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III. DECISION PROBLEMS IN THE CONTROL OF ACID PRECIPITATION: NONCONVEXITIES AND IRREVERSIBILITIES

Acid Precipitation Dose-Response Functions

The sole recurring theme of the previous two chapters is that empirical application of economic methods for assessing the benefits of acid precipitation control generally requires prior knowledge of the response of biological and material entities to variations in acid precipitation exposures, Increasing pollution has been treated as leading to progressive deterioration in the size of the resource stock and the flow of material and life support services issuing from it. Moreover, this deterioration could be reversed and, by reducing the level of pollution, recovery could occur along the same path as did deterioration. This behavior is a standard representation in the environmental economics literature. It leads to results in which some immediate environmental damages are borne in order to obtain some of the immediate benefits that a productive but polluting activity confers. Assuming the pollutant to be acid precipitation, Figure 1 introduces the costs of controlling the acid precursors in a comparative static version of the standard representation. Unit prices of the elements of the resource stock and of pollution control equipment are assumed constant.

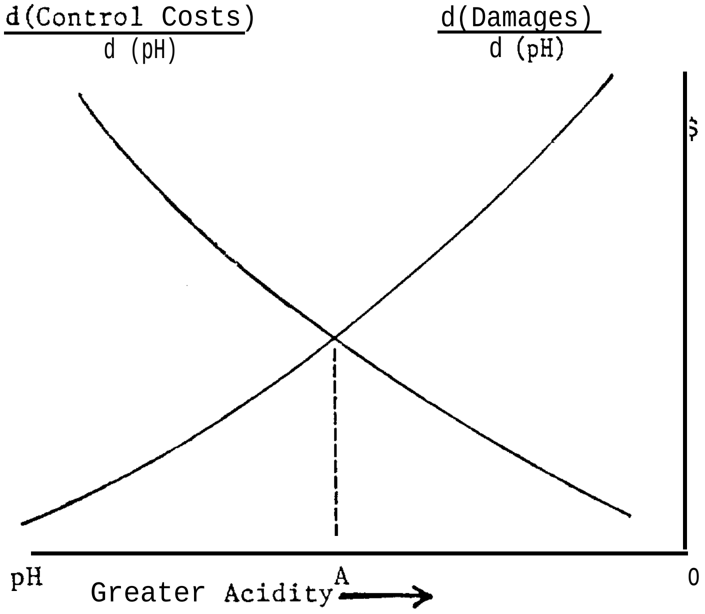
The economically efficient pH level in Figure 1 will. be at A, where the marginal benefits of reduced acidity are equated to the marginal costs of controlling acidity. The marginal benefit of reduced acidity is the marginal damage that is avoided by having less acidity. That a point such as A is optimal can be seen from the following simple argument. Suppose that the benefits are measured by the size of the fish population denoted Pop. The Pop is an increasing function of the pH level as is the cost of control, C. The net benefit of a given pH level is

$$\pi = \text{Pop}(\text{pH}) - C(\text{pH}) \qquad (1)$$

This expression is maximized when its first derivative is set equal to zero, that is:

$$\frac{d(\text{PoP})}{d\,(\text{pH})} = \frac{dC}{d(\text{pH})}\,. \qquad (2)$$

Figure 3.1
The Standard Representation



The left hand side is the marginal benefit (or marginal damage avoided) and the right hand side is the marginal control cost. In terms of Figure 1, for states to the left of A, the additional costs of control exceed the additional benefits of reduced damage; to the right of A, the opposite is true. A decisionmaker who wishes to maximize net economic benefits will, therefore, be striving for a point such as A. If instead the vertical axis represents the present value of a stream of expected damages and control costs, he will also strive for A, given independent damages and control costs across periods. In short, whether observed or inferred by benefit-cost analysis, the "prices" of additional damages or additional controls given to the decisionmaker in the neighborhood of an initial acidity state will always be a signal to move toward that state maximizing the net benefits of control.

There exist at least two reasons why the form of the underlying ecosystem dose-response function in the preceding figure may be inaccurate insofar as acid precipitation is concerned. The nature of the inaccuracies implies that the rationales usually offered for compromising between the benefits of pollution-generating activities and the prevention of ecosystem damages may not always be applicable to acid precipitation issues.

The All-or-Nothing Feature: Nonconvexities

The preceding analysis has presumed that, within any one period, the increments to ecosystem damages are monotonically increasing with respect to ecosystem acidity. At least insofar as fish and some other aquatic organisms are concerned, this presumption is contrary to some published evidence [Raddum (1978)]. Consider, for example, the following two tables constructed from data appearing in the study of Butler, et al. (1973) on the impact of acid mine drainage upon fish and other organisms in Pennsylvania streams.[1/] For varying sustained pH levels, Table 1 shows the number of stream sections that had fish populations out of 25 sampled sections in different streams; while Table 2 shows, of the 116 fish species known to exist in Pennsylvania as of 1957, the variation with respect of pH of the number of species in these stream sections. Table 2 also indicates the pH levels at which assorted game and food fish disappeared due to lethal effects and/or recruitment failures. Both tables exhibit very rapid declines in fish populations once pH drops below 6.5. However, this decline itself rapidly decreases $[(\partial^2 \text{Population}/\partial \text{PH}^2)>0]$ as PH levels reach and drop below 6.4. Assuming that the implicit unit price of remaining fish and species is a constant, Figure 2 is a sketch of Tables 1 and 2.

Returning temporarily to Figure 1, in order that A be a maximum' rather than a minimum, it is necessary that,

Table 3.1-Sections with Fish at Various PH Levels for a Sample of Pennslyvania Streams Suffering from Acid Mine Drainage

pH	Stream Sections with Fish
6.4	24
6.3	12
5.9	6
5.3	3.
4.6	1
4.5	0

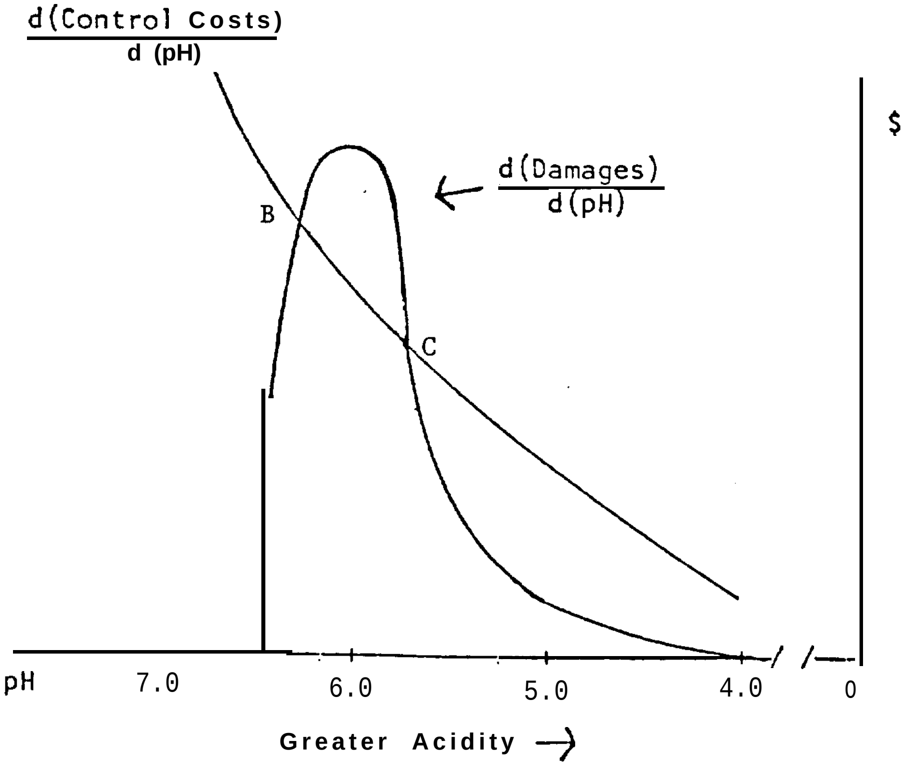
From: Butler, et al., (1973, P.112)

Table 3.2-Variation of Number of Fish Species with Respect to pH Levels for a Sample of Pennslyvania Streams Suffering from Acid Mine Drainage

pH	Number of Species Present	No Longer Present
≥ 6.5	116	
$6.4 \leq pH < 6.5$	48	Catfish, smelt
$6.2 \leq pH < 6.4$	41	Redfin pickerel
$6.1 \leq pH < 6.2$	36	
$6.0 \leq pH < 6.1$	34	Smallmouth Bass
$5.9 \leq pH < 6.0$	18	Brown Trout
$5.6 \leq pH < 5.9$	12	
$5.5 \leq pH < 5.6$	10	Yellow perch
$5.2 \leq ph < 5.5$	9	
$5.0 \leq pH < 5.2$	8	Brook Trout
$4.7 \leq pH < 5.0$	7	Largemouth Bass
$4.6 \leq pH < 4.7$	5	Chain pickerel
< 4.6	0	

From: Butler, et al., (1973, Pp. 96-99, 114)

Figure 3.2
The Nonconvexity Problem



$$\frac{d^2(Pop)}{d(pH)^2} \quad \frac{d^2C}{d(pH)^2} \leq 0 \qquad (3)$$

and sufficient that

$$\frac{d^2(Pop)}{d(pH)^2} \quad \frac{d^2C}{d(pH)^2} < 0 \qquad (4)$$

A further sufficient condition is

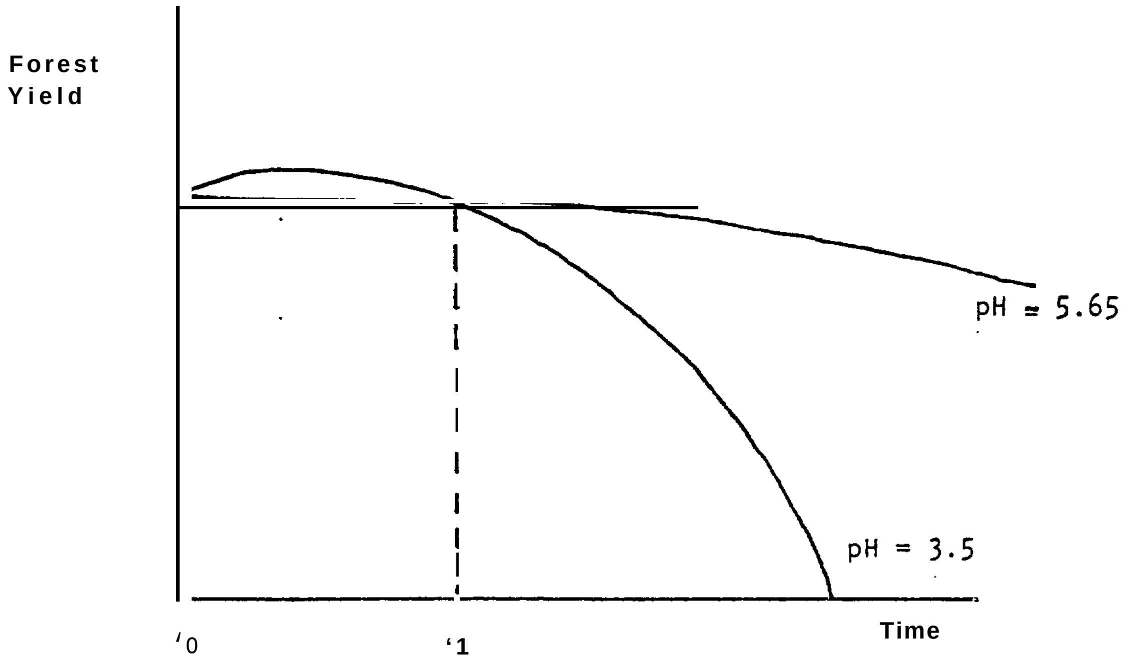
$$\frac{d^2(Pop)}{d(pH)^2} < 0, \text{ and } \frac{d^2C}{d(pH)^2} > 0, \qquad (5)$$

as Figure 1 presumes.

The data in Table 2 shows that $d^2(Pop)/d(pH)^2 > 0$. Hence the sufficient conditions may not be satisfied at a point where marginal benefits are equated to marginal costs.[27] The second order necessary condition could be violated turning such a point into a local minimum rather than a maximum. This is what happens at point C in Figure 2. The observed or inferred current prices existing at and to the right of C provide unreliable signals about whether the decisionmaker is at a maximum. or minimum and the direction in which he must move in order to obtain an increase in net benefits.

It is also evident in Figure 2 that if the environment were already highly acidified, a large cost burden with relatively few benefits would have to be borne prior to reacquiring the benefits of a relatively nonacidified state. Thus , given limited restoration resources, it may no longer appear worthwhile to restore the nonacidified state. As a result, decisions to control acid precipitation may have strong "all-or-nothing" elements: intermediate control measures can lead to burdensome control costs while generating few environmental benefits. Literal interpretations of prices applying to initial states lying at and to the right of C in Figure 2 would guarantee high levels of acidification: the ecosystem destruction wrought has been so great that the benefits from reduced acidification appear minor. To use an extreme example, the benefits from increasing fish recruitment cannot appear large when there are no fish around who can reproduce. Only by undertaking the far more arduous and complex task of empirically accounting for the ecosystem and economic adjustments and consequent changes in price structure resulting from

Figure 3.3
Possible Time Path of Acid Precipitation Effects



a large move from an initial state at or to the right of C to a state in the vicinity of B could the benefits of reduced acidification be captured.[37]

The Now-or-Never Feature: Irreversibilities

In the above, we have remarked on the distorted picture of reality that market or market-like price signals can introduce when the incremental damages of acidification within a period are declining. It is argued that if a state of high acidification is reached, the decisionmaker must expand the scope of his vision and analysis to include discrete rather than marginal alterations in existing states. Given this scope, we have presumed that he is able to reverse the current and future consequences of current and past acidification so that acidification levels henceforth remain in the vicinity of B. In short, we have presumed that the marginal damage function in Figure 2 is invariant with respect to both the status quo point and the direction of movement. The presumption appears to be incorrect for the effects of acid precipitation upon many components of forest and aquatic ecosystems.

Figure 3 is consistent with findings which attribute via soil amendments stimulator [Lee and Webber (1979); and Maugh (1979)] and debilitating [Jonnsson and Sundberg (1972); Tamm (1976)] effects upon plant growth to acid precipitation. In Figure 3, it is assumed that over some decade-or-longer period, a forested region is annually subjected to precipitation averaging pH = 3.5. The line labelled $\sim$5.65 refers to a “no acid precipitation regime. It decays slowly because of the natural tendency over millennia of soils in humid regions to become acidified. Under an acid precipitation regime, where forest management practices and influential factors other than acid precipitation are assumed invariant, the line labelled pH = 3.5 becomes relevant. Acid precipitation thus accelerates the natural tendency over time of soils to become acidified, as McFee, et al. (1976) and Peterson (1980) emphasize.

Over the $t_1 - t_0$ interval, the acid precipitation (or acidifying deposition) is neutral with respect to or contributes positively to forest yields. The sulfur and nitrogen compounds in the precipitation can directly and indirectly enhance the nutrient content of the forest soils. After t_1, however, the atmospheric inputs of positively charged hydrogen ions are greater than the ability of the forest soils to neutralize them. Organic and mineral nutrients are then leached from the forest soils at a rate more rapid than they can be replaced from atmospheric, decomposition, weathering, and microbial sources [Likens (1977)]. Simultaneously, phytotoxic metals, such as soluble inorganic aluminum and iron, are made more available and organic matter accumulates to seal the upper layers of the soil column while permitting various phytotoxins to be formed from the matter [Brady (1974, Chap. 14)]. As time passes, with the frequency and intensity of acid precipitation invariant, the rate of nutrient leaching and phytotoxin formation accelerates [McFee (1978, p. 66)]. In turn, this is expected to cause forest yields to decline at an increasing rate. Moreover, since water bodies serve as catchment basins for land areas, they too are expected to experience increases in hydrogen ion concentrations and heavy metals.

Once levels of forest soil (and water body) acidification beyond t_1 are widespread, there is no evidence that large-scale reverses are economically (or even technically) feasible in anything other than geologic time. The addition of lime to acidified soils and water bodies is the only widely considered technical remedy. It is, of course, a commonly used remedy in agriculture. However, as Tisdale and Nelson (1976, p. 428) note, limestone particles cannot move in the soil and must therefore be placed where they are needed in the soil column. Rorison (1980, p. 206) remarks that isolated additions of lime to acid sulfate soils are of no lasting value. Tilling lime into extensive areas of forest soils with standing trees would seem an economic, if not a technical, impossibility.[4/] Moreover, Tamm (1976, p. 338) adds that when lime has been added to forest soils in small-scale experiments, tree growth rates have typically not been enhanced. He attributes this to the tendency of the lime to immobilize the nitrogen in organic matter and thereby reduce its availability to trees. Abrahamsen, et al. (1980, p. 357) found that soil animal populations nearly always failed to increase when soil acidity was reduced by liming.

The practicality of large-scale liming to resolve the problems life forms have in acidified water bodies appears to be no better than for forest soils. As Holden (1979, p. 11) emphasizes, the effective use of lime to raise the pH of natural water bodies requires a great deal of information about the hydrological and chemical properties of each body of water. He notes that most of the added lime is flushed out, fails to dissolve, or remains in the sediment. Reactivity of the lime will vary with its purity, particle-size, hardness, magnesium content, chemical constituents and stratifications of the water body by season, and a host of other factors.

Finally, according to Dickson (1978, p. 58) and Bengtsson (1980), care must be taken when raising aquatic pH levels to ensure that they are not allowed to persist in the 4.5-6.0 range. Heavy metals, particularly the inorganic aluminum that acidified waters contain in abundance, becomes especially toxic to older fish. Thus liming must be calibrated for the state of the fish as well as for the state of the water. This toxicity is dramatically illustrated in Bengtsson's (1980) report on the successes of Swedish lake liming experiments. His data indicate that the perch in one lake before liming were all large and mature individuals. After liming, the number of perch increased by a factor of 100 but the size of the representative individual had declined by a factor of 10. Liming redresses the balance of harm by destroying the older and larger fish surviving the original acidification. As Bengtsson (1980, p.35) states, “when liming an acid lake the organisms suffer a transition period before the metals have been precipitated . . . liming has even killed salmon and trout when the aim was to save the fish." This problem is further substantiated by Professor Harold Harvey a zoologist at the University of Toronto. In a July 15 article on the "Acid Lakes" in the Toronto <u>Globe and Mail</u>, Professor Harvey is quoted as saying, "Noone knows to what degree of certainty what liming will do." He adds that indiscriminate liming "may improve the pH and end up killing all the fish" by setting off a chemical reaction involving lime and heavy metals in the lake. If continuing acidification requires intermittent liming, Bengtsson's (1980) data are therefore consistent with an inability to retrace the damage function relevant to declining pH.[5]

This litany of complexities in deciding how much lime an acidified water body requires and when this lime is required by no means suggests that widespread and large-scale intermittent or continuing liming is likely to be economically attractive. At best, the litany suggests that a subtraction of the expected costs of successful liming from the marginal damage (marginal benefit) curve of Figure 3 will drastically lower the curve when the status quo point is less than pH = 6.0. Thus for given marginal costs of reducing actual emissions, even though pH may vary over the same interval, the net benefits of recovering the pH at the high end of the interval will be less than the net benefits of preventing a decline of pH to the low end of the interval.: the marginal benefits of raising pH are less than the marginal benefits of preventing declines in pH.[6]

As is true for nonconvexities, the irreversible features of acid precipitation-induced ecosystem deterioration can mean that current prices will provide misleading signals about the most valuable corrective steps to take.

Standard economic representations of the efficient depletion of environmental or other assets require that the present value of the gains from further depletion in any period be equal to the sum of the depletion losses and interest charges. When property rights to the resource are secure, this implies, as Scott (1973) has shown, that the present value of the marginal unit of depletion in each period must be the same in all periods; otherwise, gains could be obtained by shifting units of depletion from periods where their present value is lower to those where it is higher. Delays avoid the costs of engaging in the activity that causes the depletion, but they also require an increased waft for the benefits the activity yields. Given a positive discount rate, if the present value of marginal depletion units is to be the same across all periods, the current undiscounted value of the marginal unit in each subsequent period must be greater by the rate of interest than the current value of the marginal unit in the immediately proceding period. In short, the rate of increase in the value of the resource that remains will tend to approach the rate of interest.[7]

The above result explicitly weighs the impact of current depletion activities upon the opportunities for depletion that remain in future periods. This result can be contrasted with a situation where the depletion is reversible. Consider, for example, the agriculturist who acidifies his soils by the use of ammonia fertilizer amendments. He will simply allow acidification to continue until the current period net gain from further acidification no longer exceeds the current period net gain from. restoration accomplished by liming. Since his soil acidity can easily be reduced by liming at any time he wishes, there is no reason for him to weigh the impact of his current fertilization practices upon his future opportunities for growing corps. There are no future opportunity losses for him to count as a cost: he will therefore base his decisions only upon current market prices.

Acid precipitation accelerates the rates of depletion of the buffering capacities of forest soils and water bodies in addition to reducing the current flows of material goods and amenity and life support services from these resources. Any control plan which accounts only for the value of the reduction in current flows, as registered in actual or inferred current market prices, will thus underestimate the damages acid precipitation is causing. Stated in an alternative manner, even though the current net benefits of continuing acid precursor emissions may still be positive, it may be optimal to cease emitting. Some immediate losses must be borne in order to avoid the possibility of even greater losses later on that the current precursor emissions can readily cause.

If the benefits of acidification decline over time relative to the benefits of natural environments, the irreversible effects of acidification, when combined with a positive discount rate, lend the acidification issue a now-or-never character. This is most easily seen by assuming perfect foresight and by disregarding anv short-term fertilization benefits. In particular with a positive discount rate, any delay in causing above-background acidification will only make it look progressively less attractive. Not only are the relative benefits of acidification declining over time by assumption, but the positive discount rate causes the present value of acidification benefits to be reduced with every delay. In the meantime, since the unacidified ecosystems already exist, the material goods and life support and amenity services they produce continue unabated. Therefore, cet. par., the net gains from ecosystem acidification will never be greater than they now are.

The presence of declining relative benefits of acidification (or increasing relative benefits for preserving natural environments) is a necessary condition for the above conclusion. As set forth by Smith (1974) and others, two key propositions lead to a prediction of increasing relative benefits for natural environments. First, environments that have remained unsullied by man's activities and artifacts are superior goods. That is, as real incomes increase, the willingness-to-pay for natural environments increases at an even greater rate. Man-made substitutes become progressively less attractive. Second, because of the imperfect reproducibility of natural phenomena, technological change tends to reduce the supply prices for man-made goods relative to the supply prices for natural environments. The obvious general conclusion is that both the relative cost of supplying and the willingness-to-pay for natural environments are going to increase progressively over time. Both of these countervailing supply and demand forces imply that the citizenry will attach increasing values to natural environments relative to fabricated goods.

When combined with the fact that at present very little is known about many of the social, environmental, and financial consequences of ecosystem acidification, the irreversibility phenomenon introduces yet another basis for expecting declines over time in the relative benefits of acidification. As Arrow and Fisher (1974) have demonstrated, the possibility that current actions might burden and constrain (deplete) future opportunities must be counted as a cost against the current action. In short, the irredeemable nature of current acidification may foreclose valuable future options, whether due to currently unknown technologies, price structures, or changing tastes. Since new information can be exploited only if irreversible consequences have been avoided, the consequences of a decision to acidify cannot be undone even if the new information suggests that the decision was mistaken. Thus if acidification is ultimately discovered to have only trivial irreversible and undesired consequences, a delay in the decision to acidify can only mean that the present value of its ultimate benefits is reduced. On the other hand, if these undesirable consequences will actually be present, delay serves to enhance the probability they will be discovered, thus making a decision to acidify appear less attractive than it now does. Of course, the chances of discovering nontrivial adverse consequences of acidification might reasonably be directly related to the completeness of the existing state-of-knowledge about these consequences and the prospects for rapid advances in this knowledge.[8/] If this relation is direct, it follows that the expected decline in the relative benefits of acidification will be less than otherwise: delays in the acidification decision are then made to appear more favorable.

Summarv and Conclusions

We have discussed two decision problems in the optimal control of acid precipitation. The first problem concerns the shape of the dose-response function while the second concerns a possible ratchet-effect associated with movements along a given dose-response function.

The shape of the dose-response function determines the shape of the marginal damage (benefit) function associated with varying levels of acidity. Studies of the impact of acidity on fish species suggest that the relevant marginal damage curves are nonmonotonic functions of the acid level. As a result there may exist more than one level of acidity and associated price structure which balances the marginal benefits and marginal costs of reducing acidity. Not all of these levels and price structures will be welfare maximizing, some may be welfare minimizing in the sense that small deviations in either direction may improve welfare.

The analysis presented with respect to the shape of the dose-response function did not explicitly consider the dynamic costs of adjustment. If an ecosystem becomes highly acidified as a result of having made decisions based upon prices in the n.eighborhood of a minimum point, then it may become optimal to forget about attempts to control. This result occurs because the possibly large short-run costs of control dominate the benefits of the action. This result was obtained. by Forster (1975) in a study of water pollution control. For sufficiently high levels of pollution, it is economically optimal to allow a waterway to become biologically dead. This result depends upon a high rate of discount. As the discount rate approaches zero, the result evaporates, This is not surprising since the adjustment costs loom large in the short-run while the discount rate shrinks the present value of future benefits. We will not enter into a debate over the appropriate discount rate--but its importance should be noted.

The ratchet-effect of the dose-response function refers to the possible irreversibility of the environmental disruption caused by increased acidity. A given increase in acidity reduces natural resources by an amount ΔR determined by the dose-response function. Subsequent equivalent reductions in acidity may not increase natural resources by as much as AR or may not increase them at all. As long as this relationship is known and understood by all, then market price signals should correctly reflect the net benefits of the situation. If the relationships are not known, however, then current market prices will not reflect the future costs of current actions and acidification will proceed too far.

These decision problems suggest certain research and policy strategies for acid precipitation. The potential irreversibilities dictate that systems which are on the verge of acidification be subjected to immediate research to ascertain the properties of their dose-response functions. Fisher and Krutilla (1974) have argued that uncertainty regarding any irreversible destruction that might be caused by an activity may be sufficient reason to justify postponing the activity until the relevant information has been collected. In the case of disruption due to acid precipitation, the activity is now occurring and may intensify even while the information gathering is taking place.

The discussion regarding the shape of the dose-response function suggests a possible policy strategy for control in aquatic ecosystems. It suggests that systems may be classified into two groups according to their current acidity levels. The first group consists of those systems whose pH levels are sufficiently high (to the left of B in Figure 2) to make them worth saving. The second group consists of those that are not worth saving--the adjustment costs dominate potential benefits.[9] This negative prescription may be put in a more positive light. Much work needs to be done quickly to keep more systems from moving from the first group to the second. At the same time, the frequency with which this nonconvexity issue occurs in the responses of ecosystems must be more completely identified. Table 2 raises the possibility that it could be a creature of ecosystem diversity. It is to the problem of valuing this diversity that we turn in the next chapter.

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[1] Although waters that are acidified from mine drainage perhaps contain more iron compounds than waters derived from acid precipitation, mine drainage otherwise seems to have a chemistry generally similar to that of precipitation-derived water. The high concentrations of iron hydroxides present in acid mine drainage are known to intensify the harmful effects of pH ≤ 6.5.

The situation in lakes may be different than in streams. Streams may be more capable of flushing themselves than lakes. Also the ability of fish to migrate in order to avoid high levels of acidity may be greater in steams than in lakes.

Fromm (1980) warns that "Data relating to the specific effect of low pH on growth of freshwater fishes are ambiguous." It is significant for the purposes of the present paper which seeks to point out potential difficulties in the control of acid rain to fird one example of the type presented. However, the frequency with which this nonconvexity issue occurs in the responses of ecosystems must be more completely identified.

[2] Arthur Okun has an interesting comment on economic optimization:

> "The wise economist knows, however, that merely finding a marginal- that is not sufficient for an evaluation. A rigidly incrementalist approach can lose sight of major opportunities. Locating the least soggy spot in a swamp is not optimizing if high ground is accessible outside the swamp."

<u>The Political Economy of Prosperity</u> (Brookings Institution, 1970), p. 4.

[3] There is some evidence that there may be nonconvexities present in the benefit function for improved forest aesthetics. For example, in a psychological study of individuals' responses to insect and damaged southern pine forests, Buhyoff and Leuschner (1978) found that "visual preference" dropped rapidly as damages increased to 10 percent of the forested area but that preference declines were minor thereafter.

[4] In principle, the spreading of lime on <u>top</u> of forest soils might raise precipitation pH before it moves down the soil column. We are unaware of any commentaries on either the technical or the economic feasibility of this

practice.

5/ The tone of Bengtsson (1980) is optimistic with respect to the practicality of large-scale liming to restore acidified water bodies. He tends, however, to abstract from details that might compromise the optimistic tone. Barnes (1979, p. 1.232) speaks approvingly of the prospects for neutralizing to be obtained by placing a lime column in a river bank. Andersson (1980, p. 6) reports that six-fold higher neutralization effects have been acquired using sodium hydroxide rather than lime in laboratory experiments.

6/ Houck (1977) provides a technique for specifying and estimating nonreversible functions.

7/ Let the extraction of the marginal depletion unit be delayed from t_0 to t_1. This delay would cause the undiscounted net return in t_1 to be $(p_0-\dot{p}t_1c)$, where the dot indicates the time derivative of price. Assuming $c=0$, if instead the depletion unit is extracted in t_0 and the net returns (p_0c) invested in some other asset, the value of the investment in t_1 would be $(p_0-c)(1+rk)$, where k is the time interval between t_1 and t_0, and r is the rate of interest. Upon equating $(p_0-\dot{p}t_1-c)$ and $(p_0c)(1+rk)$, and simplifying, we are left with $\dot{p} = r(p_0c)$, which says that in a regime of secure property rights in the resource, its market price increases at the rate of interest over time.

8/ With the possible exception of limnology, where experimental means have been extensively used to study the behavior of ecosystem functions such as productivity and decomposition. [Vervelde and Ringelberg (1977)], many ecologists view the prospects for rapid accumulation of new information as unfavorable. Most of the relevant ecological disciplines lack a corpus of empirically testable propositions derived from a broadly encompassing analytical structure as well as quantitative bits of information that have been related to or associated with each other [Clark, Jones, and Helling (1979)] . Resort, therefore, has been either to simulation models or to the real-time tracking of the behavior of a system under stress.

9/ Allen Kneese has reminded us that the West Germans approximate this policy in their assignment of separate rivers and streams to pristine and highly polluting uses. Note also that the PSD program of the 1977 Clean Air Act Amendments in the United States is consistent with this policy approach.

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