Irreversibility in Economics

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Abstract

Three independent literatures have contributed to the understanding of irreversibility in economics. The first focuses on the future opportunities forgone by investments with irreversible consequences. The second considers irreversibility (and hysteresis) in the context of the dynamics of systems characterized by multiple equilibria. The third, with roots in complex systems theory, focuses on entrainment—a phenomenon recognized in economics as lock-in or lock-out. This paper disentangles the different strands in the economic analysis of irreversibility in order to identify the core ideas involved and to connect them to arguments in the parallel literatures on sustainability and uncertainty.

1. INTRODUCTION

The treatment of irreversibility in economics has a number of different origins. Indeed, the concept of irreversibility involved in the analysis of entrainment, the dynamics of multiple equilibrium systems, and the forgone opportunities to learn about system dynamics are all different. In this paper, we seek to disentangle the different elements in the analysis of irreversibility in order to identify the common threads in the arguments. At the same time, we seek to clarify the connections between the economic treatment of irreversibility and parallel discussions in other disciplines. Many of the points at issue in the analysis of irreversibility have been addressed in the literature on the stability properties of particular equilibria in ecological systems characterized by multistable states. These same points are also central to the emerging science of sustainability. We show how the treatment of irreversibility in economics relates to the sustainable management of coupled social-ecological systems and, in particular, to the management of the uncertainty associated with evolutionary change in such systems.

Three important but independent literatures have dominated the treatment of irreversibility in economic systems. The literature most familiar to economists stems from seminal papers by Arrow & Fisher (1974) and Henry (1974). These papers established that the economic significance of what Arrow and Fisher called the technical irreversibility of investment decisions lies in the forgone future opportunities—the options lost by the investment. This literature is less concerned with the factors behind technical irreversibility than with understanding its consequences for current decisions.

The second literature has its roots not in economics, but in ecology and focuses on the dynamics of systems that may exist in multiple stable states (Holling 1973).This literature considers irreversibility in the context of the stability properties of different states. Transition to an absorbing state is irreversible. Transition to a persistent state may be slowly reversible. More generally, the degree to which transition to some state is irreversible is implicitly measured by the resilience of the system in that state. The approach has been applied to a number of decision problems involving the economic exploitation of such systems (Carpenter et al. 1999, Mäler et al. 2003).

The third literature, with roots in complex systems theory, starts from the path dependence of many biophysical and social processes. Perhaps the clearest statement of the points at issue in this literature is provided by Ayres (1991), who argues that the phenomena recognized in economics as "lock-in" or "lock-out" are special cases of a more general property of complex dynamical systems—that their future is entrained by their past. Feedback effects serve to entrench or exclude some technologies or social processes, at least for a time. Agents in economic systems have more options than in other systems, given that they are forward looking and form expectations about the future, can form consortiums, and take other actions to "unlock" past choices [see, for example, the debate on the lock-in effects of increasing returns and/or network externalities (Liebowitz & Margolis 1994, Spulber 2008)].

In what follows, we identify the common strands in these literatures in an effort to characterize irreversibility and draw out the implications it has for understanding economic decision making in evolving systems. We then explore the main results from the different literatures and connect these to the emerging field of sustainability science. Because the focus of that field is the capacity of coupled economic and environmental systems to persist over time in states that are deemed desirable (Kates et al. 2001), the reversibility or irreversibility of social and biophysical processes is of central interest. In particular, it has implications for the level of uncertainty in that system, the degree of its predictability, and the time over which predictability extends.

2. CONCEPTS OF IRREVERSIBILITY

Arrow & Fisher (1974) defined an irreversible action as one that is infinitely costly to reverse, but then they immediately noted that the decision problem relating to irreversibility derives from the fact that a wide array of actions that fail this test are nevertheless sufficiently costly to reverse that this should be taken into account in the initial decision. This brings a much larger class of problems into the frame. Henry (1974) was more qualified still. He defined a decision as irreversible "if it significantly reduces for a long time the variety of choices that would be possible in the future." The phrase "for a long time" is, again, strictly relative. A long time in one decision problem may be a short time in another. So the qualification implies that we should be concerned over actions that are costly to reverse within a relevant time frame.

Many of the early papers on irreversibility focused on conservation issues that raise the question of the time frame in an acute way. The decision problem in these cases involves the choice between the preservation of some environmental asset in one form or its conversion to another. Hotelling (1931) established the conditions in which it was optimal to convert natural assets into alternative forms of capital, but, as Clark (1973) and Fisher et al. (1972) noted, the outcome depends heavily on the future value of the resource to be converted and the reversibility of the action involved within the decision maker's time horizon. In practice, most contributors to this literature have been concerned with actions that are difficult to reverse over relatively short periods. Arrow & Fisher (1974) argued, for example, that the choice between preserving a virgin redwood forest for wilderness recreation and clear-cut logging the same forest may be technically reversible, but given the length of time required for regeneration and a positive rate of time preference, it is effectively irreversible. The analysis by Fisher, Krutilla, and Cicchetti (Fisher et al. 1972) of the "irreversible" consequences of dam construction in wilderness areas falls into the same category.

The economic problem of irreversibility—for both Arrow & Fisher (1974) and Henry (1974)—was that it compromised the optimality of decisions made under uncertainty. Henry identified what he termed an "irreversibility effect": a risk-neutral decision maker deciding whether or not to undertake an irreversible investment on the basis of the expected value of the outcomes would "systematically and unduly, favor irreversible decisions" (Henry 1974, p. 1007). Arrow & Fisher (1974) were concerned with the social optimality of that bias, and they found that it would generally be optimal not to undertake an investment if there was some probability that it would be desirable to reverse it in the future. The driver in this case is the additional information to be had from waiting. Inclusion of (*a*) the option value in preservation and (*b*) the quasi-option value of the information acquired by waiting reduces the net benefits from development. More particularly, the possibility of acquiring better information about future benefits or costs regarding current actions should reduce levels of irreversible commitment relative to the case where there is no possibility of getting better information (Ulph & Ulph 1997). In this approach, therefore, the value of the options lost through undertaking an irreversible action is equivalent to the expected value of the information that could have been acquired had the action not been undertaken. In particular (rather extreme) conditions, the quasi-option value of irreversible actions taken under uncertainty is the expected value of perfect information (Conrad 2000).

For the literature that built on these foundations, irreversibility came to be equated with the sunk costs of investment, and the focus switched to the value of information either lost (Brennan & Schwartz 1985; Dixit 1992; Pindyck 1991, 2000) or acquired (Roberts & Weitzman 1981) through investment. In other words, irreversibility was considered a product of the fact that capital is not perfectly malleable. Because factories and equipment built for one purpose cannot be instantaneously switched to another purpose (Arrow 1986), this introduces constraints on the disinvestment of capital assets used to exploit resource stocks (Clark et al. 1979, Boyce 1995). Indeed, it simply reflects the difference between short- and long-run supply elasticities in an industry.

Below, we return to the implications of this approach. Note, however, that none of this literature questions the standard assumptions about the convexity of production or preference sets. Indeed, Arrow & Fisher (1974) made a point of asserting that the only effect of irreversibility was to raise the cost of investment. Irreversibility, in the sense in which they use the term, has no implications for the continuity or smoothness of the underlying production functions.

The second literature that bears on this problem focuses on the properties of the biophysical systems involved and starts from the assumption that those systems are (*a*) complex and (*b*) nonlinear. They can exist in many possible states, and the transition between states can be both abrupt and irreversible. The literature stems from a seminal paper by Holling (1973), which explored the capacity of ecosystems in one of many possible stable states to absorb perturbations without flipping to some alternate state. Holling referred to this capacity as the resilience of the system in that state (Kinzig et al. 2006, Walker et al. 2004, 2006). Resilience, in this sense, is determined by the size and depth of the basin of attraction corresponding to that state and is measured by the probability that the system will transition to some alternate state, given the existing disturbance regime (Common & Perrings 1992, Perrings 1998).

The measure of irreversibility that falls out of this literature is the probability that a system which transitions from one state to another will return to the original state in some finite time. If that probability is zero, then the transition is strictly irreversible. If the probability is one, it is strictly reversible. More generally, the degree of irreversibility of any transition will reflect the structure of the probability transition matrix as well as the limiting transition probabilities (the elements of that matrix). If the matrix decomposes to include both transient and absorbing states, then any transition into an absorbing state is irreversible (Perrings 1998). Note that, because the transition probabilities can be identified for any time horizon, the return transition probability is a measure of irreversibility over that horizon.

The relevance of Holling's work for understanding the dynamics of economic systems has since been extensively explored, both with respect to the general properties of nonlinear dynamical systems (Common & Perrings 1992, Brock & Starrett 2003, Brock et al. 2002, Dasgupta & Maler 2004) and the properties of specific systems (Carpenter et al. 1999, Mäler et al. 2003, Rondeau 2001, Horan & Wolf 2005, Perrings & Walker 2005). The specifics of this analysis are discussed below, but the concept of irreversibility it contains is the same as that implicit in Holling (1973), i.e., it is a property of the resilience of states to which the system transitions. The degree of resilience in this work tends to be measured through the return time to the original state, and it is frequently approximated by the extent of hysteretic effects.

The last concepts of irreversibility we discuss derive from another property of complex systems: that of path dependence or entrainment. This is closely related to the concept of irreversibility that falls out of the stability of particular equilibria. Field effects that concentrate activities, expectations, or beliefs, for example, may lock economic systems into particular technologies or preferences (Arthur 1989, Aoki 1996), though the ex-post evidence for lock-in in some frequently cited cases has been disputed (Liebowitz & Margolis 1994, Spulber 2008). Whereas some common examples of field effects, such as speculative bubbles, may be relatively short-lived, many examples of technological lock-in and even more examples of social customs are more long lasting. Social customs can be thought of as field effects that tend to retard change and, where codified into law or reinforced by institutions, can significantly reduce the probability of transition into alternate states. Holling (1973, 1986) argued that the vulnerability of ecological systems to perturbations depends on where they are in a cycle of states that corresponds, loosely, to the birth, growth, maturity, death, and rebirth of the system. Ecoystems that are in a mature, highly connected, brittle state (what he called the K phase) are less resilient than ecosystems in a newly emerging, rapidly growing state (what he called the r phase). But transition into a particular sequence may imply that the system is locked into that sequence until it becomes more vulnerable to exogenous shocks.

The concept of irreversibility that falls out of this is relatively weak, but it is more than just a notion that time is a one-way street. Wherever the dynamics of a system are entrained, the scope for reversing the process and the costs of doing so are diminished. Ayres (1991) characterized the phenomenon as hyperselection in the neighborhood of alternative attractors: A transient stage of evolution enables a system to "choose" between disjoint "attractors," which are thus equated with "lock-in." This reflects Arthur's (1989) perception that selection of one among a number of paths may be accidental, and yet that path may be evolutionarily dominant for a considerable period of time. Holling (1986, 1992) and Gunderson & Holling (2002) addressed the same phenomenon in terms of system reorganization—or transition between stable states—once its structure has collapsed under external shock or stress.

This has some similarities to sunk-costs effects, in the sense that the nonmalleability of capital does entrain production decisions, but notice that the emphasis in this literature is on the role of investment in shifting the whole system from one basin of attraction to another. Investment in new technologies and the attendant field effects induce the evolution of the system at moments when a number of alternative paths are open (Arthur 1989). They drive macro, system-level, change. The sunk-cost effect experienced by firms influences their investment decisions, but it is not sufficient to explain irreversibility as a macrophenomenon. To be sure, the benefits of delaying investment may lie in information on field effects—on which standard or technology is likely to "win", for example—but the evolutionary drivers are the factors that tip the system one way or another during transient states. All investment is associated with sunk costs, but whether or not they matter depends on the uncertainty associated with investment. The option and quasi-option value of particular investment decisions are sensitive to the evolutionary state of the system. In rapidly evolving systems, where investment may induce transition to states for which there are few or no historical precedents, the uncertainty associated with the investment is likely to be very high, and the irreversibility effect identified by Arrow & Fisher (1974) and

Henry (1974) is likely to be pronounced. More than 50 years ago, Shackle (1955) referred to such decisions as "crucial." They are potentially transformative decisions without precedent. They involve fundamental uncertainty, in the sense that there are insufficient historical precedents to identify either the set of possible outcomes associated with the decision or the probabilities attached to each of those outcomes. In other words, they are beyond conventional risk analysis.

Van den Berg & Gowdy (2000), in reviewing the application of evolutionary theories in economics, noted that "evolution can be characterized as disequilibrium and qualitative (structural) change that is irreversible and unpredictable, can be gradual and radical, and is based on microlevel diversity (variation) and selection, as well as macro-level trends and shocks ('large-scale accidents')" (p. 38). Economic models that leave room for evolution—i.e., that admit the diversity among economic agents that allows selection (or sorting) to take place—have tended to adopt an incrementalist Darwinian approach to economic development (Hirshleifer 1985), but the kind of discontinuous change that follows transitions between stability domains is closer to what biologists refer to as punctuated equilibrium (Eldredge & Gould 1972). In punctuated equilibrium, periods of stability are interspersed with periods of rapid change, similar to the processes described by Holling (1973, 1986). In evolutionary terms, this is induced by macroselection processes superimposed on the microevolution that stems from individual selection (Gould & Eldredge 1993). This has also led biologists to distinguish between selection and sorting, in which the causal aspect of individual selection is contrasted with the random events that drive sorting at macroscales. We argue below that if the transition between states is a function of random perturbations in the neighborhood of the thresholds or unstable manifolds of a system that can exist in multiple stable states, then individual actions that move the system closer to a threshold in any particular state will affect the probability of transition between states. Evolution of the system is not independent of the behavior of individual agents. Moreover, as Norgaard (1984) observed, evolutionary pressures in the biophysical system interact with evolutionary pressures in the social system.

So, what are the common threads in the various literatures on irreversibility? Four elements in the concept of irreversibility are general. First, irreversibility is a measure of the difficulty of returning to an initial state within an economically meaningful time frame following some perturbation. In the economic literature, perturbation has generally been interpreted as investment. Yet, even in 1974, Arrow and Fisher cited the impact of carbon emissions on climate change as an example of irreversibility, and most empirical studies have focused on environmental change.

Second, the focus on return time makes it possible to evaluate the "reversibility" of perturbations both within and across stability domains. Indeed, many of the examples of irreversibility cited in the literature are not irreversible in any strict sense but are simply examples of variables that are slow relative to the time horizon of the decision maker. There are, in fact, two measures of resilience in ecological theory: Aside from Holling's measure of the strength of the perturbation a system can absorb without transitioning to a new stability domain, there is a second measure [due to Pimm (1984)] that is the speed of return to equilibrium. Both measures are relevant in this context.

Third, irreversibility is a consequence of entrainment or path dependence. At its simplest, this means that perturbations induce positive feedback effects, at least over the relevant time horizon. The link between this aspect of irreversibility and the stability of equilibria is direct. Irreversible decisions are necessarily destabilizing. They are also a driver of evolutionary change, both within the economic system and within the biophysical systems on which the economy depends.

Fourth, irreversibility poses a meaningful problem only when it alters the decisions that individuals or societies would choose to make. In the economic literature, this has been identified with the scope for reducing the associated uncertainty. That is, there is a quasi-option value to deferring (or accelerating) an investment decision. The seminal work on this is by Dixit & Pindyck (1994).

3. MODELS OF IRREVERSIBILITY

Epstein (1980) completed the basic results on irreversibility and learning introduced by Arrow & Fisher (1974) and Henry (1974). We summarize these using the variant of the Epstein model developed by Ulph & Ulph (1997). They took a decision problem involving two periods: present and future. In the first period, the state of the world and the payoff associated with that state are known. In the second period, there are S possible states of the world, each of which yields an uncertain payoff, $\theta_i, i = 1, \ldots, S$. Uncertainty is reflected in the prior probability of state i occurring given by $p_i > 0, \sum_{i=1}^{S} p_i = 1$. The decision problem involves choice of actions x in period 1 and y in period 2 so as to maximize the expectation of a concave benefit function, $W(x, y, \theta)$.

Let

$$J(x, p; k) := \max_{y \varepsilon Y_{kx}} \{ \sum_{i=1}^{i=S} p_i W(x, y, \theta_i) \}.$$

Here, $Y_{kx} := \{y | y \geq kx\}$, with $k = 0$ if the effects are reversible and $k = 1$ if they are irreversible. Note that irreversibility is taken to mean that a decision variable in the future period is constrained by the choice of a decision variable in the current period. In other words, y is constrained more by x in the irreversible case ($k = 1$) than in the reversible case ($k = 0$). The main focus of Ulph & Ulph (1997) is to locate interpretable sufficient conditions so that if an irreversibility effect applies, (i.e., $k = 1$), then the optimal choice of x will be reduced relative to the case where there is no irreversibility effect (i.e., $k = 0$).

It turns out that whether or not an irreversibility effect applies depends on whether or not the decision maker is able to learn about the system by waiting. Take the polar cases first. If there is no scope for learning, decision makers remain ignorant about the state of the world in the future and face the same decision problem in period 2 that they face in period 1. In this case, action y will be the same irrespective of which state of the world eventuates. If, on the other hand, the decision maker is able to acquire complete information about the states of the world in period 2 before choosing y, then they are able to condition y on the state that actually eventuates. Now suppose that the choice of y is constrained by the choice of x. The polar cases are as follows: y is independent of x, and y is completely determined by x. In the first case, there is no entrainment, and the decision reached in period 1 is completely reversible. In the second case, y is entrained, and the decision taken in period 1 is irreversible. The cases treated by Ulph & Ulph (1997) are defined by Y_{kx}, $k = 0,1$.

The first point to make about this model is that the irreversibility effect is strictly a function of learning. Denoting the polar cases on learning N and L, Ulph & Ulph (1997) noted that sufficient conditions for the irreversibility effect to hold, i.e., for $x^N \geq x^L$, depend only on how uncertainty is resolved over time.

Recalling that $J(x,p;k) := Max_{y \varepsilon Y_{kx}}\{\sum_{i=1}^{S} p_i W(x,y,\theta_i)\}$, Epstein (1980) demonstrated (*a*) that if $J_x(x,p;k)$ is convex in p, then $x^N \leq x^L$ and that if it is concave in p, then $x^N \geq x^L$ and (*b*) that this is independent of whether or not the changes induced by x are irreversible. Here, $J_x(x,p;k)$ denotes the partial derivative of J w.r.t. x. In other words, the sufficient condition for an "irreversibility effect" to apply does not at all depend on irreversibility, but on how information is acquired. It is not surprising in these circumstances that both cases are feasible, depending on whether action now (Roberts & Weitzman 1981) or waiting (Pindyck 1991) yields the better information about future states of nature.

Ulph & Ulph (1997) also noted that all of the early models of the irreversibility effect (Arrow & Fisher 1974, Henry 1974, Freixas & Laffont 1984) assume intertemporal separability in the effect—i.e., no entrainment. To see whether irreversibility in this sense induces an irreversibility effect, they reformulated the problem to address the question of emissions in two periods and their impact on climate change. The payoff function now takes the form $W(x,y,\theta) = W^1(x) + W^2(y-x) - \theta D(y)$, with W^1 and W^2 and strictly increasing and concave and $D(y)$ is strictly increasing and convex. By symmetry with the Epstein (1980) result, they showed that if the partial derivative w.r.t. x of the cost function $C_x(x,\theta,k) = Min_y\Big(\theta D(y) - W^2(y-x)\Big)$ is convex in θ, then $x^N \geq x^L$ and that if it is concave in θ, then $x^N \leq x^L$. As in the Epstein result, this is independent of whether the problem is irreversible and merely reflects the value of information and the way that information is acquired.

For the cost function $C(x,\theta,k) = Min_y\Big(\theta D(y) - W^2(y-x)\Big)$, the irreversibility effect implies that $x^{Nk} \geq x^{Lk}$. The marginal cost of irreversible first-period emissions is strictly greater than the marginal cost of reversible first-period emissions. However, they showed that first-period reversible emissions are at least as great as first-period irreversible emissions both where there is learning and where there is no learning, i.e., $x^{Nk} \geq x^{Lk}, k = 0, 1$.

Defining the expected damage cost associated with first-period decisions with reversible and irreversible effects, and with and without learning, as $C_x(x,\bar{\theta},0)$, $C_x(x,\bar{\theta},1), \sum_{i-1}^{n}\pi_i\bar{C}_x(x,\theta_i,0), \sum_{i-1}^{n}\pi_i\bar{C}_x(x,\theta_i,1)$, Ulph & Ulph (1997) argued (recalling that $0 \leq \theta_1 < \theta_2 < \ldots < \theta_S$)

$$\text{for } x \leq \tilde{x}(\theta_1), C_x(x,\bar{\theta},1) = \sum_{i-1}^{n} p_i\bar{C}_x(x,\theta_i,1), \text{ and} \tag{1}$$

$$\text{for } x \leq \tilde{x}(\bar{\theta}), C_x(x,\bar{\theta},1) \leq \sum_{i-1}^{n} p_i\bar{C}_x(x,\theta_i,1). \tag{2}$$

From Equation 1, if choice of x is such that the irreversibility constraint is binding in the state of the world with lowest damage cost, then it will be binding in all states of the world, and marginal costs with learning and irreversibility are the same as marginal costs with no learning and irreversibility (because choice of second-period emissions is fixed by the irreversibility constraint). From Equation 2, if emissions are irreversible and if the choice of x is such that the irreversibility constraint bites at the expected level of damage costs, then marginal costs with learning must be at least as great as marginal costs with no learning. From this, Ulph & Ulph (1997) offered the following sufficient condition for an irreversibility effect: If $x^{N1} \leq \tilde{x}(\bar{\theta})$, then $x^{N1} \geq x^{L1}$ with the corollary that if $x^{N1} \leq \tilde{x}(\theta_1)$, then $x^{N1} = x^{L1}$. The proposition states that if there is no learning but there is irreversibility, then the irreversibility effect will hold: First-period emissions with learning will be no higher than first-period emissions with no learning. The corollary states that if there is irreversibility (in all states of the world), then the optimal choice of first-period emissions is independent of whether there is learning.

The treatment of the irreversibility of underlying processes in all of these models is rudimentary, because the objective was primarily to uncover the consequences of learning with and without entrainment. Subsequent contributions have explored the significance of different types of learning—whether active or passive (Chavas & Larson 1994, Chavas & Mullarkey 2002)—and have elaborated the quasi-option value in information flows (Hanemann 1989; Fisher & Hanemann 1986, 1990), but they have not qualified the basic insights that flow from Arrow & Fisher (1974) and Henry (1974).

Applications to particular systems have introduced more realism into the underlying dynamics of the system but with limited entrainment of investment. Clark et al. (1979) explored the implications of the nonmalleability of capital in a Schaefer fishery and found that nonmalleability primarily influenced the smoothness with which the long-run equilibrium capital stock is approached. Specifically, the initial development of the fishery generates overcapitalization relative to the long-run optimum, which is followed by contraction of that stock through depreciation until the long-run equilibrium stock is attained. Variants of the same approach have generated different investment paths (e.g., Boyce 1995), but the stickiness of investment has remained an essential part of the story.

The irreversibility of changes in the underlying biophysical system is the subject of a growing literature in economics. Although there is no standard reference for this work, the "shallow-lake" problem has come to be seen as an archetype and has attracted considerable attention (Carpenter et al. 1999, Mäler et al. 2003). We accordingly use that problem to illustrate the principal results. The problem has the convenient properties that the system can exist in one of two states, oligotrophic or eutrophic, and that whether it is one or the other state is a function of a single variable, nutrient loading—which may be a product of a number of different economic activities. Irreversibility (and hysteresis) in the model is the result of a typical "cusp catastrophe" of the sort illustrated in **Figure 1**.

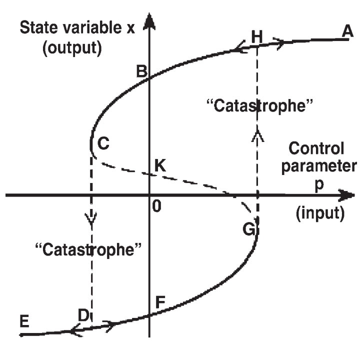

Figure 1

Equilibrium values for the state variable x for different values of the "control" parameter p. Source: Göcke (2002).

In the shallow-lake model, nutrient dynamics are described through a conveniently simple differential equation:

$$\frac{dP}{dt} = \ell - sP + \frac{rP^q}{m^q + P^q},$$

where P is the concentration of phosphorus in the water column, ℓ is the rate of phosphorus loading, s is the rate of phosphorus loss (through sedimentation, outflow, and sequestration in biomass of consumers or benthic plants), r is the maximum rate of recycling of phosphorus from sediments or by consumers, and q determines the shape of the (sigmoidal) curve describing phosphorus fluxes. The concentration at which phosphorus recycling reaches half the maximum rate is m.

Depending on the parameter values, phosphorus loading can lead to changes that are reversible, hysteretic, or irreversible (**Figure 2**). Note that in this case the existence of the two states is known. Uncertainty relates only to the precise value of the parameters that will, in a given set of environmental conditions, induce a transition between the states.

Carpenter et al. (1999) established that the system will be optimally managed close to the threshold between the states—what they call the edge of hysteresis. They noted that the effect of uncertainty about the transition probabilities should, in hysteretic and irreversible lakes, induce a precautionary response—equivalent to an irreversibility effect. That is, uncertainty about the values of P, ℓ, and r that induce a transition from an oligotrophic to a eutrophic state should cause lake users to adopt lower phosphorus loads than would be optimal under complete information. Although the irreversibility effect is not directly addressed in the model, it is easy to see how uncertainty about the value of b is directly equivalent to uncertainty about θ in Ulph & Ulph (1997) and how it would affect the nutrient-loading decision with and without learning.

The shallow-lake model has also served as the focus for a set of dynamic models of learning. Recent work by Dechert et al. (2007) studied optimal Bayesian learning about the parameter b when it is unknown but is known to lie in a finite set $B := \{b_1, \ldots, b_n\}$ of possible values. This problem can become challenging if n is large because the state vector

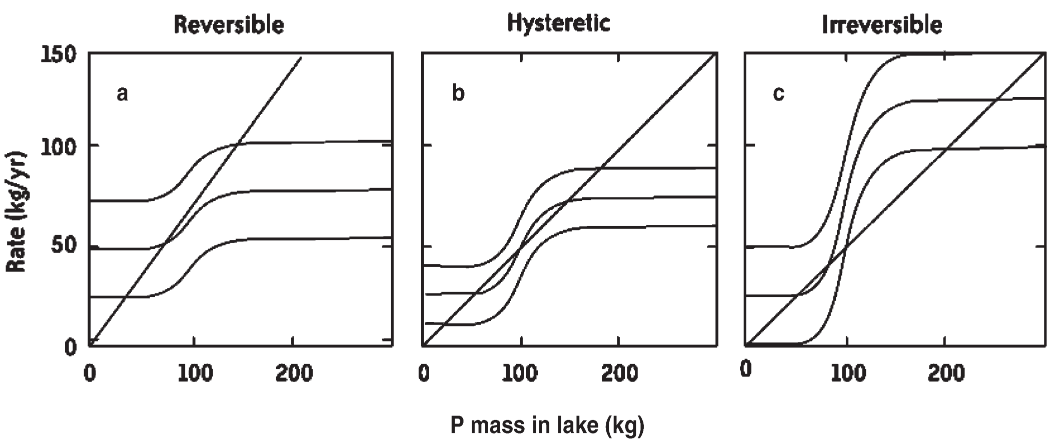

Figure 2

P sources (*sigmoid curves*) and sinks (*diagonal lines*) for (*a*) reversible lakes, (*b*) hysteretic lakes, and (*c*) irreversible lakes. Source: Carpenter et al. (1999).

must now be expanded to include the current vector of prior probabilities $\{p_{1t}, \ldots, p_{nt}\}$ on $\{b_1, \ldots, b_n\}$ as well as the state x_t of the lake at each date t. Dechert et al. (2007) built on the stochastic-lake problem of Dechert & O'Donnell (2006) to locate sufficient conditions for convergence of optimal Bayesian learning to the true value of b even when discounting is present. Discounting tends to lower the chance of convergence of Bayesian learning to the truth in this kind of problem. However, the effect of the interaction between discounting and the detailed structure of the problem on the speed of learning cannot be evaluated in two-period or even multiperiod deterministic models. We see this as a very important and wide open research area.

Subsequent papers have established that the transition probabilities between states in the shallow-lake model are highly sensitive to institutional conditions. Mäler et al. (2003), for example, optimized a welfare function of the form

$$\sum_i \ln a_i - ncx^2,$$

where n is the number of communities impacting the lake. This is subject to a transformation of the phosphorus-loading equation used by Carpenter et al. (1999):

$$\dot{x}(t) = a(t) - bx(t) + \frac{x(t)^2}{x(t)^2 + 1}, x(0) = x_0,$$

where $x = P/m$, $a = \ell/\mathrm{r}$, $b = sm/r$, the time scale is rt/m, and $c > 0$ is the loss of ecological services relative to the value of the lake as a waste sink for phosphorus. They selected parameter values such that the lake will settle in an oligotrophic state but close to the threshold of transition to a eutrophic state.

In the absence of cooperation between the communities, the outcome is a Nash equilibrium in which the steady-state phosphorus loading is a solution to

$$b - \frac{2x}{(x^2+1)^2} - \frac{1}{n} 2cx\left(bx - \frac{x^2}{x^2+1}\right) = 0.$$

For $n = 2$, there are three solutions, two of which are Nash equilibria. One lies between the full cooperative outcome and the threshold, implying that the lake is managed even closer to the latter. The second has the lake in a eutrophic state (with welfare well below either the cooperative or the "oligotrophic" noncooperative cases). Which solution dominates depends on the initial phosphorus loading: A high loading will lead to a eutrophic steady state; a low loading will lead to an oligotrophic steady state. Moreover, because the distance to that threshold is lower in the noncooperative than it is in the cooperative case, the probability that the system will transition to a eutrophic state is higher in the noncooperative case.

The interdependence between the social and biophysical systems is reflected in the notion of coevolution (Norgaard 1984) in which the path dependence of a coupled system reflects the dynamics of both constituent parts and their interactions. Indeed, entrainment in the shallow-lake case follows from the impact of noncooperative behavior of those responsible for the pollution of the lake on the probability of transition between lake states.

More generally, let us reconsider the case where there are S possible states of the world, and suppose that the state of the system at time t, x_t, takes value i with probability $p_i = p(x_t = i)$. Entrainment implies that this probability is influenced by the choice of the actions available to the decision maker(s), u_t. If we call the set of actions over time a "policy," this defines as a sequence of functions that determines a probability law for the process $(x_t)_{t\geq 0}$ (Perrings 1998, 2001):

$$p^u(x_{t+1} = i_{t+1}|x_0 = i_0, \ldots, x_t = i_t) = p_{it,it+1}(u_t(i_0, \ldots, i_t)).$$

Thus, the optimal policy is that which maximizes the expected present value of the appropriate index of well-being:

$$W^u(i) = E^u \sum_{t=0}^{T} W(x_t, u_t(x_0, \ldots, x_{t-1})).$$

So the entrained trajectory of the system is $x_t = f(x_0, u_1, \ldots, u_{t-1})$. Note that the time taken for a system perturbed from a subset of the state space, S_A, to return to that state—the first return time—is $\sigma_A = \min(t \geq 1 : x_t \in S_A)$.

Not all states are reachable from x_0. If we define the set of states that are reachable from x_0 at time t as $S^t(x_0)$ and the set of all states that are ultimately reachable as $S^\infty(x_0)$, we can tighten the concept of irreversibility considerably. Specifically, if all states in S can be reached from x_0, then no action in a policy is irreversible. Technically, this implies that the probability transition matrix governing the evolution of the system, $\mathbf{P} = (p_{ij}, i, j \in S)$, will be irreducible. If $S^t(x_0) < S^\infty(x_0)$, implying that not all states that are ultimately reachable are reachable at time t, then some actions in a policy may be irreversible within that time frame. This is the example of the felling redwoods cited by Arrow & Fisher (1974). If not all states are ultimately reachable from x_0, then $\mathbf{P}$ will be reducible—and it can be written in normal form as

$$\mathbf{P} = \left[\begin{array}{ccc|ccc} \mathbf{P}_{11} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{P}_{mm} & 0 & \cdots & 0 \\ \hline \mathbf{P}_{m+1} & \cdots & \mathbf{P}_{m+1m} & \mathbf{P}_{m+1m+1} & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{P}_{s1} & \cdots & \mathbf{P}_{sm} & \mathbf{P}_{sm+1} & \cdots & \mathbf{P}_{ss} \end{array}\right].$$

In this case, the first m states are "closed": In effect, if x_0 corresponds to any of these states, the system will remain within that state. If x_0 corresponds to any of the remaining states, it will be able to reach alternative states with some probability. If $\mathbf{P}$ is decomposable in this way, the state space can be partitioned into two groups, S_m and $S_{s\text{-}m}$, where S_m is the set of closed blocks on the principal diagonal of the probability transition matrix. Separating the welfare functions corresponding to the two groups of states, W_m, W_s, we can write the expected net benefits of the control policy that determines the probability law for this system as

$$W^u(i) = E^u\left[\sum_{t<\tau} W_s\Big(x_t, u_t(x_0, \ldots, x_{t-1})\Big) + W_m(x_\tau)\right],$$

where τ is the hitting time of W_m. That is, we can separate benefit streams associated with both reversible and irreversible states. Depending on the payoff associated with each of the states, the policy will be chosen to either shorten or lengthen the hitting time τ. In other words, the decision to slow or accelerate evolution toward an irreversible state will depend on the expected payoffs associated with that state.

Note that uncertainty about the impact of the policy on transition probabilities will have the same effect in this case as in the cases considered by Epstein (1980). If probing the system generates information about its dynamics, then the optimal policy will intensify the stressor (*sensu* Roberts & Weitzman 1981). If waiting reveals information about the system, allowing passive Bayesian learning, then the optimal policy will reflect a classical irreversibility effect (*sensu* Arrow & Fisher 1974). In both cases, however, the real impact of irreversibility will be to build the locked-in payoffs associated with irreversible states into the optimal policy.

4. IRREVERSIBILITY AND SUSTAINABILITY

Above, we highlight the close relationship between the issues raised in the literature on irreversibility and the emerging sustainability science. At the most general level, Kates et al. (2001) defined sustainability science as the science of the interactions between nature and society across both space and time. A similarly general measure of the sustainability of coupled systems is their capacity to maintain the flow of services on which people depend over time. This implies that the option and quasi-option values that are the focus of the irreversibility literature are nondeclining (Dasgupta 2001). Although the existence of a stable equilibrium (a steady state) may be sufficient to assure the sustainability of some dynamical system by this criterion, it is not a necessary condition. Nor is it necessarily attainable in an evolutionary system subject to selective and sorting pressures, irreversible changes, and fundamental uncertainty.

Recalling that irreversibility implies loss of stability, if the coupled system is only partially observable and controllable, then policies that perturb the unobserved and uncontrolled parts of the system may be destabilizing, i.e., may have unforeseen and potentially unforeseeable positive feedbacks on the economic system. In this case, the most that may be achieved is the "stabilization" of the system, i.e., the regulation of stresses on the uncontrolled part of the system to maintain stability given uncertainty about that part of the system (Perrings 1991). Stabilization strategies apply both to protect a system in a desired state and to avoid transition into an alternative undesired but irreversible or at least hysteretic state. So they fit the shallow-lake problem. But they are also strategies for maintaining stability (avoiding irreversible change) in systems that are imperfectly understood—they are not strategies for learning.

The scientific problem posed by the maintenance of sustainability in imperfectly observed or controlled complex coupled systems is to learn the dynamics of those systems without compromising their ability to deliver valued services (Perrings 2007). Most technological or policy innovation represents an experiment undertaken in largely uncontrolled conditions—a perturbation of the system that may be bounded by the scale of the experiment, but which is generally not isolated. Indeed, the more integrated the global system, the harder it is to isolate the subjects of such experiments. Many current environmental "experiments" are far from bounded—climate change and biodiversity loss among them. Both are irreversible, and both have the capacity to transform existing life-support functions of the biosphere. Yet, if technological or policy experiments are to yield a better understanding of the system dynamics without risking system stability or system sustainability, then they do need to be bounded. The most secure option in the case of economic systems—or coupled ecological-economic systems—is the development of models, along with criteria for model selection. Although there are few models of macro-environmental and -social processes, there exist reasonable selection mechanisms to discriminate between models on the basis of their fit to the data, predictive capacity, or the loss associated with decision-model error. Bayesian model updating on measures of output dispersion—the variation in the loss function associated with a decision rule applied to different models—is one such mechanism (Brock & Carpenter 2006).

The policy problem posed by sustainability is to assure that the irreversible changes induced by policies do not reduce the value of the system assets, especially the value of the options to use those assets in the future. In an evolutionary system, this implies maintenance of future evolutionary potential. There are two related criteria identified in the literature for this. The first is the maintenance of diversity. Evolutionary potential depends on selection and sorting, and both depend on diversity—among species, populations, cultures, institutions, technologies, and policy options (van den Berg & Gowdy 2000). Yet, diversity is threatened by the homogenizing force of competitive exclusion, which becomes more effective the more spatially integrated the system becomes. The aspect of irreversible loss of diversity that has attracted the most attention from economists is the loss of biological diversity, but the loss of diversity in other dimensions of the system similarly restricts its evolutionary potential. The displacement of local firms and local products and the displacement of alternative technologies and knowledge systems has the same effect. Indeed, that is the original concern over the phenomenon of lock-out—the exclusion of certain technological options as a result of the dominance of one (Arthur 1989). Nor is it sufficient to protect diversity in one dimension only, because the effect—particularly at the macro level—depends on the interaction between different types of diversity (Levin et al. 1998).

The second criterion identified in the literature depends not only on diversity, but also on the capacity of the system to respond constructively and creatively to external shocks. The capacity to respond to shocks without losing function defines system resilience. This is an area of explosive growth in the literature starting from the seminal contribution of Walters (1986). The link between loss of resilience and irreversibility is discussed above, but it is worth repeating that, because loss of resilience signals the transition of a system from one stability domain to another, such loss is generally associated with either irreversible or hysteretic change. This says nothing about the desirability or otherwise of that change, which depends on the payoffs associated with the system in either state. The desirability of maintaining adaptive capacity depends on the desirability of the reference state—or sequence of states. So an optimal policy in a desirable state would be one that reduces the probability that the system will flip into a less desirable state, and this is equivalent to assuring that it can adapt to the external stresses and shocks it faces.

5. IRREVERSIBILITY AND PRECAUTION

Consider the connection between irreversibility and a principle that is generally considered to be conservative: the precautionary principle. A widely held interpretation of the principle is that where the costs of current activities are uncertain but potentially both high and irreversible, then a precautionary response requires action before the uncertainty is resolved. Implicitly, it applies where the costs of inaction may exceed the costs of anticipatory action, but where there are insufficient data to form an expectation about the payoff (Taylor 1991). This principle was adopted at the 1992 Rio Conference as Principle 15: "[W]here there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (Gollier 2001). It is also enacted into law in a number of European countries. In French law, for example, it is defined as follows: "[T]he absence of certainty, given our current scientific knowledge, should not delay the use of measures preventing a risk of large and irreversible damages to the environment, at an acceptable cost" (Gollier et al. 2000). Notice the key role of irreversibility in both of these statements.

Application of the principle in the past has been extremely inconsistent. Harremoës et al. (2001) showed that in several cases where early scientific results indicated the potential for widespread, significant, and irreversible consequences, but where there was no basis for estimating a probability distribution of outcomes—e.g., halocarbons, polychlorinated biphenyls, and methyl tert-butyl ether (MTBE)—policy makers failed to respond. This partly reflects more widespread distortions in people's perceptions of certain types of risks. Empirically, decision makers generally underestimate risks from frequent causes and overestimate risks from infrequent causes (Pigeon et al. 1992, Starmer 2000). For example, insurers faced with low-probability, high-loss risks systematically quote rates that exceed the expected losses (Katzman 1988). To capture this, the weighted expected utility approach supposes that there exists an estimate of the probability distribution of outcomes that is known to the decision maker, but that the decision maker then weighs the various outcomes of their actions. It has, for example, been argued that decision makers weigh outcomes relative to some reference point (Starmer 2000). Decision makers' weighted preferences over outcomes can be represented by the function

$$W^u(i,p,\psi) = \sum_{t=0}^{T}\sum_{i=1}^{S} p_{it}g(\psi_t)W_{it}(x_t, u_t(x_0,\ldots,x_{t-1})),$$

where $g(\psi_t)$ is the weighting function that depends on the state of knowledge at time t, Ψ_t. If the weights attaching to all outcomes are identical, implying that the decision maker has no reason to discriminate between outcomes, this reduces to standard expected utility. If the weights are inversely related to the decision makers' confidence in the science behind particular estimates, then extreme, unique, rare, and irreversible events with few historical precedents will attract greater weight than they might objectively deserve. Uncertainty aversion of this sort will induce a response that looks precautionary.

For the most part, the irreversibility affect discussed above makes no assumption about either risk or uncertainty aversion, and it has been interpreted as a precautionary response. But note that we do need something like weighted expected utility to explain the more classically precautionary responses to novel threats. In the context of the irreversibility problem, identification of outcomes that are both potentially irreversible and potentially high cost can increase the value of additional information to the point that decision makers are prepared to carry a significant cost in terms of forgone output in order to acquire that information.

Although much has been done to clarify the theoretical points at issue in the precautionary principle (Gollier et al. 2000, Heal & Kristom 2002, Gollier & Treich 2003), significant questions remain about how to operationalize it—especially about how to discipline application of the principle by data and theory and to respect the true level of uncertainty that policy makers face. One option is to adapt recent work on Bayesian model averaging and model uncertainty to environmental issues. Brock et al. (2003, 2007) developed this approach in the context of monetary policy and growth policy. Their conclusion is that the "true" level of uncertainty is typically understated when a commitment (implicit or explicit) is made to one estimated model, albeit with the usual econometric measures of uncertainty reported for the estimated coefficients. Ludwig et al. (2005) noted that that there are two main sources of model uncertainty in environmental accounting applications: (*a*) model uncertainty in the discounting process and (*b*) model uncertainty in the underlying socioecosystem dynamics. The former reflects intense debates about the appropriate rate at which to discount far-future relative to near-future effects—what may be referred to as theory uncertainty (consider the debates in Chichilnisky 1996; Heal 1998; Weitzman 1998; Gollier 2001, 2002).

Brock et al. (2003) argued that one should approach model uncertainty through the following hierarchy: (step 1) theory uncertainty, (step 2) model uncertainty given each theory, (step 3) proxy uncertainty in the empirical counterparts of the theoretic objects in each theory. The idea is that each step leads to a class of models and each model contains relationships among theoretic objects. Thus, the empirical researcher must produce proxies for the theoretic objects contained in each theory. For example, Ludwig et al. (2005) cited a set of empirical studies of discounting processes and ecosystem dynamics that would go into a proper Bayesian model averaging study. However, Ludwig et al. (2005) sketched only how this might be done and illustrated by sketching a potential application for three problems: (*a*) What population size is optimal for a harvested resource? (*b*) Should North Atlantic Right Whales be protected? (*c*) How much phosphorus should be discharged into a lake? Extinction is irreversible for the first two problems, and the lake may be flipped into an essentially irreversible state in the third case.

Brock et al. (2007) argued that the scientific team should create a display that they call "action dispersion" and "value dispersion" plots where for each estimated model, the optimal action and optimal value of that action conditional upon the given model is displayed with data-disciplined Bayesian posterior probabilities. Brock et al. (2007) argued that the policy makers then can impose their own attitudes toward uncertainty and risk on these plots and make the policy choice as representative of the public. Ludwig et al. (2005) gave an argument that such a process tends to lead to precaution against irreversible actions for two reasons. The first is that the far-distant future has some probability of getting a large weight due to theory uncertainty and model uncertainty in the discounting process. The second is that the worst-case scenario of a totally irreversible possibility gets some probability due to theory uncertainty and model uncertainty in the underlying socioecosystem dynamics.

How should policy makers use the data/theory-disciplined display of action dispersion plots discussed above, which gives them an estimate of the "true" measure of the uncertain consequences for social value of their potential actions? Lempert & Collins (2007) presented an interesting approach and comparison of robust, optimum, and precautionary approaches. In the above discussion, we stress the problems with committing to a particular model and optimizing conditional on estimates of that model (even if one assures robustness to estimation uncertainty of that particular model). The problem with this commonly used approach is that it is too "brittle" in case the model specification is wrong. Hence, we argue that the Bayesian model uncertainty approach discussed above is a possible remedy to this "excessive brittleness" problem. But an excessively precautionary approach would be to maximize against the worst-case scenario, which represents the worst-case model that has positive posterior probability in the Bayesian model uncertainty approach. Because the maximin approach to assuring robustness seems too precautionary and, hence, may fall victim to the flaws pointed out by Gollier (2001), recent research has approached the problem via minimax regret (Iverson 2008). Minimax regret approaches to assuring the robustness of decision making choose the action that minimizes a measure of maximum regret over all models that have positive posterior probability in a Bayesian model uncertainty application. Variations on maximin and minimax regret in Bayesian model uncertainty applications "trim" away models that have positive but "small" posterior probability (Brock et al. 2007, Iverson 2008).

6. CONCLUDING REMARKS

The economic treatment of irreversibility discussed in this paper centers on two core ideas. The first is that the foregone options associated with any action that entrains the future should be taken into account in deciding that action (i.e., it has option value). The second is that, in a system that is imperfectly understood, the information offered by foregone options should also be taken into account (i.e., it also has quasi-option value). When combined with the wider literature on the nature of irreversibility in complex, evolving systems, these ideas provide a straightforward way of analyzing strategies that affect the transition probabilities for a system in any given state. Although they provide a compelling logic for the conservation of many environmental resources, irreversibility does not necessarily indicate a conservative policy. Whether a policy is optimally stabilizing or destabilizing depends on (*a*) the value of the system in alternate stable states and (*b*) the way that uncertainty about future states is best resolved. The cases that motivated Fisher et al. (1972) and Arrow & Fisher (1974) indicated that the socially optimal outcome would be more conservative than the privately optimal outcome, but that need not be true in all cases.

Indeed, the inconsistency of policies to address irreversible environmental change suggests that there is still much to do. Although economics has made significant progress in the theory of uncertainty management in dynamic coupled socioecological systems facing irreversible change, more needs to be done to develop a coherent framework for policy implementation.

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