ENVIRONMENTAL PRESERVATION, UNCERTAINTY, AND IRREVERSIBILITY *

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I

A number of recent contributions by economists have provided a clear insight into the causes of the varied forms of environmental deterioration, and have also suggested, implicitly or explicitly, policies for more efficient management of environmental as well as other resources.[1] Yet, as Allen Kneese has pointed out in a review of empirical studies of pollution damages, "a general shortcoming of [these studies] has been that they have treated a stochastic or probabilistic phenomenon as being deterministic."[2] The purpose of this paper is to explore the implications of uncertainty surrounding estimates of the environmental costs of some economic activities. It is shown in particular that the existence of uncertainty will, in certain important cases, lead to a reduction in net benefits from an activity with environmental costs. In such cases the implication for an efficient control policy will generally involve some restriction of the activity.

Any discussion of public policy in the face of uncertainty must come to grips with the problem of determining an appropriate attitude toward risk on the part of the policy maker. Thus in the essay quoted above, Kneese asks, "Is the concept of mathematical expectation applicable here or must we give attention to higher moments of the probability distribution. . . ?"[3] Although the question has not, to our knowledge, received consideration in just this form in the environmental literature, received theory does shed some light on the issue it poses.

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1. Also some not so recent, as in the classic work of Pigou. For a review of some more recent contributions, see E. J. Mishan, "The Postwar Literature on Externalities: An Interpretative Essay," *Journal of Economic Literature*, Vol. 9 (March 1971), 1–28.

2. A. V. Kneese, *Economics and the Quality of the Environment — Some Empirical Experiences*, Reprint Number 71 (Washington, D.C.: Resources for the Future, 1968), p. 172.

3. *Ibid.*, p. 172.

Burton Weisbrod first suggested that where there is uncertainty in demand for a publicly provided good or service, there may be some benefit ("option value") to the individual in addition to the conventional price-compensating consumer surplus.[4] More recently Charles J. Cicchetti and A. Myrick Freeman III have shown that, where there is uncertainty in either demand or supply, Weisbrod's option value will be positive for risk-averse individuals.[5] In the Cicchetti-Freeman analysis this extra benefit from the public good is in fact equivalent to a premium for risk bearing. Examples of such goods in the environmental sector (to which we will return) might be the preservation of certain valuable natural phenomena or the abatement of pollution.

At this point a very interesting corollary question arises. It is this: even assuming a nonneutral attitude toward risk, hence the need for some adjustment of expected benefits and costs *to the individual*, as demonstrated by Cicchetti and Freeman, does it necessarily follow that the social calculus should properly make the same adjustment? It does seem plausible, but a challenge to this point of view has been put forward in an analysis of the evaluation of benefits from more traditional public investments by Arrow and Lind.[6] They show that, as the net returns to an investment of given size are shared by an increasingly large number of individuals, the individual risk premium, and more importantly and perhaps unexpectedly, the aggregate of all such premiums go to zero. Only expected returns, then, should be taken into account in evaluating the investment.

This is the approach taken in the next section, in which the discussion focuses on a decision as to how far, if at all, to proceed with some form of commercial development of an unspoiled natural area that is also capable of yielding benefits in its preserved state. In particular, the question considered is, does the introduction of uncertainty as to the costs or benefits of a proposed development have any effect on an appropriately formulated investment criterion beyond the replacement of known values with their expectations? It turns out that, if the development involves some irreversible transformation of the environment, hence a loss in perpetuity of the benefits from preservation, and if information about the costs and

4. B. A. Weisbrod, "Collective-Consumption Services of Individual-Consumption Goods," this *Journal*, Vol. 78 (Aug. 1964), 471–77.

5. C. J. Cicchetti and A. M. Freeman III, "Option Demand and Consumer Surplus: Further Comment," this *Journal*, Vol. 85 (Aug. 1971), 528–39.

6. K. J. Arrow and R. C. Lind, "Uncertainty and the Evaluation of Public Investment Decisions," *American Economic Review*, Vol. 60 (June 1970), 364–78.

benefits of both alternatives realized in one period results in a change in their expected values for the next, the answer is yes — net benefits from developing the area are reduced and, broadly speaking, less of the area should be developed.

II

In this section we are concerned primarily with the effect of uncertainty on the criteria for choice between two alternative uses of a natural environment — preservation and development. As an example of the type of problem to which the analysis might be applied, consider the choice, at each moment in time, between preserving (part of) a virgin redwood forest for wilderness recreation, on the one hand, or opening (part of) it up to clear-cut logging, on the other. Although this sort of transformation may be technically reversible, the length of time required for regeneration of the forest for purposes of wilderness recreation is so great that, given some positive rate of time preference, it might as well be irreversible.

A problem having just these characteristics has in fact been studied by Fisher, Krutilla, and Cicchetti.[7] Without going into the structure of the problem in more detail, their results, following results obtained by Arrow [8] and by Arrow and Kurz [9] in dynamic optimization theory, can be summarized as follows. First, it will in general be optimal to refrain from some development that is currently profitable if in the near future "undevelopment," which is impossible, would be indicated. Second, if net benefits from development are in fact decreasing over time relative to benefits from preservation, as shown in an empirical application to proposed further development of hydroelectric capacity along the Hells Canyon reach of the Snake River, it will be optimal to develop either immediately or not at all. It is then shown that even the most profitable of current development projects there can be expected at this time to yield a smaller return than the preservation-recreation alternative.

The notion of "irreversibility" underlying these results might be spelled out a bit more. Ordinarily, it would be technical. Thus the construction of a major dam or series of dams in the Hells

7. A. C. Fisher, J. V. Krutilla, and C. J. Cicchetti, "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis," *American Economic Review*, Vol. 62 (Sept. 1972), 605–19.
8. K. J. Arrow, "Optimal Capital Policy and Irreversible Investment," in J. N. Wolfe, ed., *Value, Capital and Growth* (Chicago: Aldine Publishing Company, 1968), pp. 1–20.
9. K. J. Arrow and M. Kurz, "Optimal Growth with Irreversible Investment in a Ramsey Model," *Econometrica*, Vol. 38 (March 1970), 331–44.

Canyon clearly could not be undone in such a way as to make possible the enjoyment of the recreational and other services currently provided by the free-flowing stream through the deepest canyon on the North American continent.

Conceivably, construction of an alternative power source could preclude development of the hydroelectric potential there. This would, however, be an economic decision, and one that might in any case be reversed — although this would not be indicated by a continuation of present trends in benefits from wilderness preservation versus power development there, as assumed in the Fisher-Krutilla-Cicchetti study.

Of course, a technically irreversible development could be characterized as one that would be infinitely costly to reverse. More generally, the cost of reversal may take intermediate values that would vary with the alternative chosen. For the remainder of this section, however, it may be helpful to rely on the intuitive notion of a technically irreversible development, such as the placing of a dam.

As the Fisher-Krutilla-Cicchetti study adopts the risk-neutral approach in its specification of only expected costs and gains in the investment criterion with no adjustment, for example, for option value in preserving, the bias against development is due solely to the restriction on reversibility. By joining to this restriction the additional and plausible assumption that realizations in one period affect expectations in the next, as spelled out in the following simple model, we discover, consistent with the continuing assumption of risk neutrality, a "quasi-option value" having an effect in the same direction as risk aversion, namely, a reduction in net benefits from development.

Consider, now, the development of an area d over a two-period time horizon consisting of a first period followed by all future intervals compressed into a single second period. Though not particularly elegant, this formulation seems sufficient to capture the essential features of the process described above.

Let $d =$ unity (a normalized unit of land)
$d_1 =$ the amount of land developed in the first period
$d_2 =$ the amount of land developed in the second period
$b_p =$ benefits from preservation of d in first period
$b_d =$ benefits from development of d in first period
$\beta_p =$ expected benefits, conditional on b_p and b_d, from preservation of d in second period

β_d = expected benefits, conditional on b_p and b_d, from development of d in second period

c_1 = investment costs in first period

c_2 = investment costs in second period.

Several remarks can be made concerning the structure of this model.

1. Though explicitly dynamic, it need not deal with time discounting in any meaningful way. Thus the second-period benefits and costs β_p, β_d, and c_2 can be viewed as present values, and the results are not affected.

2. It is assumed that development entails investment costs but preservation does not. Costs of preservation could easily be introduced (where meaningful) but again, results would not be affected, and extra terms would clutter the model. The real difference between the alternatives is that one is assumed to be reversible, and the other not.

3. Note that second-period expectations are conditional on first-period realizations. Some amount of development is planned at the start of the first period, but the plan can be revised (at least in the direction of additional development) at the start of the second period, based upon information that has accumulated concerning benefits in the first period.

4. Note, finally, that all benefits are specified as coefficients, so that constant returns to any level of development or preservation are assumed. Later on, this assumption is relaxed.

Let us focus now on the decision at the start of the second period. If $\beta_d - \beta_p > c_2$, then $d_2 = 1 - d_1$. If $\beta_d - \beta_p < c_2$, then $d_2 = 0$. Define $z = \beta_d - \beta_p$, $w = b_d - b_p - c_1$, and event A as $z > c_2$. If A occurs, total benefits from the area are

$$b_p(1-d_1) + b_d d_1 - c_1 d_1 + \beta_d - c_2(1-d_1) = w d_1 + c_2 d_1 + b_p + \beta_d - c_2. \tag{1}$$

If A does not occur, then benefits are

$$b_p(1-d_1) + b_d d_1 - c_1 d_1 + \beta_p(1-d_1) + \beta_d d_1 = w d_1 + z d_1 + b_p + \beta_p. \tag{2}$$

The expected benefits from developing $d_1 > 0$ in the first period are

$$E[(w + \min(c_2, z)) d_1 + b_p + \max\ (\beta_d - c_2, \beta_p)]. \tag{3}$$

Now suppose that $d_1 = 0$. If A occurs, total benefits from the area are $b_p + \beta_d - c_2$; if A does not occur, benefits are $b_p + \beta_p$; and expected benefits are $E[b_p + \max(\beta_d - c_2, \beta_p)]$. Then the difference (in expected benefits) between developing $d_1>0$ and $d_1=0$ is

(4) $$E[(w+\min(c_2, z))d_1+b_p+\max(\beta_d-c_2, \beta_p)] - E[b_p+\max(\beta_d-c_2, \beta_p)] = E[(w+\min(c_2, z))d_1].$$

We are interested in the sign of the expression $E[w+\min(c_2, z)]$. If it is positive, it will be optimal to develop in the first period.

Now suppose that the decision maker ignores uncertainty, i.e., he lets z and w be replaced by known numbers $E[z]$ and $E[w]$, so that the criterion is $E[w]+\min(c_2, E[z])$. Either $c_2<E[z]$, or $c_2>E[z]$. Consider the case in which $c_2<E[z]$, so that the criterion is $E[w]+c_2$. Clearly,

(5) $$\min(c_2, z)\leqslant c_2;$$

with

(6) $$P[\min(c_2, z)<c_2]>0,$$

where $P[\ ]$ represents the probability of occurrence of the expression in brackets. Thus

(7) $$E[\min(c_2, z)]<c_2;$$

and

$$E[w+\min(c_2, z)]<E[w]+c_2.$$

The expected value of benefits under uncertainty is seen to be less than the value of benefits under certainty. There exists a range of values for z and w for which development should not, then, take place under uncertainty but should under certainty. An interpretation of this result might be that, if we are uncertain about the payoff to investment in development, we should err on the side of underinvestment, rather than overinvestment, since development is irreversible. Given an ability to learn from experience, underinvestment can be remedied before the second period, whereas mistaken overinvestment cannot, the consequences persisting in effect for all time.

Similarly, for the case in which $c_2>E[z]$,

(8) $$\min(c_2, z)\leqslant z;$$

with

(9) $$P[\min(c_2, z)<z]>0.$$

Thus

(10) $$E[\min(c_2, z)]<E[z].$$

Note that the assumed rigidity of the benefit (and cost) coefficient requires that, if the criterion is positive, the entire area be developed. Our result then states that the entire area is less likely to be developed under uncertainty. It might be desirable to have a result of this type in more flexible form, in particular that less of a given area be developed under uncertainty — rather than less chance of the entire area's being developed.

Let (as yet) undeveloped area d be divided into n units, $\mu_1, \mu_2, \ldots, \mu_n$, each with fixed coefficients. Suppose, now, we consider development of d on a unit-by unit basis, proceeding exactly as above, but with the benefit and cost coefficients referring, respectively, to the first unit considered, then the second, etc. Under the plausible assumption of diminishing returns to both development and preservation, it is easily verified that, if it does not pay to develop the first unit considered, then it does not pay to develop any of the others. If, on the other hand, it pays to develop the first unit, then the second must be considered and so on. Corner solutions are possible as before, but so are interior solutions of part preserved and part developed.

In order to avoid confusion over the terms "constant returns" and "diminishing returns," we can define them more precisely. Let each of the n units μ_i, $i=1, \ldots, n$ be further divided into m subunits μ_{ij}, $i=1, \ldots, n$, $j=1, \ldots, m$, each with fixed coefficients. Constant returns to, say, first-period development within any unit μ_i can be represented as

$$b_{di_1}=b_{di_2}= \ldots =b_{di_m},$$

with

$$b_{di_1}+b_{di_2}+ \ldots +b_{di_m}=b_{di},$$

where b_{di_1}=benefits from development in the first period of unit μ_{i1}, etc. Diminishing returns to development across units μ_i can be represented as $\frac{db_{di}}{di}<0$. (Note that $\frac{db_{pi}}{di}>0$, as benefits from preserving the marginal unit increase with the number of units already developed.) In this formulation the size and number of units μ_i are defined by the condition that returns are constant within each.

III

The foregoing analysis indicates that, even where it is not appropriate to postulate risk aversion in evaluating an activity, something of the "feel" of risk aversion is produced by a restriction on reversibility. If one takes the view that some means of spreading the risk associated with the uncertain environmental costs of the activity is likely to be feasible in most cases, then there are clear policy implications to this result, as it sharply distinguishes between reversible and irreversible changes in the environment.

One such implication, however, is *not* the overthrow of marginal analysis. Just because an action is irreversible does not mean that it should not be undertaken. Rather, the effect of irreversibility is to reduce the benefits, which are then balanced against costs in the usual way.

The analysis can be applied to problems of pollution control as well. Let b_d and β_d represent the benefits from an investment, and c_1 and c_2 the direct costs, as before. Then b_p and β_p can be taken to represent the benefits (reduced losses) from the cleaner or less toxic air, or water, that would be enjoyed were the investment not made.

Of course, the dynamic model is relevant only if the pollution is in some sense irreversible, as is the extinction of a form of life, or the destruction of a unique geomorphological phenomenon. This is an empirical matter. Clearly, much pollution is short-lived, sufficiently diffused or degraded by the assimilative medium to render it negligible in concentration and harmless in effect beyond some point in time. To this type of pollution the model does not apply.

On the other hand, there is evidence that some pollution does accumulate in the environment, perhaps sufficiently to be considered irreversible. Recent research has shed light on the toxicity and the persistence, indeed the increasing concentration, of the "hard" or nondegradable pesticides such as DDT, for example, and of industrial substances such as lead. A decision on a project involving discharge into the ambient environment of any of these or other potentially harmful and persistent substances should then take into account the continuing effect, as in the analysis of the preceding section. The same reasoning would apply to cumulative "macro" environmental effects, such as the increasing concentration of carbon dioxide in the global atmosphere, with its attendant climatic changes, as predicted by some ecologists.

The point about uncertainty, information, and irreversibility might be made still more generally, i.e., without reference to environmental effects. Essentially, the point is that the expected benefits of an irreversible decision should be adjusted to reflect the loss of options it entails.[1]

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1. For an earlier statement see A. G. Hart, "Risk, Uncertainty, and the Unprofitability of Compounding Probabilities," in *Studies in Mathematical Economics and Econometrics*, ed. by O. Lange, F. McIntyre, and T. O. Yntema (Chicago: University of Chicago Press, 1942).