V. NATURAL SCIENCE RESEARCH USEFUL TO THE ECONOMIST

Introduction

Throughout the preceding chapters, we have emphasized the necessity of knowing the influence of various physical and biological factors upon some ecosystem variable of interest if economic methods for assessing the benefits of controlling acid precipitation are to be applied.[1/] At the same time, we have formulated several analytical and empirical characterizations of the acid precipitation problem intended to be helpful in deciding which of these relations are likely to be worthy of more immediate research attention. For example, our discussion of nonconvexities and irreversibilities in Chapter 111 leads to the conclusion that the very early stages of ecosystem acidification often have the greatest economic consequences. The devotion of research resources to understandings of the behaviors of already highly acidified systems may, therefore, yield little information that is economically important. However, before abandoning or greatly reducing research on already highly acidified systems, it is obviously important to establish accurately the temporal and spatial frequencies of the nonconvexity and irreversibility issues. If these issues appear with considerable frequency, then an allocation of research resources that accords with the ordering of current annual sectoral control benefits estimated in the "first exercise" of Chapter II might well be mistaken. The economic import of a unit of information on indirect ecosystem effects could presently be much higher than would more information on materials damages or direct agricultural effects.

The treatment in Chapter IV is intended to reinforce the theme that the (relatively) easily observed current direct economic effects of acid precipitation could readily have the least long-term economic significance. By providing a skeleton for combining economic analysis with ecological energetic that is built upon resource allocation processes, we have tried to establish a basis for valuing the possible effects of acid precipitation upon the life support services and human pleasures that ecosystems supply. Traditional economic assessment methods, as set forth in Chapter I, disregard these services except insofar as they are valued independently of the the environmental states that produced them. Any empirical implementation of the skeleton set forth in Chapter IV that captures at least some features of the values of these life support services will clearly require substantial contributions from that part of ecology which describes the combinations and quantities of ecosystem components resulting from various quantities of available energy.

Although knowledge of the response of some result to various mixes and magnitudes of inputs is central to the concerns of previous chapters, we have as yet discussed few criteria for deciding when a particular response, given limited research resources, is worthy of attention. In succeeding sections of this last chapter, we present some qualitative criteria for deciding when attention is warranted. We also shall point to some factors that might determine the relative benefits and costs of alternative research efforts into particular ecosystem responses to acid precipitation. In economic language, the concern of this chapter is with the value of research into the effects of acid precipitation upon ecosystem production functions or response surfaces. Because the economist's concept of the production function often differs in subtle but economically important ways from the natural scientist's idea of a dose- response function, we take a brief respite in the next section from the central purpose of the chapter to present a brief overview of concepts in production theory particularly relevant to later discussion.

The Production Function

All results or outputs require at least two kinds of causative agents or inputs. Usually many more than two inputs are required. In general:

$$Y = f(X_1, X_2, \ldots, X_n), \tag{1}$$

where Y is the quantity in similar units of an output rather than the number of possibly dissimilar individuals in some biological. population, the X_i (i = 1,...,n) are input quantities which may themselves be an output of some other production process, and Y, $X_h \geq 0$, without exception. It is usually, but need not be, assumed that (1) is twice differentiable, with $\partial Y/\partial X_i > 0$, $\partial^2 Y/\partial X_i^2 < 0$, and $\Sigma(X_i/Y)(\partial Y/\partial X_i) < 1$. Negative inputs such as acid precipitation can be defined so that redactions in their levels constitute positive inputs. The first two assumptions are typically referred to respectively as positive but diminishing marginal products, while the third assumption represents decreasing returns-to-scale. The expression (1) is typically viewed as being perfectly reversible, where reversibility is defined as the absence of asymmetrical changes with respect to the status quo point and the direction. of movement. Rarely are any restrictions placed upon the sign of $\partial^2 Y/\partial X_i \partial X_j$ for $i \neq j$.

Expression (1) implies that all the X_i are variable and of relevance for determining the value of Y. However, there are many instances where the influence of an X_i upon a Y is trivial or nonexistent either because the X_i is fixed or has so little influence that it can be disregarded. Thus if n-m inputs are fixed or considered to be trivial, (1) can be written as:

$$Y = f(X_1, \ldots X_m; X_{m+1}, \ldots, X_n), \qquad (2)$$

with the X's to the right of the semicolon being treated as irrelevant for the problem at hand.

Neither (1) nor (2) are necessarily concerned with growth in terms of the number of individuals in some biological population. Temporal considerations may nevertheless be introduced by treating time as one of the inputs or by treating the inputs themselves as functions of time. However, most economic treatments treat the time interval as fixed and emphasize various relations between and among the biophysical and human inputs and between these inputs and the outputs. These latter relations, rather than population dynamics considerations, tend to be emphasized because they are the key to most applications of the economic assessment methodologies outlined in Chapter I.

For a particular level of output, Y, rates of substitution, dX_1/dX_2, between any pair of inputs, X_1 and X_2, can be determined by total implicit differentiation of $\bar{Y} = f(X_1, X_2)$. Thus, since $X_1 = f(X_2, \bar{Y})$, we have:

$$\frac{\partial Y}{\partial X_1}\frac{dX_1}{dX_2} + \frac{\partial Y}{\partial X_2} = 0$$

and therefore:

$$\frac{dX_1}{dX_2} \qquad \frac{\partial Y/\partial X_2}{\partial Y/\partial X_1} \qquad (3)$$

where, as before, the numerator and the denominator on the right-hand-side are the marginal products of the respective inputs. If the marginal products are positive, (3) means that the level curve or isoquant depicting dX_1/dX_2 for a particular $\bar{Y}$ must have a negative slope as in Figure 1. The isoquant, $\bar{Y}$, in Figure 1. does not represent the rate of substitution of X_1 for X_2 in any basic biochemical. or physiological process or production technique. It merely displays the fact that within limits the same quantity of output can be obtained from various combinations of possibly very diverse inputs. For example, there are probably numerous combinations of reductions in acid precipitation and liming of forest soils which will result in identical standing stocks of timber. The underlying physiological processes are of interest only insofar as they contribute to comprehension of the effects of input mixes and magnitudes upon an output or result that has economic relevance.

Given that there are positive marginal products for all inputs, there will exist a series of isoquants like those depicted in Figure 1. Levels of output are increasing as one moves away from the origin. The set of all such isoquants is a response surface. If all inputs but one are fixed, say at X_2 in Figure 1, then the response of Y to various applications of X_1 is a response function.

If the marginal products of each input are someplace positive but diminishing ($\partial Y/\partial X_i > 0$, $\partial^2 Y/\partial X_i^2 < 0$), then some portion of a level curve or isoquant depicting dX_1/dX_2 for a particular Y will have a convex shape as in Figure 1. 2/ This implies that as one moves up (down) the isoquant, it becomes progressively more difficult to substitute $X_2(X_1)$ for X1(X2); that is, a larger and larger quantity of $X_2(X_1)$ is required to replace the loss of a unit of $X_1(X_2)$ if the level of output is to remain. unchanged. There is, of course, no reason whv the isoquant could not be depicted as in Figure 2, where the concave interval ABCD implies either that the marginal product of one or the other inputs has become negative (the intervals AB and DC), or that the marginal products of both inputs are negative (the interval BC). Whether reference is to human decisions or to the behavior of a nonhuman organism, if the isoquant were everywhere concave, only one input would ever be used since the marginal benefits of use of the first input would decrease the more of the other input was used. The use of only one input does not usually accord with experience in either the human or natural worlds, thus implying convexity of the level curves. Production objectives would be ill-served by operating in the concave portion of the isoquant (the interval ABCD): the same level of output could be obtained by using less of both inputs or less of one input and no more of the other input. 3/

In Figure 2, we see that the concave portion (the interval ABCD) of an isoquant need not be described in any detail because these portions ill-serve any organism that acts "as if" it wishes to minimize the resources that must be expended to reach a given level of an objective. For example, a human might wish to minimize the costly resources he must use to achieve a given goal, and a nonhuman organism might behave so as to minimize the available energy it must expend to acquire a particular amount of nutrition. If only those portions of the response surface are studied where all inputs have positive marginal products, one may rest assured that concave portions are being avoided.

Economic analysis can be employed to delimit further the portions of the response surface that are worthy of description if organisms behave as if they minimize the resources that must be expended to reach a given level of an

Figure 5.1
A Response Surface

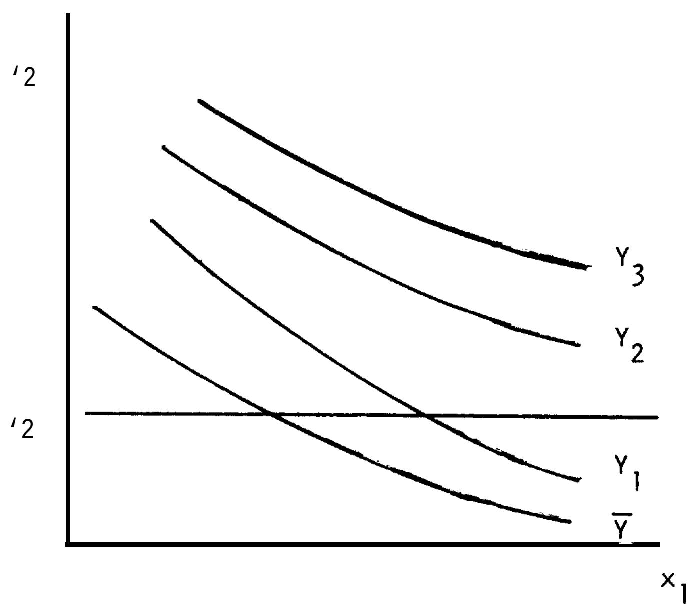
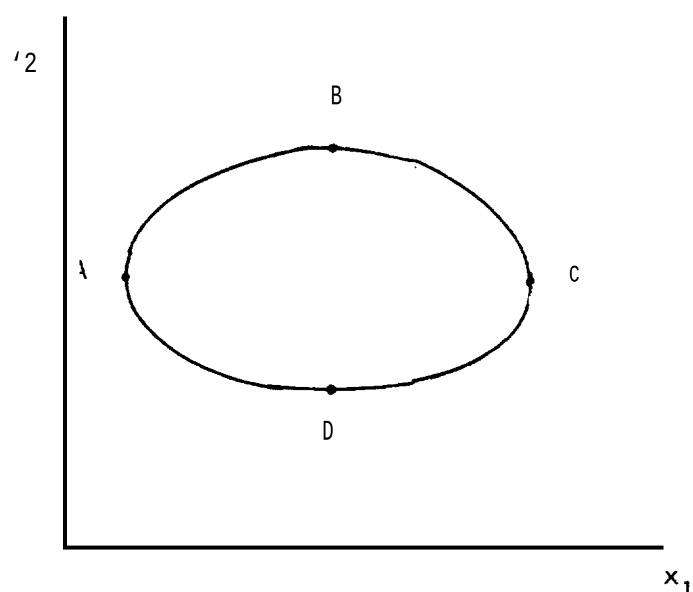


Figure 5.2
Convexity and Concavity



objective, or, equivalently, as if they maximize subject to available resources the level of attainment of some objective, whatever this objective might be. Reconsider the fox in Chapter IV who obtained his nourishment from various combinations of rabbits and squirrels. The combinations that he chose and therefore the only steady-state or long-run equilibrium combinations that would be observed in nature would conform to a condition where any reduction in the net input of energy obtained from rabbits (squirrels) would be matched by an increase in the net input of energy obtained from squirrels (rabbits). Thus, if one were trying to describe the effect of pollution upon the feeding habits of foxes with respect to rabbits and squirrels, only those combinations of rabbits and squirrels on the convex portion of each fox isoquant that conformed to the condition under various pollution levels would be of interest. Of course, these combinations mav themselves constitute the object of any research effort. Nevertheless, it is likely that an accumulation of research knowledge would ultimately indicate that some rabbit and squirrel combinations on the convex protions of the isoquants are clearly inconsistent with the condition, meaning that their impact upon the well-being of the fox need not be candidates for description. They would certainly be of no concern to the fox, and if the only research object is to describe naturally occurring states, information about them would be of no value to humans. Alternatively, if it is initially thought that any one of the combinations on the convex portion of a particular isoquant could ultimately prove to conform to the condition, information on the state of the fox's well-being under each of these combinations would have some positive value. In short, the researcher, if he is interested in describing naturally occurring states must dismiss consideration of input combinations known to be inconsistent with the behavior of the organism that is the subject of the research. Economic analyses of research allocation processes, as set forth in this and the previous two chapters, can contribute to identifying the aforementioned combinations. Those who refuse to let the behavior of organisms direct their research would apparently perceive no qualitative difference between studying the effect of feeding corn to a beached whale and studying the impact of SO_2 fumigations upon a laboratory plant that is supplied with more nutrients than it could or would acquire in its natural or agricultural state.

The Value of Information and of Alternative Models

Returning momentarily to (1), there are several levels of completeness of knowledge that one might acquire about the effect of pollution on a given production or response surface. Completeness would involve knowledge of the coefficients attached to each of the input variables on the right-hand-side of (1) and of its functional form. In the absence of knowing the values of the coefficients knowledge of whether each input variable has a "strong" or a "weak" influence on the output would be nearly as useful. If this knowledge is not directly available, knowlege of the functional form of (1) can allow deductions to be made about the relative levels of influence of particular input variables, given that one has some _a priori_ idea about the plausible bounds for the values of some coefficients. Moreover, knowledge of functional form assists in directing research to those input variables likely to be most influential in determining output magnitudes. However, _a priori_ knowledge of the functional form of (1) is very frequently beyond the analytical powers of the relevant disciplines to obtain. Most often, the specification of functional form must wait for the gradual accretion of empirical experience. Usually well before this empirical experience has been fully accumulated, deductive or empirical insight is acquired into the signs of $\partial X_i/\partial X_j$, $\partial Y/\partial X_i$, $\partial^2 Y/\partial X_i^2$, and $\partial^2 Y/\partial X_i \partial X_j$. As the bodies of theory in many disciplines, including macroeconomics and ecology, attest, knowlege of these signs can be most helpful. in drawing inferences about the underlying structure of the natural or social system being investigated. Having acquired these structural insights, bounds can often be imposed upon functional forms, the relative influences of variable pairs, etc. If knowlege of the signs attached to the preceding derivatives cannot be obtained, decisions founded on particular production or response surfaces must resort to simple listings of all or some of the variables thought to enter the right-hand-side of (l). However, unless these listings can ultimately be molded into a theoretical structure, they can contribute little to ultimate knowledge of the production or response surface. Only by sustained and substantial efforts to accumulate empirical experience can this knowledge be acquired. Even then, it must remain. unknown whether the accumulated empirical knowledge is generalizable to as vet unobserved events or whether different results obtained from seemingly similar settings are reconcilable.

There exist, as is clear from the preceding remarks, two mutually reinforcing yet partially substitutable fundamental ways in which knowlege about response surfaces can be acquired. Two legs, the theoretical and the empirical, are required to walk well, but for some tasks, one leg can accomplish more than the other. The question nevertheless remains as to how far toward complete specification of the form of the response surface investigation, whether theoretical and/or empirical, must proceed. This question can best be understood within the context of the economics of information. Two concepts, the value of information and the value of alternative models, are central to any research effort into the effects of acid precipitation upon the response surfaces of various ecosystems components.

The results of this research are intended to be of direct use to persons who must make decisions about the control of acid precipitation or to serve as inputs into other research efforts providing results useful to decisionmakers.

Research designed _only_ to reveal a greater understanding of basic biochemical or physiological processes must be evaluated on some basis other than that developed here. In order to establish a framework for evaluating research into the effects of acid precipitation upon the response surfaces of ecosystem components, one must consider together the decision which is at issue and the decisionmaker. As Crocker (1975, p. 342.) remarks, "the choice of a particular research effort or information system implies the use of a particular class of decision models since certain types of information are relevant to some models and not relevant to others. Conversely, the choice of a decision model implies the use of a particular class of information systems yielding the parameters of the model. [1/] The decision variable of interest here is the amount of acid precipitation to which an ecosystem component is to be subjected. The payoff from the decision is the net benefits of controlling the acid precipitation, defined as the economic value of the ecosystem component damages prevented less the cost of controlling the acid precipitation. The payoff is related to the decision through some imperfectly understood response surface.

As earlier noted, the arguments of the response surface include a great many other variables in addition to acid precipitation. The imperfectly understood response surface is approximated by some expression such as (1), where some X's might represent a taxonomic system (e.g., soil classes) originally established for an entirely different purpose, other X's might be measures set up specifically for the study of acid precipitation effects upon the ecosystem component of interest, and still other X's are inputs which can be measured but not predicted. Finally at least one X in (1) must represent a residual or error term intended to capture unknown, unacknowledged, and purely stochastic influences on the response surface.

The payoff, π is approximately related to the decision variable as:

$$\Pi = p_1 f(\cdot) - CX_A \qquad (4)$$

where p is the observed or inferred unit price of the ecosystem component of interest, c is the cost of reducing acid precipitation by one unit, and X_A is the number of units of acid precipitation. Since there exist unknown, unacknowledged, and purely stochastic influences upon $f(\cdot)$, and since the values of some other variables cannot be predicted prior to the control decision, for any given level of acid precipitation, the payoff is a random variable.

Whether performed by economists or noneconomists, the standard way to account for the randomness in expressions such as (4) has been to use range sensitivity tests. Waddell (1974), for example, includes upper and lower bounds and "best guesses" for various air pollution damage categories. A similar procedure is adopted in most of the ambitious work in d'Arge, et al. (1975) on the economic impact of climatic change as well as in Fisher's, et al. (1979) work on air pollution. damages in the State of California. An alternative but unfortunately rarely used procedure is to generate probability distributions for the random variables or the right-hand-side of (4), and then to aggregate these distributions to produce a probability distribution for the payoff measure.

Two readily un.derstandable examples of this approach, where the Weibull (1951) family of distributions is employed, are Pouliquen (1.970) and Mercer and Morgan (1975). These studies demonstrate that the valuable information made available to the decisionmaker and the researcher can be considerably enhanced: not only is he provided with the range of possible outcomes and payoffs but he is also presented with various common summary statistics allowing him to assign a probability statement to each outcome. These statements can be subjective rather than objective. Accumulated wisdom and intuition can be incorporated in an explicit and communicable fashion. Although many would object to the inclusion of subjective information, the question of real importance is not whether a particular probability assessment is subjective or objective but whether it has important consequences for the decision problem. Rather than fulminating over variables in some particular algebraic specification that fail to have coefficients significantly different from zero, most concern should be displayed about whether the formulation in question predicts better than the next best alternative. Errors of omission would seem no less worthy of critical scrutiny than errors of commission.

Another major advantage of the probability approach is that it does not throw away useful information. For example, in a poorly coordinated group research effort attempting to assess direct acid precipitation damages to commercial crops, the biochemist or agronomist might specify a response function relating some attribute of the crop to acid precipitation. This function, which the economist will employ to perform his assessment tasks, will likely be what the natural scientist considers to be the "best" of a set of several alternatives. In the absence of a thoroughly coordinated research effort in which the economist specifies the variables, units of measure, and sampling procedures the natural scientist is to use, it is likely that the natural scientist's conception of "best" does not coincide with the economist's.

It is then up to the economist, who usually is only semi-literate in the relevant natural science, to translate the natural scientist's results into something useful for purposes of economic analysis. Moreover, by being asked to present a "best" function, a great deal of the natural scientist's unique knowledge is being thrown away. Finally, the failure to report the full set of probable outcomes to the economist and thereby the decisionmaker means that yet another decision problem has been introduced: the natural scientist must assess which of the alternative formulations the decisionmaker will find most useful. By requiring that probabilities be assigned to the various plausible outcomes, the force of this decision problem is greatly ameliorated.

Any specification of a reponse surface will, except by chance, always be wrong. The suggested probability approach to the study of acid precipitation-induced response surfaces captures this fact. The implications of this for planning research into these response surfaces can be perceived by considering the investigator who must begin with very little information about the surface to be investigated. Guided by the principle that information should be acquired only as long as its value exceeds the cost of obtaining it, he can search for a finite number of kinds of information in varying quantities. Paraphrasing Marschak and Radner (1971), the value of additional information is the difference between the decisionmaker's current expectations of: (a) the payoff value that will occur if he chooses his act as well as he can without the information; and (b) the payoff value that will occur if he were to obtain the information and then choose his act as well as he can. In short, the value of the information is the increment in expected payoff that can be realized by having the information contribute to the decision.

When additional information is defined as a finer partitioning of some natural state, it may consist of both observations and experiments on a greater number of variables or on a particular variable, and a more discriminating model of the surface, i.e., a model that is better able to distinguish among alternative outcomes. The researcher must decide whether the reduced uncertainty and systematic broadening of identifiable alternatives that more information offers outweighs the costs of acquiring the information. The number of distinctions drawn can be no greater than the number of measurable consequences, if differences in payoffs are distinguishable only insofar as they generate measurably different results. In the next section, we take note of some of the more important aspects from the economist’s perspective of this problem.

Issues in Designing Studies of Response Surfaces

Anyone who proposes to engage in estimation of, as opposed to expatiation about, response surfaces must give pragmatic consideration to several practical and interrelated issues. All these issues require compromises with the abstract analytical frameworks of the applicable disciplines. A reasonably complete listing with particular relevance to the study of acid precipitation-ecosystem component response surfaces might be as follows: the design of response surface experiments; the estimation of these surfaces; the choice of a model to represent the surface; and the sources of discrepancies between response surfaces estimated in controlled or experimental conditions and observed in field conditions. We shall deal with each of these issues in sequence, trying to highlight those features of the issue that seem particularly relevent to studies of the impact of acid precipitation upon response surfaces.

Experimental Design: In situations where an experiment is the biologically appropriate way in which to generate and to test hypotheses about response surfaces, it is highly important that the economically relevant region (as defined in a previous section) of the surface be purposively and systematically covered. The great majority of biological research into response surface questions is of minimal use to the economist because it does no more than use analysis of variance techniques to establish only whether there exist statistically significant differences in the output obtained from a few levels of a single input. Rather than trying to design a systematic coverage of the economically relevant portion of the surface, the traditional emphasis has been and continues to be on replication, as if arbitrarily selected levels of statistical significance could impart structural understanding of system behaviour. Not only is the replication intended to improve the analysis of variance but to measure the variance as well. When the objective is to estimate a response surface, replication is much less essential. Primary concern should be with developing a model that predicts real world outcomes better than the next best alternative rather than testing whether the results of some particular model have statistically significant differences. Predictions are made so that something can be done: they are not first objects of contemplation. The proper object is informed manipulation of the system.

Changes in input mixes and magnitudes can substitute for replications of a particular input mix and magnitude since both types of observati.ons are intended to locate the response surface more accurately. For a given outlay of research resources, the information provided by more observations on output responses to an assortment of economically relevant input. mixes and magnitudes will usually be more valuable than will the information garnered from additional replications using a particular input mix and magnitude. Moreover, if alternative models have similar *a priori* plausibility as descriptors of a response surface, empirical discrimination among models will obviously be assisted more by increasing the breadth and the density of the sampling coverage of the surface rather than by replication of experiments directed at only one point on the surface. A near-infinity of models is consistent with a single point.

Bluntly put, the traditional experimental designs of biologists investigating response surfaces have been motivated by the maximization of disciplinary integrity. Designs have been structured via the mechanical application of purely statistical criteria so as to minimize the probability of accepting a false hypothesis. The result has been an excessive emphasis upon replication, if the purpose of the research is taken to be the provision of useful information to economists and to decisionmakers. To pose the point in an extreme fashion, given that it is well-known that acid precipitation harms fish, it is ridiculous even to advance for testing purposes the null hypothesis that fish are unaffected by acid precipitation. Neither the economist nor the decisionmaker cares whether there is a five per cent or less chance that a fish-acid precipitation response surface exists. Their problem is to know the value of the fish that are lost due to acid precipitation. Thus, if disciplinary custom dictates the supplication of significance tests, logic, rather than custom, requires instead that their application to the value-related quantities derived from the response surface be stressed. This stress would be consistent with our remarks in the previous section about the desirability of having probability distributions for the payoff measure.

Put in yet another way, because of the reasonable desire of each specialist to maximize his disciplinary integrity, a tension exists between the biologist and the economist with respect to the design of response surface research. The biologist will obtain less approval from his peers if he does not replicate in accordance with traditional standards. The economist will obtain less approval from his peers if he tries to draw inferences from a small undense and narrow sample of the response surface. For the latter individual, the cost of knowing nothing about large portions of the response surface will typically greatly outweigh the costs of small errors in estimates of a single point on that same surface. In design language, the economist is interested in the magnitudes of differences in treatment effects rather than in the existence of these differences.

Having pointed out a source of conflict in the desires of biologists and economists with respect to the design of response surface experiments conducted with limited research resources, we would like to provide some specific criteria a neutral observer could use to weigh the tradeoff between replication and density of coverage. Anderson and Dillon (1968) provide a detailed treatment of the efficiency conditions for this choice. Conlisk (1973), Conlisk and Watts (1979), and Morris (1979) extend earlier treatments of optimal experimental designs to cases where the form of the response function is unknown and both the research budget and the number of experimental units are limited. In the absence of a specification of a particular design problem, the three universal implications of these conditions for response surface experimental design are rather simple and apparent.[4/] First, the greater the sensitivity of the system being investigated to variations in exogenous parameters, the greater the desirability of additional replication. Second, the greater the number of factors thought to impinge in nontrivial ways upon system behavior, the more desirable is increased density and breadth of coverage of the economically relevant regions of the response surface. Third, since it is along these portions that outputs are sensitive to input mixes and magnitudes, research resources should be aimed at denser coverage and greater replication along the steeper parts of the economically relevant portions of the response surface, i.e., along those portions where $\partial^2 Y/\partial X_i^2$, $\partial^2 Y/\partial X_i \partial X_j$, $\partial X_i/\partial X_j$, and $\Sigma(X_i/Y)(\partial Y/\partial X_i)$ are substantial in absolute value. These parts have the greatest economic significance.

The preceding remarks with respect to the tradeoff between increased density of coverage of the response surfaces versus increased accuracy of estimation of a point on that surface apply with equal force to spatial and temporal influences. For example, those who determine the allocation of research resources into the ecosystem effects of acid precipitation will be faced with choices about whether it is preferable to study one or a very few locations in depth or to distribute limited research resources over a wide variety of locations. To the extent that the economically relevant portions of response surfaces are susceptible to spatially and temporally distributed factors, it is important to account for them. A one time period, one location experiment will provide little useful information for analysis. Some insight on how response experiments might best be located over space and time so as appraise variability is provided by Anderson (1.973).

Tn general, the essential fact of which the allocator of research resources must be aware is that there likely exist positive but declining marginal payoffs to additional observations drawn from any particular system or for any variable or particular combination of variables in that system thought to influence the response surface: that is, each additional observation adds something to the expected payoff, but these additions get progressively smaller as the number of observations increases. If the cost of research is a monotone increasing function of the number of observations, one obtains the familiar optimality condition determined by the equation of marginal costs and marginal payoffs.

Evenson and Kislev (1975) have made use of this condition to distinguish between basic and applied research. They describe the latter as involving drawings from a given probability distribution of the research payoff, while basic research shifts the first moment of the distribution or discovers new distributions from which to draw. A similar distinction might be made between acid precipitation response research which proposes to concentrate on one or a few locations, and thereby proposes to draw observations from only a very limited number of payoff probability distributions, and response research intended to draw from a variety of distributions by spreading out its available resources over a substantial number of locations. Research bound to one location will, by definition, have to concentrate its observations around one payoff value. There is thus very little chance of discovering different payoffs because the system responses that might yield these payoffs remain unobserved. Consideration of a larger number of spatial and/or temporal settings would bring about a large increase in the sample variance, partly because more natural experiments are likely to appear and partly because a wider range of system input combinations would come under investigation. In many areas of scientific research (e.g. , plant breeding) this wider range of natural experiments and system input combinations has ultimately led to the development of techniques to affect the distributions from which the drawings are taken, and thus to allow the acquisition of information outside the range of historical experience as well as enabling the researchers to limit drawings to those response surfaces of greatest concern. In effect, the ability of decisionmakers who use research results to predict the outcomes of alternative programs is enhanced. Or, equivalently, the range of alternative programs available to the decisionmaker will be systematically narrowed as his information structure loses its ability to discriminate among different real outcomes. Unlike programs may appear to be similar in terms of their measured results and may thus be mistakenly treated as identical. Given the apparent sensitivity of the ecosystem impacts of acid precipitation to a large number of alternative combinations of biological and geochemical factors, we feel secure in adopting the position that a deaf ear should be turned to scientific counsel that urges the concentration of acid precipitation response surface research to a very limited number of locations. There appears to be insufficient understanding at present of acid precipitation response surfaces to permit the easy transfer of a surface established at one location to other locations.

Estimation of Response Surfaces: Setting aside the issue of the unthinking application of significance tests, the circumstances in which the statistical techniques available for estimating response surfaces in well-controlled experimental settings are appropriate are well understood. Apart from analysis of variance techniques, any good econometrics text such as Kmenta (1971) will provide a detailed and thorough treatment of the subtle issues of estimation that arise in a wide variety of commonly faced contexts, i~.eluding joint outputs, nonlinearities in the parameters, observations which vary cross- sectionally and temporally, systems of equations, non-normality of error terms across experiments on the same response surface, truncated dependent variables, and other matters. Econometrics appears to have little to offer biometrics with respect to useful and correct applications of these techniques.

However, when the natural scientist uses field data rather than or along with experimental data to arrive at response surfaces, the perspective of the econometrician does have something valuable to offer. In particular, the econometrician will be sensitive to the implications for estimation of the fact that organisms make or behave "as if" they are making choices. Accurate estimation of the response surface parameters thus requires data on the factors that influence these choices. Moreover, an explicit representation of the organism's choice problem must be built into the structure to be estimated. As was argued in Chapter IV, the choice paradigm is potentially as powerful a means of explaining the behavior of monhuman organisms as it has been for human organisms. The importance of accounting for its influence even in a supposedly pure natural science exercise in estimating response surfaces is easily illustrated.

Earlier, we have indicated that if response surface research is to be most helpful to the economist, then it should be limited to what has been defined as the economically relevant portions of the surface. Identification of these relevant portions would likely be enhanced if an economist were to be included in the initial stages of research design. Research resources would be conserved. In the following illustration, inclusion in the original research design of inputs from someone who thinks like an economist is not only desirable. It is imperative if unbiased estimates of response surface parameters are to be obtained.

To make the illustration fully plausible, assume the research problem to be the estimation, through a combination of field and experimental data, of the response of trout populations to acid precipitation.[5/] In implicit form, a good approximation of the expression the natural scientist might apply to the field data collected over a given time interval is:

$$Y = f(X, W, Z, E, \varepsilon) \qquad (5)$$

where Y is the stock of trout, x is a vector of aquatic ecosystem characteristics, W is a vector of weather characteristics during the period of analysis, Z is a. measure of the fishing pressures imposed by humans upon the trout stock, E is a measure of trout stock exposures to acid precipitation, and ε is a stochastic error. The a priori information that experimental regimens have provided might be used to determine the functional form and the listing of variables on the right-hand-side of (5), to restrict the signs and/or the magnitudes of the coefficients of these variables, and/or to specify the properties of the error term. For simplicity, assume that (5) is linear in the original variables. The coefficient attached to the acid precipitation variable is then the reduction in trout stocks due to a one unit increase in acid precipitation. Would it then be reasonable to infer a dose-response association from the coefficient of this variable?

The aforementioned inference would be correct if and only if it is possible to alter the acid precipitation exposure without altering the value of any other explanatory variable in the expression. It is easy to show that this cannot be done unless the structure of the response surface is presumed to consist of no more than one relationship. More than one relationship is present in (5); it contains a variable, Z, the levels of which have been and continue to be subject to control by fishermen. That is, during the period over which it is thought acid precipitation effects can occur, the fisherman can influence by his voluntary choices the fishing pressures applied to the trout stock. For example, the reduction in trout stocks due to exposures to acid precipitation might be dependent on the number of mature fish capable of reproduction that fisherman have caught. In order to explain the trout stock outcome, the researcher must do more than simply enter the amount of fishing pressure: he must also explain the structure underlying the choice of the degree of fishing effort applied. One element in this choice will be the size of the trout stock. The following simple example shows one way in which trout stocks and fishing pressures might be jointly determined.

If both the acid precipitation-trout. stock response function and the fishing activity demand function can be linearly approximated, they can be written as:

$$Y = \alpha_1 + \alpha_2 E + \alpha_3 X + \alpha_4 Z + \alpha_4 W + \varepsilon_1 \qquad (6)$$

$$Z = \beta_1 + \beta_2 Y + \beta_3 I + \beta_4 P_N + \beta_5 P_Z + \varepsilon_2 \qquad (7)$$

Expression (7) states that the quantity of effort the fishermen choose to expend is related respectively to the trout stock, fishermen income, an index of the unit prices of substitute recreational activities, and the unit price of fishing effort.

Solving (6) and (7) for Y, we have:

$$Y = \frac{\alpha_1 + \alpha_4 \beta_1}{1-\alpha_4\beta_2} + \frac{\alpha_2}{1-\alpha_4\beta_2} E + \frac{\alpha_3}{1-\alpha_4\beta_2} X + \frac{\alpha_4\beta_3}{1-\alpha_4\beta_2} I + \frac{\alpha_5}{1-\alpha_4\beta_2} W + \frac{\alpha_4\varepsilon_2\varepsilon_1}{1-\alpha_4\beta_2} \qquad (8)$$

Consider the coefficient attached to E in (8). If E is acid precipitation, (8) shows that an estimate of (6) will not yield the response of trout stocks to acid precipitation, even though, the dose-response function is “adjusted” for aquatic ecosystem characteristics, weather, and fishing effort. Instead the coefficient for E in (8) will be an amalgam of stock effects due to acid precipitation, fishing effort, and the effects of trout stocks on fishing effort. The product of the coefficients for the latter two effects would have to approach zero in order for the response of trout stocks to acid precipitation alone to be obtained. For this to occur, trout stocks could have no effect upon the amount of fishing effort and/or fishing effort could have no effect on trout stocks. Both assertions are equally implausible. In fact, in the absence of further information, the sign that would be obtained for E when (6) is estimated alone is ambiguous since $\alpha_2 < 0$, $\alpha_4 \leq 0$, and $\beta_2 \geq 0$. It is entirely conceivable, if one were to estimate (6) alone, that one would find that acid precipitation enhances trout stocks. In any case, because the product of α_4 and β_2 is negative in sign, the effect of acid precipitation on trout stocks will be underestimated. However, this negative bias in the response estimate is not predestined. Given (7), a slightly different specification of (6) could readily introduce a negative bias.

It might be reasoned that the difficulty with the preceding example could be removed if the ability of fisherman to influence trout stocks were removed. Expression (6) would not then have any human decision variables in it and would therefore seem amenable to the customary ministrations. These customary ministrations might, however, continue to be incorrect, for the trout, while acting “as if” they maximize net energy storage, are able to alter their food gathering behavior in response to a change in the competition for food. Thus the trout stock and some of the aquatic ecosystem characteristics, X, in (6) are jointly determined: the trout stock helps to determine the competition for food, and the competition for food helps to determine the trout stock.

Arguments similar to those above can readily be constructed for forests, agriculture, materials, and most items and systems thought to be impacted by acid precipitation. For example, productivity of a forest is influenced by the management practices selected by the forest owners, who are reciprocally influenced by the forest’s chosen response to the selected practice. The selections of the forest owners are not based upon physical parameters alone but also on the economic factors that influence the benefits and costs of management alternatives. Similarly, the estimated response to acid precipitation of the salmonid species in an aquatic ecosystem is determined not only by the acid precipitation and the fishing pressures applied but also by the price of access for fishermen and the factors that determine the avoidance behavior of the fish.

To attempt to account for the additional factors thought to influence an organism's response to acid precipitation by simply stringing out variables in a single expression must clearly often be incorrect. During the period in which the response is supposed to occur, organisms can behave so as to influence the magnitudes assumed by certain of these variables. Each variable susceptible to this influence must be explained by an expression of its own if the purpose of the research is to explain the response of the organism to acid precipitation rather than simply to predict its response. Unless circumstances are identical across space and time, predictions based on some version of (8) will err for reasons no one will be able to identify until the response structure is comprehended. Because some human decision variables both influence and are influenced by the response, economic analysis is frequently necessary to impart an interpretable form to response expressions. Purely biological constructs will therefore often be insufficient tools with which to establish acid precipitation response surfaces. Moreover, even when human decision variables have no role to play, the constructs of economic analysis can assist, as was argued in Chapter IV, in explaining the behavioral adjustments that organisms make to changes in acid precipitation exposures.

The above remarks need not lead to the conclusion that research on complex basic biochemical and physiological processes is required for the estimation of response surfaces. Jointly determined variables need be of interest only insofar as they contribute to understanding to the manner in which input mixes and magnitudes act upon outputs and results having economic relevance. Nevertheless, the fact of joint determination does complicate modeling and estimation procedures, occasionally beyond the ability of available analytical and estimation procedures to grasp. For this reason, there is information to be gained by establishing baseline descriptive measurements for a variety of ecosystems and locations thought to be susceptible to acid precipitation-induced effects. These effects can be economically valued even if there is no more that an association between changes in input mixes and magnitudes and changes in levels of the economically relevant outputs. The latter change can be valued whether or not the reasons for the change are comprehended. A demonstration that the economic value of the change, whatever caused it, is great can serve to stimulate research into the causes that might otherwise have been neglected. However, if acid precipitation-induced changes are to be recognized, baselines must be established against which the change can be estimated. These baseline measures must, of course, document seasonal. variances.

Although the economic value of a change in an ecosystem can be established even though there is no more than an association between outputs and inputs, it is important to recognize that the units of analysis must be defined in terms that contribute to the informed manipulation of the system. In particular the research designer must be wary of employing measures which may be good predictors but which effectively deny the existance of certain substitution possibilities of interest to human and/or nonhuman decisionmakers. These denials are most likely to occur when the researcher aggregates or groups variables. If the aggregate is, for example, a weighted sum of a collection of inputs, there is an infinite number of combinations of the inputs consistent with anv given magnitude of the aggregate. The economically" relevant" substitution possibilities are then impossible to discover. Furthermore, if spatial or temporal comparisons are being made among ecosystems, unregistered changes in input mixes and magnitudes could readily occur. The increases and reductions in the input components could cancel each other out so that no change in the aggregate would take place. In general, therefore, researchers should be extremely reluctant to employ aggregated or grouped input variables when there exist grounds for suspecting that ecosystem components have more than one way available to adjust to the presence of acid precipitation.

Choice of Models: The comparative assessment of alternative models to explain the bahavior of identical phenomena is among the most engaging activities of any discipline. The usual criteria applied in models of ecological systems appear to be an amalgam of statistical measures of goodness of fit and significance, *a priori* considerations relating to the biology and chemistry of the process in question, subjective judgement, and computational tractability. Generalizations about the desirable properties of ecological models, whether of the axiomatic or simulation types, relative to these criteria are very scarce. This is perhaps because model appraisals based on these criteria are bound to be misdirected.

The criteria for choosing among alternative models or theories of ecosystem behavior when stressed by acid precipitation should relate to the value of information they provide. If two models have the same costs in terms of data requirements and application, the preferred model should be that which provides the greatest expected payoff. If the models differ in their costs, this difference should also be allowed for in the payoff appraisal. In general, the important question is not whether any particular type of model is biologically or statistically better than its alternatives, but whether it can better serve the objectives of decisionmakers.

Adoption of the value of information perspective does allow some obvious generalizations to be made about the value of alternative models. [67] The disciplinarian will usually opt for the analytical delights of ever increasing generality in the specification of the models supporting his empirical analysis. His ultimate objective would be the ability to predict the results of every alternative source of system perturbation without having to alter any of the relations expressed in his model. The generality and realism of the ideal model would be so great that there would never be any doubt in the researcher's mind as to whether an observed change in some variable was random and thus transitory in nature or whether it was due to changes in the values of fundamental model parameters. However, the greater the progress of the researcher toward this intellectually captivating state, the greater are likely to be the number of variables for which he must make observations, collect and organize data, and establish parameter values. Furthermore, the complexity of relations among these model variables may be so great that estimating techniques are either extremely costly or perhaps even nonexistent. In effect, the elaboration and required detail of the model may be so great relative to the availability of research resources that only superficial attempts can be made to ascertain the true value of any one parameter. The problem in this case is not with a model that involves dangerous simplification of reality but with a model which, given available research resources, is alarmingly complex. The model is insufficiently artificial. Just as one fails to capture the truth when he fails to comprehend the complete structure of a system, he also fails when he is unable to measure with some fair degree of accuracy the parameters of any given comprehension of the structure.

On the other hand, the ideal of many applied scientists is to design an experiment or research effort such that the scientist does not have to think about what the results mean: the answer the experiment gives is unequivocal. Attainment of this state requires that measurement be free from bias. That is, it must be clear that the deviation of the result of any single measurement effort from the mean of the results of repeated applications of measurement effort under the least constrained conditions is purely random. The measurement errors which occur when this condition is not fulfilled can be reduced by devoting more resources to constructing measurement devices. and techniques, by allowing more time for measurements to be made, and by better training of measurement personnel. But measurement resources are expensive.

Paratt (1961, pp. 109-118) offers the following expression as a device for weighing increased detail of model elaboration against reductions in the error with which model parameters are measured. Let u be a derived property related to the directly measured properties, $x_1, \ldots, x_n$, by $u = \mu(x_1, \ldots x_n)$. For example, u might be a measure of the economic benefits of acid precipitation control. Given that the x's are not independent of each other-- they might, for example, be the parameters of a model for estimating the effect of acid precipitation upon soil nutrient content, fresh water pH, and fish populations-- the error in u due to the accumulation of errors in the seperate estimates of the x's is given by:

$$\varepsilon_u = \Sigma \left(\frac{\partial f}{\partial x_i}\right)^2 \left(\frac{\partial \varepsilon}{\partial x_i}\right)^2 + \sum_{i \neq j}\Sigma \frac{(\partial f)}{(\partial x_i)} \frac{(\partial f)}{(\partial x_j)} \frac{(\partial \varepsilon)}{(\partial x_i)} \frac{(\partial \varepsilon)}{(\partial x_j)} r_{ij} \qquad (9)$$

where ε_u is the error in the estimate of u and r_{ij} is the correlation between i and j. The presence of the corrleation coefficient in the above expression makes apparent at least one thing to avoid in the construction and use of complex axiomatic or simulation models in ecology (and economics): do not employ variables in the same model that are highly correlated with one another. Generally, the greater the number of attributes introduced into a model in the form of properties that must be directly measured, the more likely are some pairs of these properties to be highly correlated. Relatively simple models, by definition, require fewer directly measured properties for their solution. In addition, with repeated model applications, a low value of r_{ij} means that overestimates of the payoff are likely to be compensated by underestimates, implying that the average of the expected payoffs will be close to the true average.

Further inspection of (9) readily suggests two more bases for evaluating the tradeoff between model elaboration and errors in measurement. First, the presence of the partial derivatives, $\partial f/\partial x_i$ and $\partial f/\partial x_j$, indicates that measurement resources are more likely to be allocated efficiently if they are assigned to those directly measurable properties thought to have a really significant influence upon the derived property. Since the variables that have a significant influence upon a derived property will frequently be the same in both complex and simple models, the use of the simple model is to be preferred if avoidance of substantial error in the estimate of the derived property is of high priority.

Second, given the presence in (9) of the measurement errors associated with the directly measured properties, it pays to devote resources to reducing the larger of these measurement errors, including those interactive properties (i's and j's) whose products in (9) are greatest. Since in simple models there are fewer estimates of directly measured properties to be obtained, it follows that, to a greater extent than in a complex model, a given stock of measurement resources can be used to reduce the error associated with any one property. Thus, given the cumulative nature of measurement error in models where measured properties are tied together in long chains of reasoning, this rule along with the previous two implies that simple models can be highly advantageous in esitmating ecosystem responses to acid precipitation. The advantages exist apart from the fact that simple models are relatively easy to use and, in spite of the interesting scientific detail they may neglect, they will usually give quick answers to questions.

The preceding statements about the advantages of using simple models to describe response surfaces have not been made in the absence of empirical supporting evidence. For example, Perrin (1976), while studying the responses of various Brazilian crops to fertilizer applications, has contrasted the value to farmers of the information obtained from a simple structure based on Liebig's (1855) "law" of limiting factors [7] to the information acquired from a multi-input, nonlinear (quadratic) representation commonly favored in much controlled fertilizer response research. Using a set of 28 experiments conducted at various Brazilian sites over a three year period, he compared farmers' implied ex post net revenues from the two distinct models. If soil characteristics were accounted for, the simple one input, linear model based upon Liebig performed equally as well as the nonlinear model.

Empirical. evidence similar to Perrin (1976) is now beginning to appear for the connected black box simulation models so widely favored in much applied ecological research. Stehfest (1978) has compared the payoffs from a simple Streeter-Phelps model of dissolved oxygen and a complex ecological optimal control simulation model with six state variables. Both models were built to provide information on the costs of meeting a water quality standard in a stretch of a West German river. The pavoff was defined in terms of cost minimization. The total annual costs of meeting the standard when the water treatments suggested by the simple model were implemented were 8 per cent lower than would have been the treatments recommended by the more complex model. Of course, the costs of establishing what constituted the recommended treatments were also lower for the simple model. Additional reviews of the performances relative to some objective of simple versus complex models are available in Beck (1978), Griliches (1977), and Young (1978). Outside the econometric literature [Judge, et al. (1980), Chapters 2 and 11], few, if any, implementable rules, other than those of Paratt (1961) already remarked upon, issue forth from these discussions. There is, however, general agreement that although it is naive to view simplicity per se as desirable, the research administrator should place the burden of proof that valuable information will be produced onto the proponents of proposals to build ever more complex ecological and economic models.

Whatever the virtues of model simplicity, it must be admitted that increases in model complexity are worthy attempts, in the absence of information acquisition costs, to improve model robustness, where robustness can be defined as the domain of circumstances where the model can be applied without undergoing structural revision. However, as an alternative to the devotion of more and more research resources to molding, measuring, and manipulating an ever-lengthening string of variables someone reasons or feels may influence what Young (1978) terms a "badly defined system," axiomatic methods can be used. These methods, for which an example building upon bioenergetics is presented in Chapter IV, permit inferences to be drawn about difficult-to-measure variables by deriving relationships between them and more readily observed variables. In addition, these axiomatic methods, prior to any attempt at measurement, allow discrimination between important and trivial contributors to system behavior. Suggestions for adoption of holistic methods [e.g. Levins (1974), Jorgensen and Mejer (1979)] that recurrently appear in the biological literature are in the spirit of the axiomatic means of introducing information. More broadly yet, the bioenergetics research of Bigelow, et al., (1977), Hannon (1979), and others urges both a holistic, axiomatic approach and a movement away from near-exclusive emphases upon short-run, transient population movements in one or a few species to a concentration upon long-run equilibria for entire systems. The bioenergetics framework, when considered in a long-run equilibrium context, has appeal to the economist because it closely accords as a method of reasoning with his approach to the economy, a system perhaps equally as complicated as any ecosystem. In ecological contexts, the system complexity to which ecologists constantly refer is usually incompatable with "ideal" scientific experiments that remove all responsibility for _ex post_ thinking from the researcher. If ecosystems are equally or more complicated than are economies, the ecologist must be prepared to conceptualize a model that explains the data that is to be and has been observed or generated: he must compose a plausible story having applicability beyond the immediate circumstances being investigated.

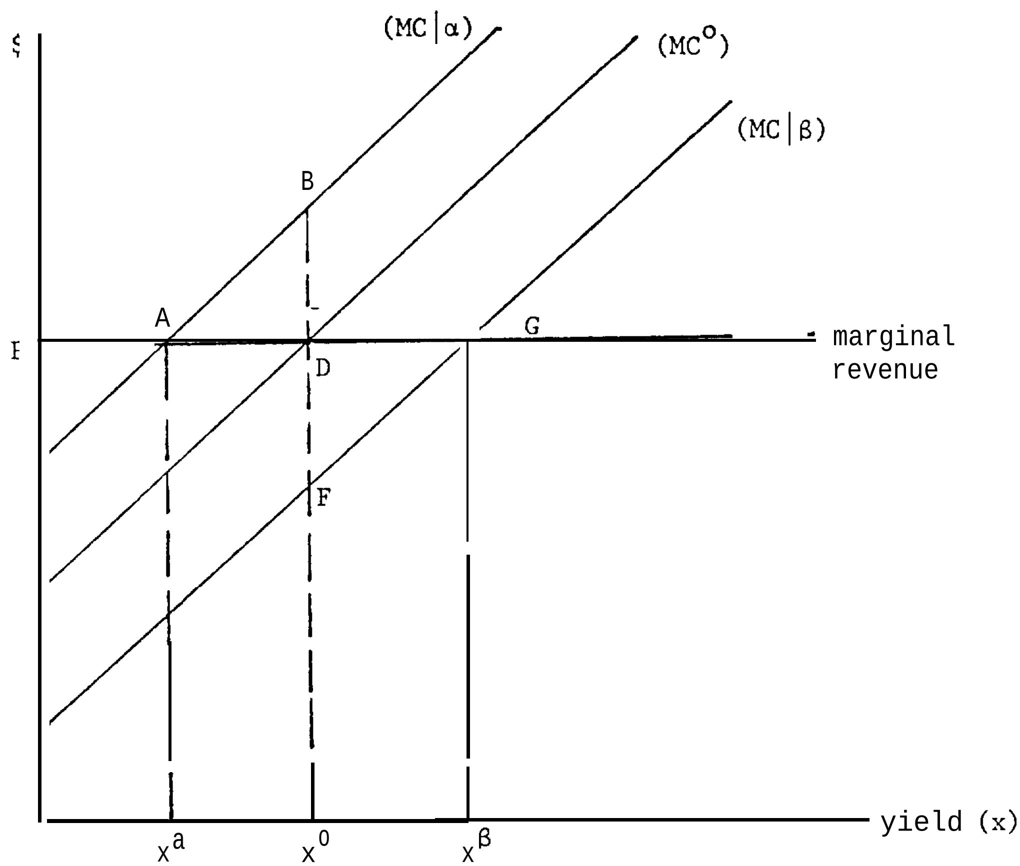
Experimental versus Field Response Surfaces: The methods of most biological research into response surfaces impede correspondences between surfaces estimated from experimental data and those estimated from data observed in the field. Generally, responses under experimental conditions will significantly exceed in absolute value the responses to be observed under field conditions.[8] Obviously, until studies are available and quantitative relations established between experimentally-derived and field-observed responses so that suitable adjustments can be made in both experimental designs and analyses, control decisions based soley on experiment-derived response surfaces must be less than fully satisfactory. Indeed, these experimental results might best be viewed as untested hypotheses. They allow firm generalizations to be made about input configurations not found beyond the experiment, in a set of exogenous parameters that nature never replicates. More important perhaps is the fact that the _a priori_ information provided by a combination of experimentation and field observations will frequently make the construction of analytical models an effective means of explaining the discrepancy. The conditions of the experiment and the field observations reduce and define the domain of circumstances which the model must capture. When unexpected and/or unexplained differences exist between experimentally-derived and field-observed outcomes, some worthwhile generalizations about system behavior can usually be made by searching out the sources of the differences.

The reasons for discrepancies between experimentally-derived and field-observed responses surfaces are probably several. Two come readily to mind. First, as Anderson and Crocker (1971, pp. 146-1.47) point out, so as to remove confounding sources of stress, all factors other than air pollution that might influence behavior in controlled experiments tend to be set at biologically optimal levels. Given that these biologically optimal levels exceed those found in everyday environments, it follows that they are less binding, implying, by the Le Chatelier principle [Silberberg (1978, pp. 293- 298)], that the contribution of an input to the behavior parameter of interest will be greater than it otherwise would be.

A second, less obvious reason arises from the role that risk plays in managed ecosystems, particularly agricultural and forest systems. In strictly controlled experimental settings, all feasible sources of random variation in output levels are excised. However, in field conditions, the system manager must adapt his activities to natural sources of random variation such as weather, insect infestations, and acidifying depositions. As Adams and Crocker (1979) and Just and Pope (1979) demonstrate, the input mixes and magnitudes the system manager selects influence both the level of output in any one time interval and the variability of these levels over time. Thus , for example, if the land area for which a farmer is responsible increases and he has no more inputs (e.g., lime, fertilizers, labor) than before, the susceptibility of his crops to any acid Precipitation events which might occur will also increase. In taking countermeasures to an acid precipitation event, he has to spread the same inputs over a greater area. The implications of this as a source of discrepancies between experimentally-derived and field-observed response surfaces become apparant with the following simple argument extracted from Adams and Crocker (1979).

Consider a risk-neutral, net revenue-maximizing farmer who must make all his input commitments before the start of any single growing season. For simplicity, further assume that acid precipitation over the growing season is expected to be either "high" (α) or "low" (β). If acid precipitation is high, the marginal cost of supplying various crop yields, given the input commitments already made, will be represented by the $(MC|\alpha)$ curve in Figure 3. This curve is the highest of the three marginal cost curves in the figure because the actual occurrence of the α level of acid precipitation will reduce the marginal products of the preselected mix of inputs, and thereby increase the marginal cost of producing any particular yield. On the other hand, if realized acid precipitation levels during the growing season were $, then, in accordance with the $(MC|\beta)$ curve, the marginal. cost of producing various yields would be reduced. The MC^{o} curve is simply the probability weighted average of $(MC|\alpha)$ and $(MC|\beta)$.

Figure 5.3
Effect of Air Pollution Risk Upon Yields



If, for simplicity, the farmer regards the occurrence of either α or β acid precipitation as equally likely, then MC^{o} is the marginal cost curve associated with the input mix maximizing his expected net revenues. Although this input mix will, on average, yield x", during any one season it will result in yields of either x^{α} or x^{β}. Thus if acid precipitation is high during one season, x^{α} will result, while if it is low, x^{β} will result. In effect, the variability in levels of acid precipitation causes yields in areas sometimes subjected to acid precipitation to be more variable than in areas where acid precipitation never affects yields or where it is always at a high level. Thus, for given input mixes, the odds of discrepancies between experimentally-derived response surfaces and field-observed response surfaces are greater in regions subject to fluctuating levels of acid precipitation.

If maximum acid precipitation levels have been increasing over time, then one would expect yield variability to increase in those areas where acid precipitation has been increasing. This is because the lowest level of acid precipitation (zero) cannot be altered while the highest level has increased, causing the $(MC|\alpha)$ curve to shift upward. Unless the farmer constantly lives in the darkest depths of despair about the acid precipitation problem, the MC^{o} curve, which is a probability weighted average of the other two curves, will never shift upward as much as the $(MC|\alpha)$ curve. The result will be increasing yield variability over time. Consequently, discrepancies between experimentally-derived response surfaces and field-observed surfaces are likely to be greater where levels of acid precipitation have historically been increasing.

A Recapitulation

Based or current knowledge, it appears that an ordered, predictable sequence of events follows the deposition of acidifying substances on ecosystems. Acid depositions cause the buffering capacities of ecosystems to decrease, the rates of decrease depending on the buffering capacity at the time of deposition. Systems with low buffering capacities will display relatively rapid decreases, whereas those with high capacities tend to have slow decreases. Also, systems with low buffering capacities generally show relatively rapid negative impacts from increasing hydrogen ion concentrations. Systems with high buffering tend to show initially positive responses from nutrients entering the system with the acidification and from nutrients mobilized by increased hydrogen ion concentrations. Over time, however, the initial positive response to acidifying depositions will reverse as nutrients leach from the system, mobilized metals reach toxic concentrations, hydrogen ion concentrations reach toxic levels, and/or nutrient cycling rates are reduced as decomposition rates decline.

SO_x and acid particles have harmful direct effects on plants. In general, when deposited on foliage surfaces, the pollutants enter the plants through the stomata. Plant seedlings and meristematic tissues are most sensitive. Therefore, acidification can cause establishment of plant species to be limited to those most tolerant of acid conditions. Over time, selection for tolerant species will simplify terrestrial communities and shift dominance.

Because of their weaker buffering systems, aquatic ecosystems tend to be more sensitive to acidifying depositions than are terrestrial systems. Within the aquatic system fish appear to be the most sensitive group of organisms and the reproductive processes appear to be the sensitive stage of the fish life cycle. Fromm (1980) ranked various reproductive processes in order of decreasing sensitivity: egg production > fry survival > fry growth > egg fertility. With declining environmental pH level, numbers of fish species are continually reduced. Available data indicates that many of the economically most valuable fish species are the most sensitive to depressed pH levels and are the first to be eliminated from the system. Continual depression of pH levels effects reductions in primary production rates, algal biomasses, and invertebrate biomasses. In addition, species diversities are reduced as the most acid tolerant species become dominant. In time, the system can reach a nearly abiotic state.

Acidifying depositions accelerate the decay rates of a wide variety of material artifacts mainly because the presence of acids upon the material surfaces increases the flow across the surfaces of the electric currents that cause corrosion, discoloration, and embrittlement. These processes are intensified for those materials, such as cement, concrete, and some metals, often used in subaqueous and/or high temperature environments.

Because of the water treatment facilities already in place, there is no substantive evidence at this time that the human health effects of acid precipitation are worrisome.

In order for the economist to be able to value the aforementioned effects of acid precipitation upon life and property, the natural scientist must provide him with information on response surfaces (see footnote 1, however). A response surface describes the magnitudes of the influences of various environmental and anthropogenic factors upon something that is valued for its own sake or for its contribution to something that is so valued. Because it emphasizes the description of substitution possibilities among the influential factors, knowledge about the response surface contributes to informed manipulation of the system of interest. Thus any natural science exercise which fails to make explicit the mapping between the influential factors and the object of value is of no use whatsoever to the economist. A study of the effect of acid precipitation upon leaf necrosis of apple trees is worthless to the economist if the relation between leaf necrosis and apple yields is unknown.

In order for natural science research into response surfaces to be most useful to the economist, it must always have certain properties.

1) Only those portions of the surface where the marginal products of the influential factors (reductions in acid precipitation are a positive input) are positive should be studied. Knowledge about other portions of the surface is economically irrelevant.

2) Only those response surface input combinations consistent with the behavior of any organism that is the object of the research is economically relevant.

3) All economically relevant portions of the surface should be systematically sampled. Coverage of these portions should be as dense as research resources permit. Achieving this broad yet dense coverage will require that substantially fewer research resources than are traditional be devoted to replications of experiments at one or a few points on the surface.

4) Replication should be given greater consideration onlv when the system being investigated is thought to be extremely sensitive to variations in exogenous parameters.

5) Increased density and breadth of coverage of the economically relevant portions of the surface should be striven for whenever there is a large number of factors thought to impinge in nontrivial ways upon system behavior.

6) Research resources should be aimed at denser coverage and greater replication along the steeper parts of the economically relevant portions of the surface.

7) When the response surface is stochastic, probability distributions should be stated for the random variables that enter. The natural scientist should not leave users of his research with only his "best" estimate.

8) The above remarks apply with equal force to temporal and spatial considerations. In particular, research into the effects of acid precipitation should neither be devoted only to immediate effects nor concentrated only in a small number of locations. Ecological theory cannot often be depended upon to allow empirical findings at one site and/or time to be generalized to other sites and/or times.

Even if the above eight factors are consistently adhered to, there remain factors about which the natural. science researcher must be cautioned if he wishes to produce results that are useful to the economist.

9) Jointly determined variables plausibly play a large role in ecosystem response surfaces. Thus attempts to account for the additional factors thought to influence an organism's response to acid precipitation by simply stringing out variables in a single expression will often yield biased estimates. Because some human decision variables both influence and are influenced by the response, economic analysis must often be involved in the initial research design.

10) Baseline descriptive measurements of ecosystem states may now be equally as worthy as research on response surfaces. If researchers are aware of the fact of change, even though they may be unaware of the causes of change, the change can, in principle, be assigned an economic value. Knowledge of the cause of the change is necessary only when one wishes to manipulate the system and/or assign responsibility for the change to human agents.

11) Aggregated or grouped variables to which natural science research is indifferent in terms of informational content may destroy the usefulness of the research for the economist. In general, natural science research should structure its units of analysis so that substitution possibilities are not hidden.

12) The farther is an affected component removed (in the sense of trophic linkages) from something economically valued for its own sake, the less research worthy is the component likely to be. This is because there are more likely to be available substitutes for the component.

We now move from cautionary statements about the performance of natural science (particularly ecological) research into the effects of acid precipitation to a set of aggressive statements about how this research might be improved to the mutual benefit of the ecologist and the economist.

13) Many ecological models appear to be insufficiently artificial, perhaps because they stress the short-run dynamics of species interactions. Their builders compound errors of measurement by introducing variables that are highly correlated; they seem reluctant to make prior judgements about the significance or the triviality of a variable's influence; and they devote inordinate research resources to reductions in the measurement errors of trivial. variables. These faults are often evident in the confusing connected black box simulation models ecologists frequently use.

14) Ecologists often remark on the great complexity of ecosystems. It is not evident that ecosystems are any more complex than economies. Economists have found that an axiomatic approach which emphasizes comparative static equilibria yields great simplifications of real-world economies at no apparent cost in robustness. The long-run equilibria are used as analytical devices rather than as descriptions of reality. There is recent interest in ecology in viewing ecosystems and their components as solving a resource allocation problem [Rapport and Turner (1977)], where energy is the scarce resource. This organizing principle permits use of the tools of economic analysis as Chapter IV demonstrates. The contribution these tools can make to understanding the ecological effects of acid precipitation should be investigated further. Agricultural systems, because they are immature in ecological terms, and therefore stressed and unstable, might be a worthwhile place for initial research efforts. Note that these systems emphasize growth. It is generally thought that the most active developing tissues in plants are most sensitive to acidifying depositions.

15) Because strictly controlled experiments on response surfaces often are poor facsimiles of the real world, their results are best viewed as untested hypotheses.

Our economic approach to the effects of acid precipitation has yielded more than a set of generalizations about natural science research into response surfaces of all sorts. We have gained some insights into particular economic features of the acid precipitation problem that might be helpful in planning natural. science research into these problems.

16) The current economic value of the ecosystem effects of acid precipitation is very small compared to the value of its direct effects upon materials and perhaps upon agriculture. However, the existing studies of

the materials damages caused by pollution are technically weak in economic terms. New economic approaches to assessing materials damages must be developed hefore trustworthy results can be obtained.

17) Potentially, the chronic ecosvstem effects of acid precipitation almost certainly dominate in economic seriousness the acute effects. Thus natural science research should give greater priority to cumulative acidity issues rather than to episodic acidic events.

18) Careful inventories of the existing stock of buffering capacities must be constructed. The frequency with which ecosystem responses to acid precipitation involve nonconvexities and irreversibilities should be identified. If, as we suspect, one or both appears with substantial frequency, natural science research should concentrate on those systems that are about to or just have exhibited the first symptoms of acidification. This, of course, presumes that good indicators of these first symptoms are available. If not, these indicators must be identified.

19) Studies of already acidified systems should be limited to attempts to establish whether natural recovery times, if any, involve less or more than two or three decades, and whether there exist any human manipulations that can slow decay rates or accelerate recovery. Because of the existence of positive discount rates, recoveries occurring more than two or three decades in the future have little value to the present generation.

20) The measurement of the changes in long-run equilibrium species assortments should be a high priority natural sciences research item because the value that humans attach to the amenities and the life support services that ecosystems provide is often conditional upon the species assortments from which they come.

21) Economists are usually unable to value dung beetles, algae, and assorted other ecosystem components because ecologists have failed to indicate how their contribution to the directly valued components of ecosystems varies with acid precipitation levels. The approach suggested in recommendation (14) might allow these contributions to be specified and thus valued.

Finally, so as to moderate our commentary about the research efforts of the natural sciences into the effects of acid precipitation, we direct a few remarks at our own discipline. We have tried to identify those sets of acid precipitation effects where one may feel resonably secure using the conventional analysis. We have also tried to identify some possible special features of vegetative and ecosystem damages that appear to require either expansions or even complete replacements of the traditional analysis.[97] In Chapter IV, we have tried to extend conventional methods to include ecosystem diversity. Unfortunately, we are unable to reject the discomforting notion that the effects for which one may feel secure using the conventional methods are those having the least long-term economic significance. If this is true, it is important, for both scientific and policy reasons, to set the strengths and limits of the conventional analysis, and to design valuation methods that can be extended to phenomena where the analysis either fails or is misleading. At least insofar as the setting of limits is concerned, it is important for obvious reasons that the task not be left soley to economists. However, meaningful participation in this task by noneconcmists means that they must learn the structure and the requirements of the conventional analysis.

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1/ As noted in Chapter I, we presume in this report that Shephard's lemma (the envelope theorem) has limited practical applicability. Nevertheless, the extent to which applications of the envelope theorem might permit assessors of the economic benefits of controlling acid precipitation to avoid having to know these biological and physical influences, awaits some detailed research attention. To see why, consider the restricted profit function of Diewert (1974) and Lau (1976). Let X denote a vector of fixed outputs and inputs, where the inputs are measured as negative quantities, thus allowing both inputs and outputs to be stated in terms of net supplies. In addition, allow p to be a vector of nominal prices of the variable net supplies and let v be a vector of their rates of production or use. The variable profit is then:

$$\pi = p' \qquad i = 1,\ldots n \tag{a}$$

The maximum variable, or restricted, profit is:

$$\pi^* = \pi(p,x) \tag{b}$$

Taking the derivatives of π^* with respect to the fixed outputs yields of the negative of the marginal cost. When these derivatives are taken with respect to the fixed inputs the negatives of the marginal valuations or demand prices are yielded. Similarly, the derivatives of π^* with respect to p yield the efficient rates of production or uses of the outputs and inputs. These results are obtained because, under appropriate conditions, every production possibility set defined with at least one fixed input or output implies a unique restricted profit function, and, conversely, every restricted profit function satisfying certain regularity conditions implies a technology. Using these results, given that nominal prices and quantities of inputs and outputs can be observed, knowledge of the exact influence of various physical and biological factors upon ecosystem variables of interest is unnecessary. However, even if these duality techniques ultimately allow economic analyses to proceed without prior knowledge of response surfaces, knowledge of thesurfaces would still prove useful as a means of checking the results obtained from applications of the duality techniques.

2/ This is not strictly true. For the statement to hold without exception even for only two inputs, it must also be true that:

$$\left(\frac{\partial^2 Y}{\partial X_1^2}\right)\left(\frac{\partial^2 Y}{\partial X_2^2}\right) - \frac{\partial^2 Y}{\partial X_1 \partial X_2} > 0.$$

3/ See Chapter III for further discussion of cancavity (nonconvexity). The discussion in that chapter is consistent with activities which operate at either A or D in Figure 2.

4/ See also Anderson and Dillon (1970).

5/ This illustration is an adaptation of a development in Crocker, et al. (1979, pp. 9-12).

6/ This and the subsequent three paragraphs draw extensively upon Crocker (1975).

7/ The "law," as succintly stated by Swanson (1963), says that yields increase at a constant rate with respect to applications of each factor unitl some other factor is limiting.

8/ Insofar as acid precipitation is concerned, nonconvexities, as was argued in Chapter 111, likely constitute an important exception to this statement.

9/ By no means is our listing exhaustive. For example, benefit-cost analysis as presently constituted, is less than robust in its treatment of the benefits and costs of alternative paths of adjustment to an environmental perturbation. Neither is it very helpful in valuing reduced uncertainty about future environmental states. Other items could be added to this listing.

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