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Fisher, Anthony C.

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DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS AND POLICY
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
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by

Anthony C. Fisher

California Agricultural Experiment Station
Giannini Foundation of Agricultural Economics
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Anthony C. Fisher
Department of Agricultural and Resource Economics
University of California at Berkeley

What is it that distinguishes environmental and resource economics from economics generally? One answer, offered by a colleague of mine at a forum in which members of our department of agricultural and resource economics were asked to describe their work to a lay audience, is that agricultural and resource economics is applied economics, as opposed to the more abstract or theoretical work that characterizes general economics today. In my judgment this is not correct or at least is not sufficient in describing environmental and resource economics. After all, there are many applied areas of economics, including such long-established, and still-active, ones as labor, development, and industrial organization. It seems to me that our uniqueness lies in the intimate relationship of our field of study to the science of the natural world. It is from the physical and biological and environmental sciences that we derive the relevant and interesting features of our models. Economics is in essence about optimization subject to constraints. In our field these constraints are imposed by the natural world. Examples include the limited stock and spatial distribution of a nonrenewable resource, the natural growth rate of a renewable one, the diffusion or decay rate of a pollutant in an environmental medium, and so on. Many of these constraints, it turns out, can be viewed as one or another kind of irreversibility, the subject of this talk.

Before I proceed to develop this point, I would like to note just briefly that natural constraints also play a key role in agricultural economics. The main feature that distinguishes the agricultural economy from the industrial economy is its seasonality. In fact, as pointed out in an illuminating recent paper by Allen and Lueck (2000), this was recognized by John Stuart Mill, who observed that agriculture is not susceptible to the specialization and division of labor so characteristic of industry because its different operations cannot be simultaneous. One man cannot always be plowing, another sowing, and another reaping. A second important influence of nature on the agricultural sector is perhaps equally obvious: the climate, and in particular the randomness of climate events such as precipitation, can have a relatively large impact on output. This is certainly one reason why much of the recent research on impacts of climate change has focused on agriculture.

I return now to the main theme of this talk, irreversibilities and other natural constraints in environmental and resource economics. Just after receiving my degree in economics, in a field unrelated to environmental and resource economics (which essentially did not exist as a field at the time), I conducted a very unsystematic survey of the emerging noneconomic literature on environmental problems. The object of the search was to learn what the problems were, as perceived by natural scientists and policy makers, and how the problems might be characterized to permit the application of models and methods from economics to their solution. What emerged from this exercise was a focus on a concept that seemed to run through much of the environmental literature:

irreversibility. By irreversibility, I mean the notion that threatened environmental losses were significant because they would be experienced in perpetuity. This may seem obvious to economists today, but it was not always so.

When John Krutilla and I put forward the proposition that irreversibility matters, in a series of articles and an RFF volume on the economics of natural environments in the early and mid 1970s, we met the following (contradictory) responses: everything is irreversible, in the sense that time does not run backwards; and nothing is irreversible, in that the consequences of any decision, for example to develop a natural environment, can be reversed given sufficient application of technique and conventional resource inputs. In the unlikely event that the decision is not technically reversible, it should at least be economically reversible, in the sense that other goods or resources might be found to substitute in consumption for the lost natural environment. This latter response, that irreversibility is an "empty box," was perhaps the dominant view among economists. We argued, on the contrary, that meaningful distinctions could be made between uses of a natural environment that are reversible and those that are not, and that these distinctions had implications for the allocation of the environment's resources, especially for problems of allocation over time.

Consider, for example, as we did, the complications that attend the decision to develop a water-storage reservoir. Correcting an ill-advised decision to construct a dam involves more than simply dismantling the structure when its environmental costs are perceived to exceed the benefits. Supersaturation of the reservoir banks at full-pool elevations may result in sloughing and landslides into the reservoir during drawdown. Moreover, if streams of high turbidity are impounded, sediment will build. Dismantling the structure would then leave the impoundment area with an abiotic base quite different from that which originally existed. Perhaps this explains the strength of the opposition, in the 1960s and 1970s, to the proposed damming of the Colorado River in the Grand Canyon. At stake, in the view of the opponents, was, among other things, permanent loss of two billion years of natural history recorded on the Canyon walls. Nor was opposition based solely on the technical infeasibility of restoring the pre-project environment. Also at issue were, and are, the preferences of individuals regarding the attributes of the environment. For some, authenticity in a natural environment is a valued attribute, as it is to others in a work of art. No matter how skillfully Disneyland simulates a lost environment, devoted Sierra Clubbers may not be satisfied. Substitution in consumption may not offer a way out, in which case a decision to construct a dam is indeed irreversible. A possible objection to this line of reasoning might be that depleting a deposit of a fossil fuel to produce the electric power otherwise produced by the dam is also irreversible, and in a sense of course it is. But in my judgment the environmental irreversibility is potentially more significant, because the environment in question, say the Grand Canyon, directly enters the utility functions of individuals, and as just noted, good substitutes may not exist. The mineral fuel, on the other hand, enters a production function where it has many good substitutes, in the form of other deposits of the same mineral, or other minerals, or for that matter renewable sources, that can be used to generate electricity.

Here it is important to note that the fact that a decision is irreversible does not imply that it should never be taken. As the original analysis of irreversibility in economic processes, especially those involving the natural environment, suggested, and as subsequent research, including some I want to talk about here, has confirmed, irreversibility does matter, in the sense that it does change the benefit/cost calculus, but this still involves trade-offs at the margin.

In any event, I think it fair to say that perceptions, at least among economists who specialize in the study of environmental and resource issues, have changed, as evidenced by the now-substantial literature. Although the example of dam construction is still relevant, the major concern today is perhaps for the biological environment, for the conservation of biodiversity, the genetic information that is potentially valuable in medicine, agriculture, and other productive activities. Of course, much of the concern is for endangered species, or habitats that support thousands or even millions of species, such as the Amazon and other tropical moist forests. But even if species survival is not at issue, biological impacts can be very difficult to reverse over any time span that is meaningful for human societies. The clear-cutting of a climax forest species, for example, removes the results of an ecological succession that may represent centuries of natural processes. Further, as illustrated in a forthcoming paper by Albers and Goldbach (2000), regeneration may not lead to the original configuration even after centuries. Opportunistic species, such as hardy grasses, may come in and preempt the niche otherwise filled, eventually, by the original climax species.

The other prominent—and linked—environmental issue today is climate change. Here too irreversibility has been identified by economists and others as a key feature of the problem faced by decision makers as they consider what adjustments, if any, to make in existing patterns of emissions of greenhouse gases. Emissions are, for the most part, irreversible, and natural scientists have emphasized the irreversibility, or at least the extremely long duration, of many of the hypothesized impacts of warming. Interestingly, economists have called attention to another sort of irreversibility in this situation: the irreversibility of an investment in energy conservation or in energy technologies that rely on sources that do not generate greenhouse gases. Some implications of investment or regulatory irreversibility are developed in recent and forthcoming papers by Kolstad (1996a, 1996b) and Pindyck (2000).

In keeping with the theme of the talk, I would like to say a bit about the other irreversibility, the climate irreversibility, as I think the relevant natural science is perhaps not well known to economists and thus not yet adequately incorporated in climate/economy models. I just said that emissions are irreversible, but this is too simple. Emissions are nonnegative, but the resulting accumulation is subject to natural decay. Typically, as in the well-known and widely-used DICE model (Nordhaus, 1993), this process is represented in a single equation, in which the accumulation, or stock, of CO_2, the main greenhouse gas, in period t is equal to some fraction of emissions in the preceding period (decade, in DICE) plus some other fraction (one minus the rate of decay over the decade) of the stock in the preceding period. The process continues unchanged over time, implying that the atmospheric concentration of CO_2 returns to its current level in a few hundred years and to the pre-industrial level within a thousand years. Yet as at least a couple of recent contributions by natural scientists have pointed out, this is not likely. The difficulty is that, after relatively rapid mixing, over a few decades, of the atmosphere with the surface ocean, further removal of CO_2 from the atmosphere depends on mixing of the surface ocean with the deep ocean, a much slower process (Joos, Müller-Fürstenberger, and Stephan, 1999). According to one calculation (Schultz and

Kasting, 1997), after a thousand years, CO_2 concentrations will still be well over twice the current level, and nearly three times the pre-industrial level, and will remain elevated even after many thousands of years. Of course, this only matters a lot if the discount rate used in evaluating programs of emissions control is sufficiently low, given the distance of the time horizon. Interestingly, Nordhaus (Nordhaus and Boyer, 2000) takes account of this criticism in the latest (unpublished) version of DICE, replacing the one-equation model of carbon decay in the atmosphere with a three-equation, three-medium, version that is designed to represent the relatively slow exchange between the surface, or upper, ocean layer and the deep ocean.

The climate irreversibility is manifested in another way, for the most part neglected in economic models, including the variants of DICE. There is some possibility of essentially irreversible catastrophic impact, as would result for example from the disintegration of the West Antarctic ice sheet and consequent rise in sea levels of 5-6 meters. Recent findings suggest that this possibility is more serious, and perhaps closer in time, than economists (and others) have realized (Kerr, 1998). Moreover, it seems plausible that the probability of such an event is positively related to the level of greenhouse gas concentrations in the atmosphere. In other words, the risk ought to be endogenous in a model of the optimal control of greenhouse gas emissions. Some current work of my own, undertaken with Urvashi Narain, is looking at implications of both endogenous risk of catastrophic damage and more persistent concentrations of greenhouse gases—along with the investment irreversibility (Fisher and Narain, 2000).

In the remainder of this talk, I would like to describe our approach in a bit more detail and indicate the main results. In addition to sunk or irreversible investment in controlling emissions, nondegradable or irreversible stocks of greenhouse gases, and endogenous risk of catastrophic damages, our model features future learning about the nature of damages. When time resolves uncertainty, there is a premium on policies that maintain flexibility (Dixit and Pindyck, 1994). The difficulty in this case is that there are two potentially conflicting sources of inflexibility: sunk capital and a nondegradable stock of gases. Investment today locks the economy into a particular use of resources which may turn out to be wasteful if tomorrow reveals that damages due to global warming are small. With a nondegradable stock of greenhouse gases, on the other hand, emissions today lock the economy into a level of future damages that may be revealed as catastrophic. We develop a two-period model with learning to ask the question: Given a stock of greenhouse gases that poses a threat of damages of an unknown magnitude and the possibility of learning about the nature of damages, how does the presence of sunk abatement capital and a nondegradable stock of gases affect the optimal first-period level of investment in controlling emissions?

The two irreversibilities were to my knowledge first recognized and jointly analyzed by Kolstad (1996a) in a two-period model of irreversibilities in stock externalities. He asks the question: How does the prospect of better second-period information about the consequences of the externality affect the desired level of first-period abatement capital? Emissions are assumed to be nonnegative, and the degree of capital "sunkness" and the decay rate of the pollutant are fixed. He finds that, if learning is significant, either or both of the irreversibilities can affect the desired level of first-period emissions and in opposite directions. Which dominates depends on the relative magnitudes of the decay and depreciation rates and on expectations about damages. In a second paper, a multiperiod simulation of optimal investment in control of greenhouse gas emissions based on the DICE model and introducing, in addition to the capital stock irreversibility, a parametric representation of the rate of learning, Kolstad (1996b) finds a significant impact associated with the capital stock irreversibility but not with the emissions irreversibility. The reason, essentially, is that in his parameterization the nonnegativity restriction on emissions is never binding. Too little investment in emission control in the early periods can be compensated by a bit more investment in later periods, but there is no scenario in which it would be optimal to emit negatively in the future to correct for overemission today. This is consistent with the main analytical result in Ulph and Ulph (1997), a two-period model of global warming, irreversibility, and learning in which there is no explicit representation of investment in abatement but, as in Kolstad, emissions are restricted to be nonnegative, the decay rate of the stock of greenhouse gases is fixed, and there is learning about damages. A sufficient condition for there to be an irreversibility effect, that is, for first-period emissions with learning to be less than first-period emissions without learning, is that the nonnegativity restriction is binding in the no-learning case.

We take a somewhat different approach. In our model, learning is fixed, in the sense that the decision maker is assumed to learn, by the start of the second period, whether the climate event—say a 5° F rise in global mean temperature—has occurred and, if it has, the nature of the impact, high damage or low. We then consider how the desired level of first-period investment varies with the degree of "sunkness" of the investment and with the degree of nondegradability of the stock of gases. A second difference, with respect to Kolstad's model, is in the definition of sunk capital. Kolstad defines this in terms of durability whereas we define it in terms of convertibility: Capital is sunk if it cannot be converted into consumption or other forms of capital. As it turns out, results are unaffected by the definition in this case though we show elsewhere that steady-state behavior of investment in a continuous-time model of the optimal control of a stock pollutant is affected (Narain and Fisher, 2000). The most important difference in the present model, however, is that we treat the risk of high, or catastrophic, damages, as endogenous.

The structure of the model is that an economic agent is assumed to allocate a fixed endowment to either consumption or investment (in abatement capital) in each of two periods. The agent also has the option of increasing consumption by disinvesting (at a cost) in abatement capital. The objective is to choose consumption (and investment) in each period to maximize the sum of utility over both periods. Since the agent learns about second-period damages at the start of the second period, the optimization problem is solved through backwards induction. First choose the optimal level of investment in the second period, when the state of nature is known. This yields in the first period an expected continuation value, expected second-period returns given that second-period investment is optimally chosen. The problem then is to choose the level of first-period investment given both first-period returns and the expected continuation value.

Results can be summarized in the following propositions:

1. The optimal level of investment in the first period when the risk of a climate-changing event (say the 5° F rise in temperature) occurring is endogenous is greater than in the case of exogenous risk if and only if utility in the second period in the absence of the event is at least as great as the expected utility should the event occur.

(As long as we expect climate change to be damaging, on balance, investment is greater with endogenous risk. If, on the other hand, this were not the case, the agent may choose to increase consumption to trigger the event.)

2. Investment in the first period is a decreasing function of the degree of sunkness of abatement capital if risk is exogenous. (This is Kolstad's result, though arrived at somewhat differently: the more sunk the capital, the less investment).
3. The sign of the relationship between first-period investment and the degree of sunkness is ambiguous if risk is endogenous. (The tendency to decrease investment as capital becomes more sunk is compensated by the need to increase investment to reduce the probability of the climate-changing event occurring.)
4. Investment in the first period is a decreasing function of the rate of decay of the stock of greenhouse gases if risk is exogenous. (The more persistent are greenhouse gases in the atmosphere, the more first-period abatement is warranted).
5. Investment in the first period is a decreasing function of the rate of decay of the stock of greenhouse gases if risk is endogenous under three sufficient conditions. (The sufficient conditions are an expanded version of the condition in proposition 1: in essence, that the agent not have an incentive to trigger the event).

These results have a somewhat different flavor than those obtained by Kolstad and Ulph and Ulph. Loosely speaking, we find more of a tendency for the irreversibility associated with the accumulation of greenhouse gases to matter and a weaker effect of irreversibility associated with investment in abatement capital. No doubt these results reflect our different assumptions, especially the assumption that the risk of climate change is endogenous, i.e., is a function of the accumulated stock of greenhouse gases. I believe that this assumption better reflects physical reality, and the findings of climate scientists, but in any event it is clear that policy implications in this area can be quite sensitive to the way we model that reality.

I suggested at the outset that what chiefly distinguishes our field from others in economics is its intimate relationship to the science of the natural world. Irreversibility in the various forms that I have considered here is an important example of the constraints imposed by that world on an economic agent's efforts to make the best use of resources. In my judgment, there remains a large payoff to further thinking about creative and rigorous ways to integrate irreversibilities and other natural and environmental constraints into economic models.

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