuated by the sudden reorganisation of the stock resources. This often occurs after long periods of apparent stability, and often after some 'exogenous' perturbation of the system. Second, ecosystems do not have single equilibria. Indeed, different equilibria define functionally different states of a system and characterise its structure and diversity. Third, the dynamics and stability of systems vary non-linearly with their scale.

The existence of multiple equilibria in natural systems invites reconsideration of their stability. In ecology this has centred on the discussion of system resilience: a concept related to but not the same as stability. Recall that resilience has been defined in two rather different ways in the ecological literature. The more 'traditional' of these two definitions focuses on the properties of the system near some stable or asymptotically stable equilibrium state (in the neigbourhood of a stable focus or node). By this definition resilience is a measure of the system's resistance to perturbation and speed of return to equilibrium [Pimm, 1984; O'Neill et al, 1986]. The second definition focusses on the properties of the system further away from any stable or aymptotically stable state (in the neighbourhood of the unstable manifolds that separate the basins of different equilibria) [Holling 1973]. By this definition, resilience is a measure of the perturbation that can be absorbed before the system crosses an unstable manifold, and converges on another equilibrium state.

The second definition of resilience implicitly accepts that the multiple equilibria of ecological systems are locally stable only, and is primarily concerned to establish a measure of the limits of the local stability of each equilibrium. There is a sense in the ecological literature on this concept of resilience that as the scale or biomass of a system increases, so it becomes more susceptible to perturbation. The 'brittleness' of the system in the conservation phase may be interpreted as evidence that it is close to the limits of local stability [Holling 1986]. This notion will become relevant when we discuss the implications of resilience for economic development, but for now it is helpful to focus on the link between resilience and the limits of the local stability of system equilibria.

As has already been observed, the Liapunov function, if its exists, can be used both to characterise the system dynamics in the neighbourhood of an equilibrium state, and to ascertain the extent of the basin of that state. Hence we can use these properties of the function to explore the significance of system resilience. For simplicity, consider the case of an asymptotically stable equilibrium. The argument is first stated formally, and then intuitively.

A system at state $\mathbf{k}(t)$ in the basin of an equilibrium $\mathbf{k}^*$ may be said to be resilient (in the Holling sense) with respect to some perturbation of the state variables, denoted $\Delta(t)$, if the perturbed trajectory is convergent on $\mathbf{k}^*$: i.e. if $\lim_{t\to\infty}|(\mathbf{k}_i(t) + \Delta(t)) - \mathbf{k}^*| = 0$. More particularly, let $\mathbf{k}_i(t)$ be a solution lying in direction i from $\mathbf{k}^*$ in a neighbourhood $K' \subset K$ of $\mathbf{k}^*$. If $g{:}K' \to K$ is a Liapunov function such that $g(\mathbf{k}^*) = 0$, $g(\mathbf{k}_i(t)) > 0$, and $\dot{\mathbf{k}}_i(t) < 0$, then $\mathbf{k}^*$ is asymptotically stable, i.e. $\lim_{t\to\infty}|\mathbf{k}_i(t) - \mathbf{k}^*| = 0$, and $\mathbf{k}_i(t)$. Now let $K'' \subset K$ be the closed bounded subset of K that contains all such points, $\mathbf{k}_i(t)$, in the basin of $\mathbf{k}^*$, $B(\mathbf{k}^*)$. Let α_i define the distance in direction-i such that $|\mathbf{k}_i(t) - \mathbf{k}^*| < \alpha_i$ for all i and for all t. The α_i-neighbourhood of $\mathbf{k}^*$ is defined by

$$B_{\alpha i}(\mathbf{k}^*) = \{\mathbf{k}_i(t) \subset K|\ |\mathbf{k}_i(t) - \mathbf{k}^*| < \alpha_i\ \ \forall\ i, \text{ and } \lim_{t\to\infty}|\mathbf{k}_i(t) - \mathbf{k}^*| = 0\}$$

K'' is simply the set of all points within the α_i-neighbourhood of $\mathbf{k}^*$: i.e. $K'' = \{\mathbf{k}(t) \in B_{\alpha i}(\mathbf{k}^*)\}$.

The system at point $\mathbf{k}_i$ will be resilient with respect to perturbation in a direction that intersects the boundary of $B_{\alpha i}(\mathbf{k}^*)$ at α_j, denoted $\Delta_j(t)$, if $|\mathbf{k}_i(t) + \Delta_j(t)| < \alpha_j$. Suppose, to the contrary, that $|\mathbf{k}_i(t) + \Delta_j(t)| \geq \alpha_j$, implying that the state variables of the system lie outside the α_i-neighbourhood of $\mathbf{k}^*$. Since the α_i-neighbourhood of $\mathbf{k}^*$ includes all solutions starting in K" for which $\lim_{t\to\infty}|\mathbf{k}_i(t) - \mathbf{k}^*| = 0$, then $\mathbf{k}_i(t) + \Delta_j(t) \notin$ K", and will not, in the limit converge on $\mathbf{k}^*$. This provides the following natural measure of system resilience.

> *Resilience* . The resilience of a system at some point in the basin of a locally stable equilibrium, $\mathbf{k}^*$, with respect to change in any of the state variables of that system, is the maximum perturbation that can be sustained in those variables without causing the system to leave the α_i-neighbourhood of $\mathbf{k}^*$.

The importance of this measure is that it is defined both for an initial state, whether or not that is an equilibrium state, and for a specific direction of change. If the system is at $\mathbf{k}^*$, then the measure of its resilience in any given direction, i, is simply α_i. If the system is at $\mathbf{k}_i(t)$, $\mathbf{k}_i(t) - \mathbf{k}^* \neq 0$, it is the distance from $\mathbf{k}_i(t)$ along the direction of perturbation to the nearest point on the boundary of $B_{\alpha i}(\mathbf{k}^*)$ in that direction. It follows that the closer the system is to the limits of local stability - that is, to the boundary of $B_{\alpha i}(\mathbf{k}^*)$ - the less resilient it is to perturbation in the direction of the boundary.

This is shown in Figure 4. It is assumed that the system is at $\mathbf{k}_i(t)$, and that this is far from the stable node defined by $\mathbf{k}^*$, but lies within $B_{\alpha i}(\mathbf{k}^*)$. In the absence of perturbation, $\lim_{t\to\infty}|\mathbf{k}_i(t) - \mathbf{k}^*| = 0$. Consider the resilience of the system with respect to perturbation in two directions, i and j. The measure of system resilience in direction-i is simply $\alpha_i - \mathbf{k}_i(t)$. The measure of system resilience in direction-j is $\alpha_j - \mathbf{k}_i(t)$. If perturbation of the system in direction-j results in a fall in the value of this measure then the system may be said to have lost resilience with respect to change in that direction. If it results in a negative measure, the system may be said to have 'flipped' from one basin to another. If this is the case, the change may not be reversible, and the system will thereafter be identified with a new equilibrium.

There is a widespread perception that the state of physical systems may be associated with the equilibria to which those systems tend, simply because the equilibria are taken to approximate the long term behaviour of the systems. This would imply that the steady-state measure of resilience for any state in $B_{\alpha i}(\mathbf{k}^*)$ was always α_i. However, wherever a system is far from equilibrium, this will be a highly misleading index of its ability to withstand shocks without losing self organisation. This is what Holling's concept of resilience is designed to address.

4 Discussion

Let us now return to the link between resilience and sustainable economic development, the first point to make is that in an interdependent economy-environment system resilience is a property of the joint system. That is, the system equilibria are a product of the joint dynamics of both natural and produced capital, and the stability of those equilibria as well as the resilience of all possible states are characteristics of the system as a whole. Since resilience is defined with respect to perturbation in some well defined direction, one may discuss the resilience of the joint system with respect to change in the value of natural capital, but this is not the same thing as the ecological resilience of that system. Nevertheless, it is useful to introduce discussion of the implications of this approach by focussing, once again, on the ecological literature on managed systems.

Holling [1986] has described most historical attempts to manage ecosystems as 'weak experiments testing a general hypothesis of stability/resilience', by which he means that management has been directed at minimizing the variance of some ecological variable. However, this has generally led to qualitative changes in the wider system, and has often caused that system to lose resilience. Frequently, the source of the problem has been the reduction in the diversity of communities and species within the system as a result of economic specialisation on a single species, and management policies designed to achieve constant yields [Holling et al, 1994].

In terms of the development process, the phenomenon he describes represents the conversion of natural to produced capital. For purposes of this paper, development is taken to be equivalent to the accumulation of produced capital. Since it is assumed that the growth path for produced capital is optimal by some welfare criterion, this is not overly restrictive. It does imply that economies will be considered to be more developed the greater the value of produced capital (or some measure derived from the value of produced capital, such as national income). But it does not imply that the implicit social welfare function assigns zero weight to the value of natural capital.

The distinction between produced and natural capital in the joint system is, to a very large extent, the distinction between the controlled and the uncontrolled parts of the system. Since the accumulation of produced capital is a choice variable (via investment decisions) the ratio of produced to natural capital may also be chosen, at least in so far as the behaviour of the uncontrolled ecological part of the general system is predictable. The problem identified by the ecologists lies in the fact that the dynamics of the ecological system are predictable only if the system retains its resilience: i.e. only if it remains within basins whose topology is reasonably well understood. If ecological systems lose resilience, they also lose their predictability since the general topology of the basins of any new equilibria cannot be inferred in the absence of observations. The dynamics of new states of nature have to be seen before they can be understood.

The implications of the very limited structure imposed in section 3 on the equations of motion for produced and natural capital include the following. There does exist a locally stable equilibrium for systems with these general features, $\mathbf{k}'$, and that equilibrium satisfies the requirement for sustainable development. That is $\dot{k}_p \geq 0$ and $\dot{k}_p + \dot{k}_n \geq 0$. It is also resilient with respect to perturbation up to α_i for all i. However, it is characterised by low levels of produced capital and high levels of natural capital. This may be said to correspond to the quasi-stable equilibria long observed by development economists in subsistence or close-to-subsistence economies [see, for example, Liebenstein, 1957; Myrdal, 1957; Lewis, 1954; Fei and Ranis, 1964]. The development process, through the conversion of natural capital and the accumulation of produced capital, moves the system away from such stable equilibria towards the boundaries of the surrounding basin. The highest sustainable level of development is at the equilibrium k". This too satisfies the requirements $\dot{k}_p \geq 0$ and $\dot{k}_p + \dot{k}_n \geq 0$, but it is unstable (the system has no resilience). States close to the separatrix converging on k" from below may exhibit some resilience in all directions, but the closer it gets, the lower the resilience of the system with respect to perturbation towards the separatrix. That is, the smaller the shock needed to dislodge the system onto a path along which both natural and produced capital decline in value.

To the extent that this offers a reasonable approximation of the trade-offs involved in the expansion of produced relative to natural capital, it raises a number of interesting questions about the management of environmental resources in the development process and about the sustainability of that process. The welfare gains secured through productivity improvements due to the conversion of natural capital involve a cost, and that cost is the loss of resilience in the general system. It is measured by the resources committed to protecting an unstable equilibrium and insuring against the losses caused by movement away from that equilibrium. In agriculture, for example, it is measured by the value of the increasing quantities of herbicides, pesticides, fertilisers, irrigation and other inputs needed to maintain output at or above current levels in increasingly impoverished environments. It includes the cost of relief where output fails, the cost of relocation where soils or water resources have been irreversibly damaged, and the cost of rehabilitation where damage may be partly reversible. It includes the cost of insurance against crop damage by pest or disease, along with the cost of monitoring the state of the crops, and the cost of developing new 'solutions' to the problem of novel pests and diseases. It includes, in other words, the cost of the heightened environmental management required by the choice of activity levels at or close to the threshold of resilience of the agricultural system.

The problem for policy lies in the fact that the standard indicators - market prices - do not signal whether a system is approaching the thresholds of resilience. Market prices are not adequate observers of the natural part of the system. There are various reasons for this including the well worn facts that many environmental resources are in the nature of public goods, that government policies exacerbate price distortions, and that the structure of property rights authorises users to ignore the cost of their actions. They also include the facts that the poverty of resource users encourages excessively myopic behaviour, while ethnic, national, cultural and sectarian rivalries encourage excessively parochial behaviour. But at the root of the problem is a rather less well-worn fact that many the key ecological processes are neither observable nor controllable, and that the basin boundaries are not well defined. No allocation of property rights, no reform of government pricing policies, no estimate of the willingness to pay for public goods can change this. In these circumstances, the best that can be achieved through environmental management is the stabilisation of the system at sustainable levels of activity, and this is the same as the protection of system resilience [Perrings, 1991]. Nor is it possible to evaluate the costs and benefits of stabilisation. Since the location of the unstable manifolds that constitute the thresholds of resilience and the system dynamics beyond those thresholds are generally not known, there is a very large element of fundamental uncertainty about the cost of approaching the thresholds of resilience. The distribution of outcomes beyond the thresholds cannot be inferred from the history of the system, and certainly cannot be inferred from the current set of prices.

From the perspective of a strategy for sustainable development, the two properties of the system that are important are (i) its resilience along the development path on which it is now set, and (ii) its controllability. If the structural conditions for the controllability of the ecological components of the general system are not satisfied, and if the system is imperfectly observed, then whenever it is close to the thresholds of resilience there exists the potential for unanticipated and 'catastrophic' effects at points far removed from the original source of change. These are the 'risks' of development within a finite system. A strategy for sustainable development within a finite system is essentially a strategy for containing and insuring against these risks.

Figure 1: Ecological system dominant

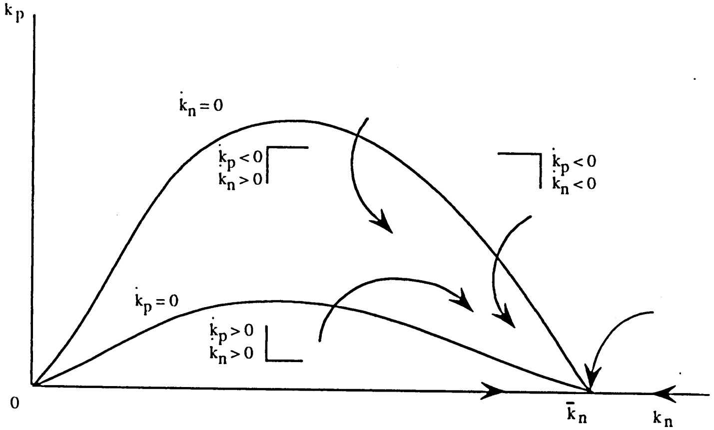


Figure 2: Economic system dominant

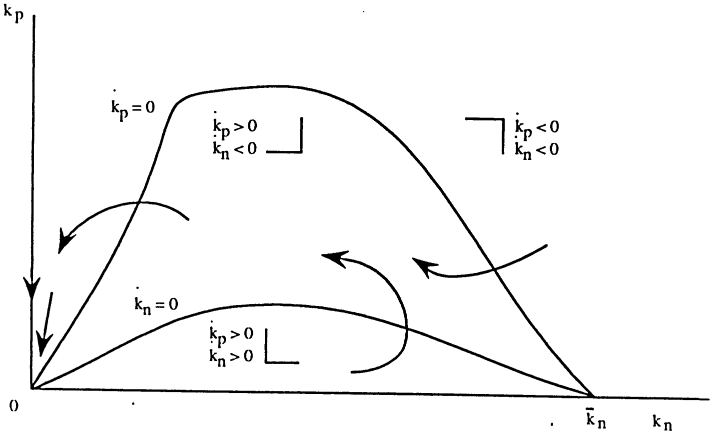


Figure 3: Co-dependent ecological and economic systems

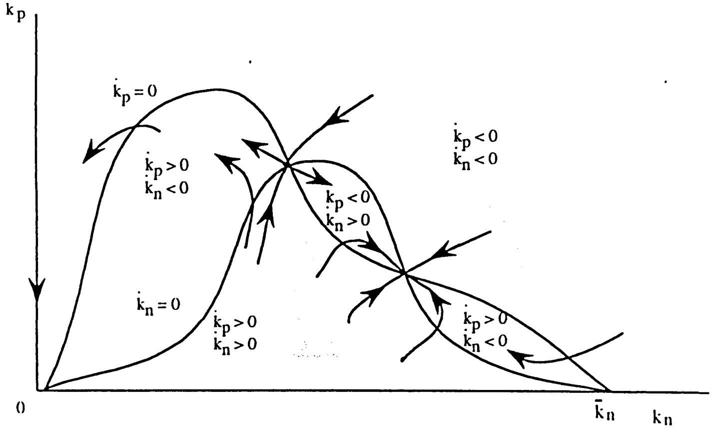
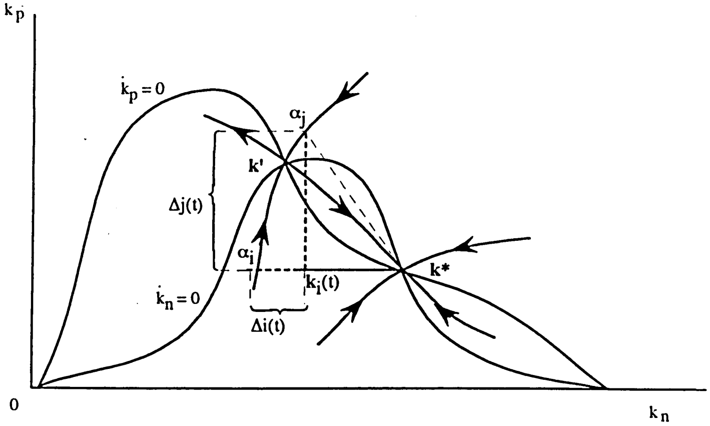


Figure 4: Measures of system resilience



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