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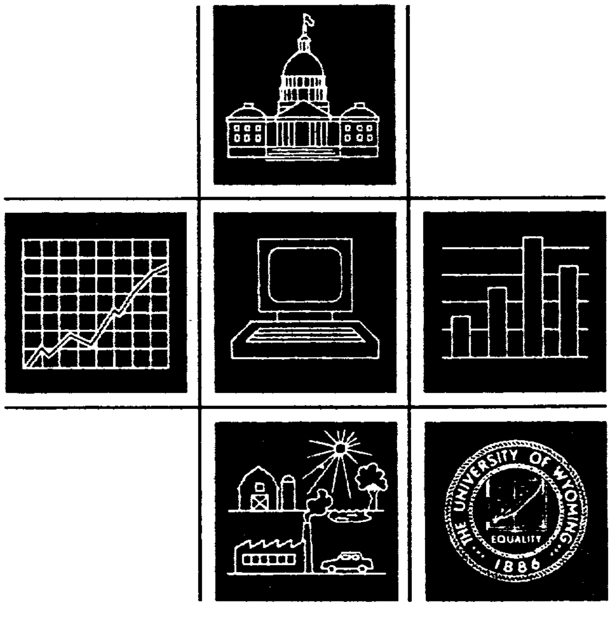

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Volume IV

VALUING ECOSYSTEM FUNCTIONS: THE EFFECTS OF AIR POLLUTION

METHODS DEVELOPMENT IN MEASURING BENEFITS OF ENVIRONMENTAL IMPROVEMENTS

Volume IV

VALUING ECOSYSTEM FUNCTIONS: THE EFFECTS OF AIR POLLUTION

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CHAPTER 1

INTEGRATING ECOSYSTEMS AND ECONOMICS

by

John Tschirhart and Thomas D. Crocker,
with assistance from S. Kask

SECTION 1

INTRODUCTION

Population growth and human territorial expansion are placing unprecedented burdens on ecosystems. While forests are being converted to farmlands, farmlands are being converted to suburbs. The Amazon forest, earth's richest biological region is losing to development each year an area half the size of Great Britian [Prance (1977)]. Pollution is now recognized as a global problem with particular emphasis on acid precipitation and the greenhouse effect. Estimates of species lost to extinction worldwide are as high as 1000 per year [Myers (1979)].

But what values are reflected by this and similar data on our dwindling natural environment? Part of the answer can come from a study of ecological systems placed in an economic framework. Ecological systems must be reduced to tractable analytical frameworks which can then be incorporated into economic models that are able to ascertain benefits and costs. For example, in environmental economics, studies have estimated the willingness to pay for trout fishing along a particular stream. These studies could then be used to estimate the value that the effect of a pollutant such as acid precipitation has on trout populations. Trout have value to people, and if the trout were to vanish so would the benefits of the fishing. But trout are only one species in a complex ecosystem. By removing other species, say certain insects that may appear to be of no value, the trout may also vanish. Thus, a proper valuation of an ecosystem entails not just the valuation of end products like trout, but a recognition of the interactions between trout and other species so that the value of these other species can be established. By doing this, better estimates can then be made of the uncompensated costs associated with population growth and industrial expansion which affect the sources of pleasure and life support services that ecosystem provide.

Ecosystems are incredibly complex. They may be composed of thousands of species interacting in diverse ways. Each species fills a niche in the overall system, and depends on one or more of the other species for survival. But complex systems are not foreign to economists who have the difficult task of sorting out complex economies. Notions such as short-run and long-run equilibriums, steady states, and exogenous shocks appear to be applicable to both ecosystems and economies. For an economy, the economist uses models to determine the effect a tax in one sector has on other economic sectors. For an ecosystem, the ecologist (and the economist) may need to know the effect that a particular pollutant harming one insect species will have on all other species.

The parallels between ecosystems and economics suggest that similar models may be used for each. Moreover, if this can be accomplished, then linking ecosystems with economies is possible. Such a linkage would permit not only detailed descriptions of how a pollutant will effect an ecosystem, but how the changes brought about in the ecosystem will effect the economy and, in turn, how these changes in the economy will influence the ecosystem.

Ecologists attempt to answer such questions by using energy as a unit of value. By measuring the flow of energy through an ecosystem, one can determine how an exogenous shock might affect that energy flow [Grodzinski (1975)]. The effect is then evaluated using some pecuniary value placed on an energy unit. Some support for this approach once was found among economists. The English economist, J.A. Hobson (1929) has remarked that:

> "...all serviceable organic activities consume tissue and expend energy, the biological costs of the services they render. Though this economy may not correspond in close quantitative fashion to a pleasure and pain economy or to any conscious valuation, it must be taken as the groundwork for that conscious valuation. For most economic purposes we are well-advised to prefer the organic test to any other test of welfare, bearing in mind that many organic costs do not register themselves easily or adequately in terms of conscious pain or disutility, while organic gains are not always interpretable in conscious enjoyment." (p. xxi)

According to one's perspective, Hobson's statement can be taken as support for an energetic basis of value, and as a plea for economists to devote more attention to the workings of the biological world and its implications for human welfare, both as a source of pleasure and as a life-support system. Hobson's first point has been received warmly by ecologists such as H.T. Odum (1971), to the point where it has been enshrined alongside cost-benefit analysis as a means of evaluating proposed energy technologies [Energy Research and Development Agency (1975)]. However, it has been coldly received by modern economists. Georgescu-Roegen (1979) neatly expresses the economists' source of difficulty with energy as the unit of value for the satisfaction of human wants:

> "The entropic nature of the economic process notwithstanding, it would be a great mistake to think that it may be represented by a vast system of thermodynamic equations...The entropic process moves through an intricate web of anthropomorphic categories, of

> utility and labor above all. Its true product is not a physical flow of dissipated matter and energy, but the enjoyment of life...pleasure is not related by a definite quanitative law to the low entropy consumed." (p. 1042)

The correct approach is therefore to include the ecosystem in the economy where the uses of the ecosystem can be evaluated relative to all other goods.

Hobson's second point, that economics should give deeper consideration to the role of biosphere in human affairs, has suffered from neglect. With the exception of the work inspired by Boulding (1966) and Krutilla (1967), the economics discipline continues to be notable for its inability to capture many of the concerns of biological scientists, particularly ecologists, about the impacts of human activities upon ecosystems and, via these ecosystem impacts, ultimately upon human welfare. Perhaps economists have dismissed these themes simply because the economics discipline has lacked a means of fitting them into the framework of economic analysis.

The purpose of this paper is to develop a link between ecosystems and economies that will allow an economic evaluation of ecosystem structure and diversity. We try to broaden traditional approaches to environmental economic problems by encompassing bioenergetics, but without resorting to the use of energy as the unit of value used by humans. There are two main phases of the development. First, an ecosystem model is described using the notions equivalent to production functions, optimization, and equilibria. Humans are absent from this phase. All energy input into the model derives from the sun. In the second phase, humans are introduced under the familiar guise of utility maximizers. This leads to behavior that interferes with the ecosystem through changes in the sources and uses of energy.

Section II develops a model of the optimizing behavior of a single organism in an ecosystem. Section III extends this idea to multiple organisms and to ecosystem equilibrium. Section IV suggests that there is empirical support for the results in Section III. Sections V, VI and VII introduce the economic problem. This is where human perspectives of the ecosystem enter. Section VIII introduces a methodology for valuing species. IX deals with ecological diversity.

SECTION 2

SINGLE ORGANISMS AS ENERGY MAXIMIZERS

Initially, a model of an ecosystem is developed where humans have neither a direct nor indirect influence. In this world, all energy is derived from the sun.[1] Organisms may use this energy directly, in the case of plants, or indirectly, in the case of herbivores and carnivores. Each organism is a member of a particular trophic level, where a trophic level is defined as "...a collection of species which feed from the same set of sources and which do not produce for each other" [Hannon (1976, p. 260)]. In essence, each trophic level can be thought of as a stratum in a food pyramid. The objective is to link mathematically the trophic levels. This will provide a framework for discussing equilibria in the ecosystem.

Before deriving the links, however, the actions of the individual organisms must be described. In a general equilibrium model of an economy, individual consumers and firms are usually described as utility and profit maximizers, respectively. But in an ecosystem, do nonhuman organisms maximize? Can a weasel be credited with thoughtful preference revelation when it raids the chicken coop instead of ferreting out a mouse or two? "...men consciously optimize, animals do not - they survive by adopting successful strategies 'as if' conscious optimization takes place" [Hirschleifer (1977, p. 4)]. This "as if" assumption is sufficient to capture much of the behavior of nonhuman organisms, and, thereby, establish a fruitful model. Indeed, "as if" is the methodological basis adopted by many modern economists [Friedman (1953)].

Various suggestions have been made as to what it is that nonhuman organisms maximize, or behave as if they are maximizing. Lotka (1925) developed a model where the maximand is the rate of increase of the species. This rate is a function of food capture, shelter, and other physical needs. Obtaining these needs requires energy expenditure. Naturally, if a species is to be successful, then the energy expended on the needs must be less than or equal to the energy acquired. Lotka characterizes a maximum in this system with a set of equations where the marginal productivity (i.e., an increase in the species with respect to net energy input) of an energy expenditure equals the marginal loss (i.e., a decrease in the species) from that energy expenditure.[2] Modern work has emphasized the role of energy more directly in the search for a maximand. Odum (1971, p. 90) points out that life requires power and "...the maximum and most economical collection, transmission, and utilization of power must be one of the principal selective criteria...". Finally, Hannon (1976) develops a model using stored energy as the maximand. Stored energy is simply the energy acquired by the organism less the energy needed to maintain itself. Hannon argues for the reasonableness of this objective based on general observation, and on the increased organism stability it provides during periods of fluctuating inputs.

The stored energy approach is used here. It does not seem to differ significantly from Lotka's approach, particularly since he viewed organisms as energy transformers. If organisms of a species are successful in storing energy, this is interpreted as leading to an increase in the species' health and numbers. Hence, the stored energy approach appears acceptable to modern ecologists, and consistent with the pioneering work of Lotka.

For specificity, suppose the organism is a fox, which as an energy transformer, gathers all its energy from food, and then assimilates this energy for various purposes. All input energy must be accounted for as output energy in the form of waste heat, metabolism, growth, reproduction, losses to predators, detritus, mechanical activities, and storage. Let x_j and e'_j, j = 0, . . . , n, be the mass flow from the jth source to the organism and the energy content or caloric content per unit of mass j, respectively. Subscript i = 0 refers to the sum so that $e'_0 x_0$ is the energy that the fox absorbs directly from sunlight. Thus, x_0 can be thought of as time spent in sunlight and e'_0 the energy absorbed per unit of time. Many but not all species absorb energy directly from the sun. If a species does not then $x_0 = 0$. For simplicity, the sun is the only input that is not derived from another species. Therefore, subscripts j = 1, . . . , n represents all species of plants and animals, and for the fox, a positive x_j, j = 1, . . . , n implies that species j is prey. Total input energy is then:

$$\sum_{j=0}^{n} e'_j x_j \qquad (1)$$

Let e''_j be the energy spent to obtain a unit of x_j, for example energy spent to run down a mouse, so that the net input of en from a unit of x_j is $e_j = e'_j - e''_j$. Therefore, total net input energy is

$$\sum_{j=0}^{n} e_j x_j \qquad (2)$$

For simplicity, all output energy will be captured by a single term. Accordingly,

$$e_{n+1} x_{n+1} \qquad (3)$$

represents the above mentioned outputs with the exception of storage and predator losses. Again, e_{n+1} is a price per unit of mass loss x_{n+1}. Some outputs, such as heat loss, can be measured in energy units and e_{n+1} be one; however, no loss in generality results from using e_{n+1}. Predator losses are not considered here because they are beyond control of the fox; and if an individual fox is taken by a predator there is no maximization problem to discuss. In a sense, there is a zero/one solution to the fox's problem. Predator losses are taken up in the next section.

Stored energy is the difference between input and output. It represents energy in excess of what is needed for maintenance. Letting r be stored energy, then from (2) and (3)

$$r = \sum_{j=0}^{n} e_j x_j - e_{n+1} x_{n+1} \tag{4}$$

Expression (4) is the objective function that the fox maximizes, and it is analogous to a firm's profit function. The chief difference is that 2 firm sells output to increase profits and purchases inputs which detracts from profits. The fox's outputs, such as heat loss, detract from stored energy while inputs contribute to stored energy.

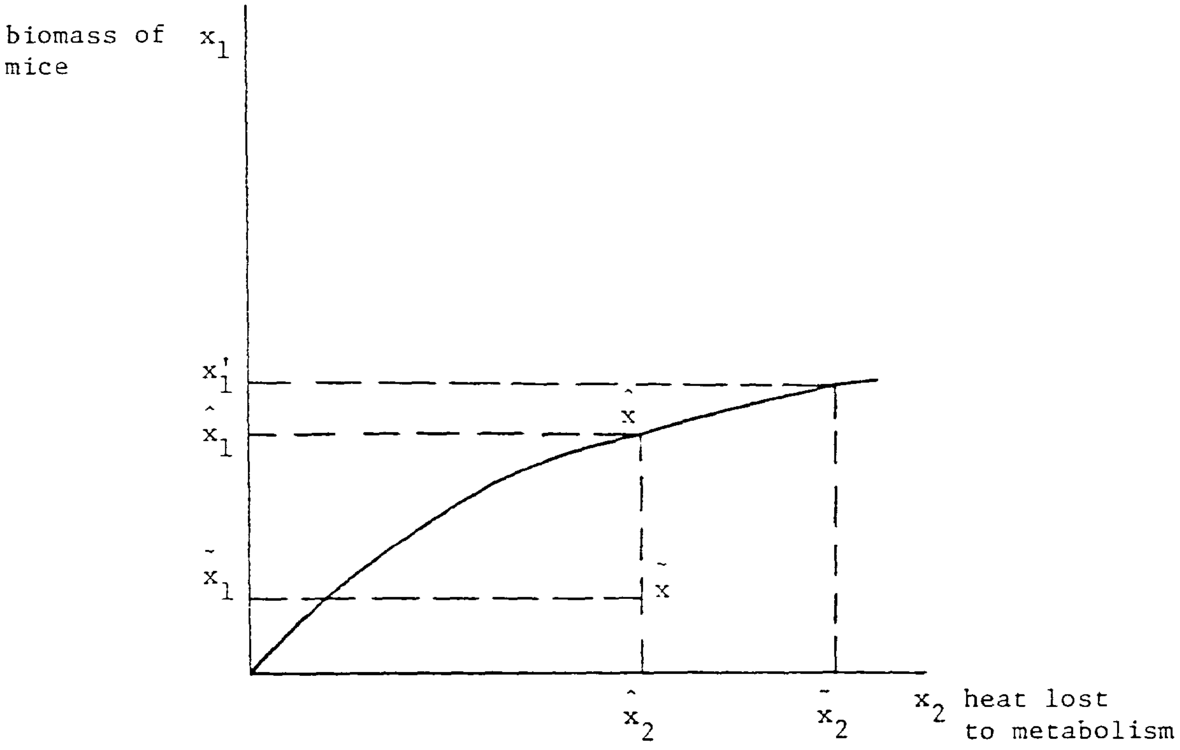
A bundle of inputs and outputs for the fox is represented by the real numbers $x = (x_0, x_1, \ldots, x_n, x_{n+1})$. Not all bundles, however, are feasible for the fox. For instance, the fox cannot continually catch mice without ever losing heat energy. The set of feasible bundles will be called the physiology set.[3] In essence, this set places constraints on what is achievable for the fox by describing the physiological processes which convert inputs to outputs. For example, as a general rule of ecology, in order for an organism to use ingested material, it must oxidize the organic molecules in the material it ingests [Morawitz (1968), Chap. 5)]. This creates useful energy, but some formerly useful energy is also lost as heat. The physiology set depends on ambient temperature, time of year, and other environmental conditions, and human activities may be influential as well. Acid precipitation is a good example of a human activity that interacts with an ecosystem via alterations in physiology sets. For now, the set is assumed to be unchanging.

Several simple diagrams illustrate these notions. Suppose for the fox there is only one input, mice, and one output, metabolical heat loss. Figure 1 shows the physiology set as the shaded region. With metabolism of $\hat{x}_2$, the fox can attain a quantity of mice $\tilde{x}$, a quantity $\hat{x}$, or any amount between $\hat{x}$ and the horizontal axis. Bundle $\hat{x}$ represents the greatest amount of mice attainable for $\hat{x}_2$. For this reason, $\hat{x}$ is labelled an efficient point of the physiology set; and all points along the upper border of the set are referred to as the physiologically efficient points. Thus, a physiologically efficient bundle is one where greater mice biomass cannot be attained without even greater metabolism.

The dependency of the physiological set on environmental conditions is depicted in Figure 2. The cross-hatched area may represent the physiological set of a lake trout prior to the occurrence of acid precipitation, while the double cross-hatched region represents the trout's set subsequent to the acid precipitation. This change indicates a detrimental effect from the pollution, since the feasible set has been diminished.

For a fixed level of stored energy, $\bar{r}$, (4) can be plotted as the

Figure 1


biomass of mice
x_1
x_1'
$\hat{x}_1$
$\tilde{x}_1$
$\hat{x}$
$\tilde{x}$
$\hat{x}_2$
$\bar{x}_2$
x_2 heat lost to metabolism

straight line in Figure 3 labelled $\bar{r}$. A higher fixed level of stored energy is shown by the line r. The further these lines are above the origin, the greater is the stored energy. These lines can be referred to as iso-stored energy lines, since every point on any given line represents a combination of x_1 and x_2 that yield the same stored energy at the given energy prices. The vertical and horizontal intercepts are the stored energy in units of mice biomass and heat loss, respectively. The slope of the line is the ratio e_2/e_1.

The fox is assumed to take e_1 and e_2 as given; that is, it has no control over these values and they enter as parameters in the maximization process. Maximum stored energy will be given by that iso-stored energy line that is furthest above the origin, but still having at least one point in common with the physiology set. Obviously, this point will be one that is physiologically efficient. Figure 4 illustrates maximums of $\bar{r}$ for values $\bar{e}_1$ and $\bar{e}_2$ and, $\hat{r}$ for values $\hat{e}_1$ and $\hat{e}_2$. The maximizing solution depends on the shape of the physiology set and tie values of e_1 and e_2. The solution at $\hat{x} = (\hat{x}_1, \hat{x}_2)$ contains greater levels of heat loss and mice than $\bar{x} = (\bar{x}_1, \bar{x}_2)$, because biomass of mice has more energy content $(\hat{e}_1 > \bar{e}_1)$ and/or metabolism results in less heat loss $(\hat{e}_1 < \bar{e}_1)$. For values $\bar{e}_1$ and $\bar{e}_2$, the fox would not move beyond point $\bar{x} = (\bar{x}_1, \bar{x}_2)$. To do so would mean more heat loss and more mice, but the energy gained would be less than the energy lost. For instance, moving from $\bar{x}$ to $\hat{x}$ at prices $\bar{e}_1$ and $\bar{e}_2$ would mean a drop in stored energy from $\bar{r}$ to $\bar{\bar{r}}$. However, suppose mice were to become more plentiful, then e_1 would increase because e_1'', the energy required to catch a mouse, would decrease. If $(\bar{e}_1, \bar{e}_2)$ became $(\hat{e}_1, \hat{e}_2)$ the fox would move to $\hat{x}$ where stored energy increase from $\bar{r}$ to $\hat{r}$.

A maximum will exist provided certain restrictions are placed on the physiology set. In particular, the set must be bound above and include its boundaries. These restrictions do not seem unrealistic in a real ecosystem. Figure 5 illustrates a set that is not bounded. For positive e_1 and e_2, maximum stored energy is infinite since even higher iso-stored energy lines are feasible. The shape of the set must be left to experiments, observations, and statistical analysis, and it can be expected to vary significantly among organisms.

Further insights into the maximization model can be gained by returning to the general case. The concept of a physiology function is introduced using the physiology set. For any set of values of all but one of the net flows, x_j, there is only one value of x_j that is compatable with physiological efficiency. This is obvious for the two variable case from the above figures. For n+2 variables, let $x^{-j} = (x_0, \ldots, x_{j-1}, x_{j+1}, \ldots, x_{n+1})$, then there is a one-to-one correspondence between the n+2-1 dimension vector x^{-j} and the scalar x_j. In functional form,

$$x_j = f(x^{-j})$$

or equivalently

$$F(x) = x_j - f(x^{-j}) = 0 \qquad (5)$$

Figure 2

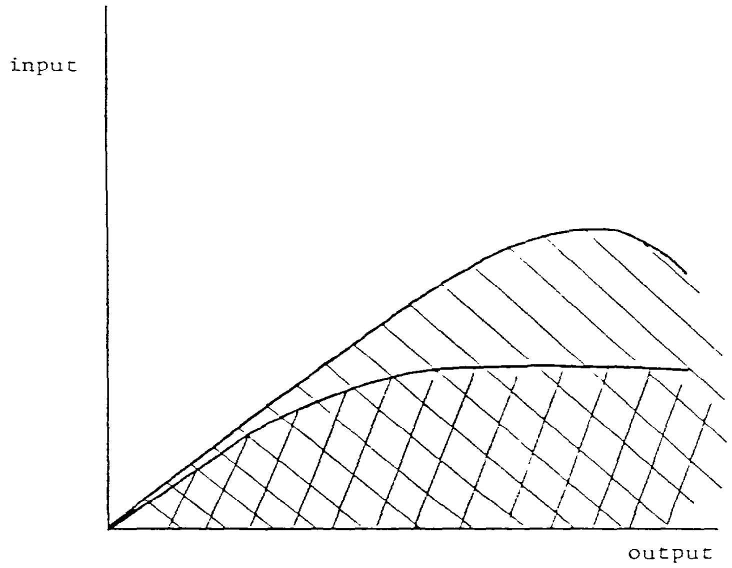


Figure 3

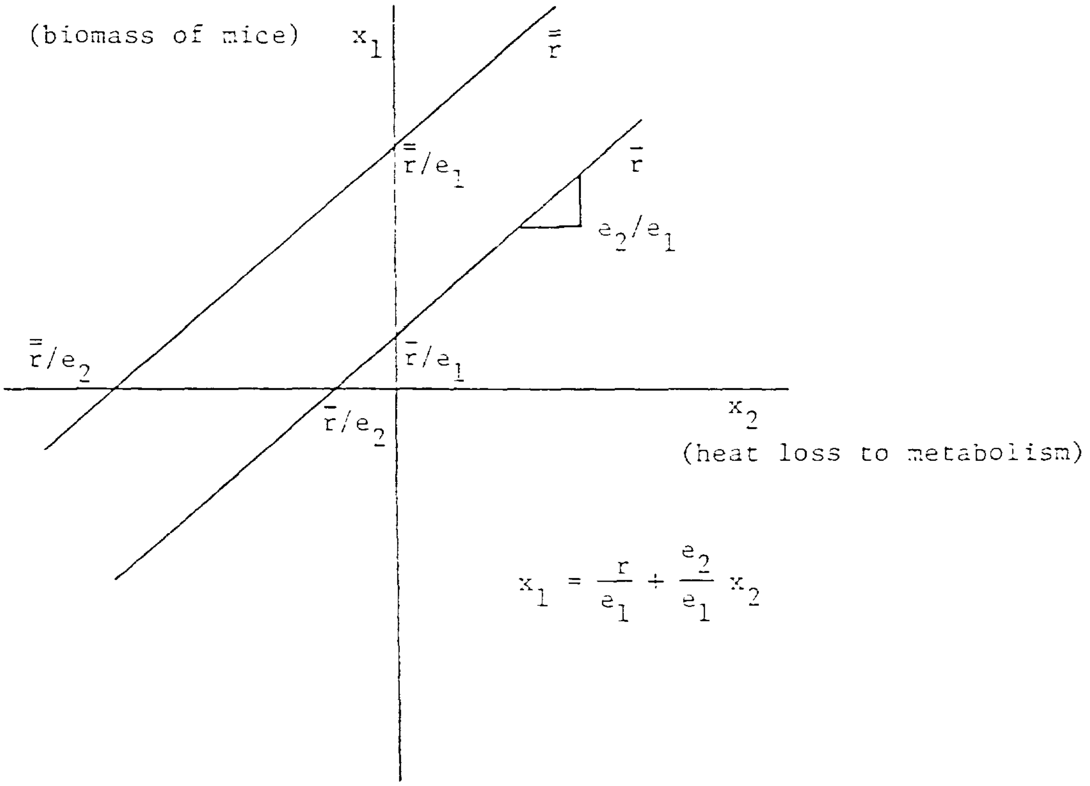
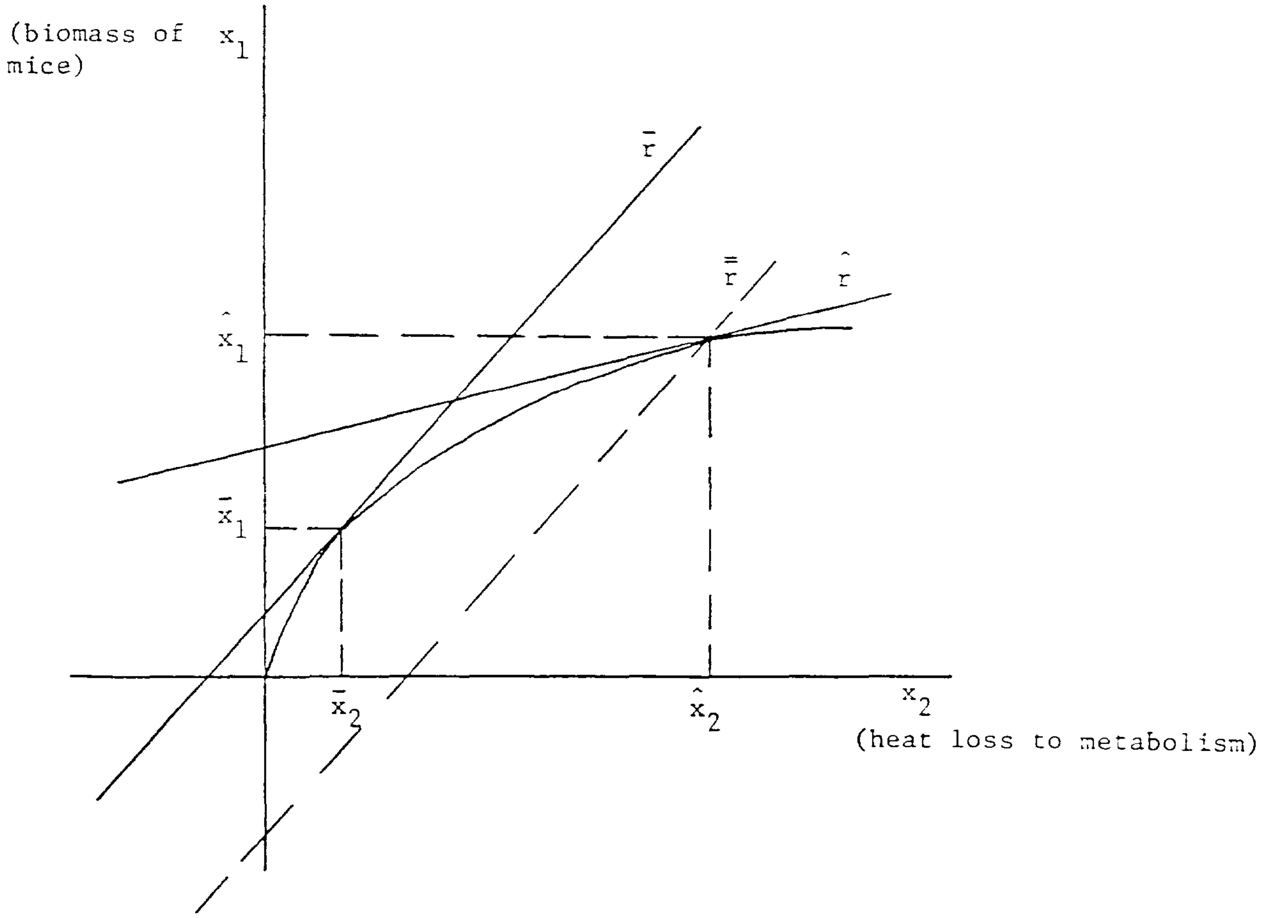

(biomass of mice)
x_1
$\bar{\bar{r}}$
$\bar{r}$
$\bar{\bar{r}}/e_1$
e_2/e_1
$\bar{\bar{r}}/e_2$
$\bar{r}/e_1$
$\bar{r}/e_2$
x_2
(heat loss to metabolism)
$x_1 = \frac{r}{e_1} + \frac{e_2}{e_1} x_2$

Figure 4


(biomass of mice)
x_1
$\bar{r}$
$\bar{\bar{r}}$
$\hat{r}$
$\hat{x}_1$
$\bar{x}_1$
$\bar{x}_2$
$\hat{x}_2$
x_2
(heat loss to metabolism)

The function F(x) i the physiology function, and, by construction, it embodies physiological efficiency. That is, $\hat{x}$ is physiologically efficient if and only if $F(\hat{x}) = 0$. In two dimensions, $F(\hat{x}) = 0$ implies that $\hat{x}$ is on the border of the physiology set.

The maximization problem can be restated as

$$\max r = \sum_{j=0}^{n} e_j x_j - e_{n+1} x_{n+1} \tag{6}$$

subject to F(x) = 0

where F(x) is assumed to be twice differentiable and the physiology set is assumed to be strictly convex. Strict convexity assures that the second-order sufficiency conditions of the maximization problem are satisfied, and that there is a unique maximum. The Lagrangian for problem (6) is

$$L(x, \lambda) = r + \lambda F(s) \tag{7}$$

and the first-order conditions for a maximum are

$$x_j: \quad e_j + \lambda \frac{\partial F(x)}{\partial x_j} = 0, \qquad j = 0, \dots , \tag{8}$$

$$x_{n+1}: \quad -e_{n+1} + \lambda \frac{\partial F(x)}{\partial x_{n+1}} = 0 \tag{9}$$

$$\lambda: \quad F(x) = 0 \tag{10}$$

Dividing any two conditions in (8) by one another yields

$$\frac{\partial F(x)/\partial x_i}{\partial F(x)/\partial x_j} = \frac{e_i}{e_j} \tag{11}$$

so that for a maximum, the ratio of partial derivatives of F(x) must be equal to the ratio of energy prices. Using (5),

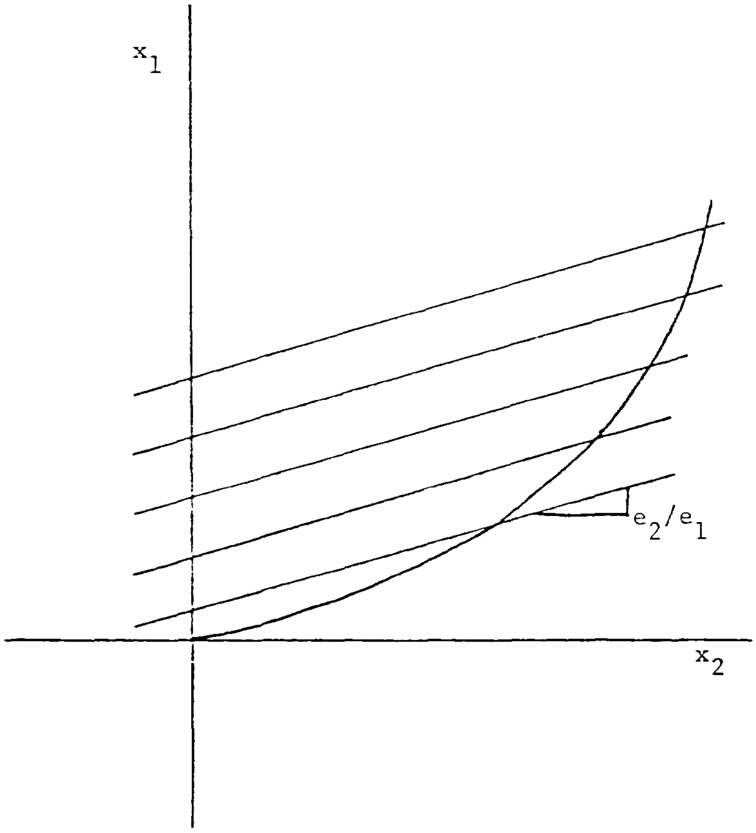
$$F(x_0, \dots , x_{j-1}, f(x^{-j}), x_{j+1}, \dots , x_{n+1}) = 0$$

and differentiating with respect to x_i, $i \neq j$, yields

$$-\frac{\partial f(x^{-j})}{\partial x_i} = \frac{\partial F(x)/\partial x_i}{\partial F(x)/\partial x_j} \tag{12}$$

Thus, the left-hand-side of (11) can be interpreted as the rate at which x_j must be substituted for x_i while all other values are held constant. Or, for the fox's predatory behavior, (11) states that the rate at which he can

Figure 5



trade mouse biomass for say rabbit biomass, while achieving the same stored energy must equal the ratio of the energy contents in units of mouse biomass and rabbit biomass. Alternatively, (11) and (12) can be used to obtain

$$-\frac{\partial e_j f(x^{-j})}{\partial e_i x_i} = 1 \tag{13}$$

The left-hand side of (13) is the rate at which energy from source j must be traded for energy from source i in order to be physiologically efficient. Or, substituting mice for rabbits must lower the input of rabbit energy at the same rate mouse energy is increased.[4] To see the rationale behind this result, suppose the fox was obtaining more stored energy from the last unit of rabbit biomass than from the last unit of mouse biomass. Then (13) would be an inequality. The fox would begin to consume more rabbit biomass and less mouse biomass. Giver, the shape of the physiological function, eventually, the amount of mouse biomass given up for each unit of rabbit biomass consumed, and it must be given up with a fixed level of outputs (x_{n+1}), becomes so great that further rabbit biomass is undesirable. The tradeoff of mice for rabbits stops when (13) is satisfied as an equality.

In a similar fashion, (9) can be combined with any of the n+1 conditions in (8) to obtain

$$-\frac{\partial F(x)/\partial x_j}{\partial F(x)/\partial x_{n+1}} e_{n+1} = e_j \tag{14}$$

for j = 0, ... , n. The interpretation is that all n+1 inputs are obtained such that their energy contribution to the metabolical processes are in proportion to their energy prices.

The first-order maximum conditions given by (8) - (10) constitute n+3 equations which can be solved for the optimum values of the x_0 and λ as functions of the energy prices. A solution is guaranteed by the assumption of a convex physiology set. Thus, there exist the functions:

$$x_j = x_j(e) \qquad j = 0, \ldots , n+1 \tag{15a}$$

$$\lambda = \lambda(e) \tag{15b}$$

The function $x_j(e)$ indicates the amount of the jth input acquired or jth output spent, given the energy prices of all inputs and outputs. Substituting these amounts back into the objective function gives the maximum stored energy,

$$r = \sum_{j=0}^{n} e_j x_j(e) - e_{n+1} x_{n+1}(e) \tag{16}$$

If j represents rabbits, $x_j(e)$ can be thought of as the fox's demand for rabbits at prices 2.

Finally, the x,(e) terms can be substituted into (8) - (10) and derivatives can be taken with respect to the e_j. This yields the system of equations:

$$\begin{bmatrix} 0 & F_0 & F_1 & \cdots & F_{n+1} \\ F_0 & 1+\lambda F_{00} & \lambda F_{01} & & \lambda F_{0n+1} \\ F_1 & \lambda F_{01} & 1+\lambda F_{11} & & \\ \vdots & \vdots & & & \\ F_{n+1} & \lambda F_{0n+1} & & & -1+\lambda F_{n+1\ n+1} \end{bmatrix} \begin{bmatrix} \lambda_0 & \lambda_1 & \cdots & \lambda_{n+1} \\ x_{00} & x_{01} & \cdots & x_{0n+1} \\ x_{10} & x_{11} & & \\ \vdots & & & \\ x_{n+10} & & & x_{n+1\ n+1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \cdots & & 0 \\ -1 & 0 & & & 0 \\ 0 & -1 & & & \\ 0 & 0 & & & \\ \vdots & \vdots & & -1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{17}$$

where subscripts indicate partial derivaties. For instance, $x_{ij} = \partial x_i(e)/\partial e_j$. This system can be used in a comparative static analysis (see e.g., Chiang) to solve for the $\partial x_k(e)/\partial e_j$ values to obtain

$$\frac{\partial x_j(e)}{\partial e_j} > 0 \qquad j = 0, \ldots, n \tag{18}$$

$$\frac{\partial x_{n+1}(e)}{\partial e_{n+1}} < 0 \tag{19}$$

The interpretations of (18) is that an increase in the energy price of a net input results in an increase in the use of that input, _ceteris paribus_. If the net energy the fox could obtain from rabbit biomass were to increase while the net energy obtained from mouse biomass remained the same, the fox would chase more rabbits and fewer mice. A similar interpretation holds on the output side and (19).

SECTION 3

MULTIPLE ORGANISIMS AND NATURAL EQUILIBRIUM

The individual organism in the previous section must now be placed in the context of an entire ecosystem. Each organism belongs to a species, and sets of species form trophic levels. The trophic levels are links in a food chain or levels in a hierarchy. Species may feed on other species in lower trophic levels, and in turn may provide substance for species in higher trophic levels.

To simplify the following analysis and to avoid notational complexity of defining the ecosystem, individual. organisms will be aggregated to the species level. Thus, the collective goal of an entire species is to maximize stored energy which is the sum of stored energy for all the organisms in the species. This also avoids certain complications that occur when, say a bobcat consumes a rabbit. The bobcat receives an input but the rabbit is gone. At the species level, however, the bobcats collectively receive an input, while the rabbits collectively yield an output.

In aggregating, all individuals in a species are assumed identical; that is, their physiological functions are the same. This avoids having to consider the distribution of resources among individuals, and a single physiological function can be used for an entire species. The problem for species i is to

$$\text{maximize } R_i = \sum_{j=0}^{n} E_{ji}\, X_{ji} - \sum_{j=1}^{n} E_{ij}\bar{X}_{ij} - E_{i,n+1}X_{i,n+1} \qquad (20)$$

$$\text{s.t. } F^i(X_i, \bar{X}_i) = 0$$

where R_i, is the species stored energy E's are the energy prices, x_{ji}'s are inputs in the first summation and $\bar{x}_{ij}$'s are outputs to other species in the second summation, n is the number of species, x_i is a vector whose elements are the x_{ji} and $x_{i,n+1}$, and the bar notation on x_{ij} is to indicate that outputs to other species are fixed. Most of these terms require a more detailed discussion. In general for outputs and inputs, X_{ij}, i, j=1, ... , n, is the output of the ith species to the jth species. Thus it is an input to the jth species. The $\bar{X}_{ij}$'s enter parametrically into a species physiological function. If these outputs were decision variables, the species would set their values to zero; therefore, these outputs are fixed. They are exogenous to the individual species, but endogenous in the entire ecosystem since they are inputs of other species. For example, oak trees cannot avoid having squirrels consume their acorns; therefore, the output of acorns to squirrels is fixed in the oak trees' maximization problem.

Figure 6 illustrates the effect of these fixed outputs on the fox species' physiological function. The axes are the same as in the previous section, except that they represent aggregates for the entire fox species. Also, $\bar{X}_3$ is an output to a predator of foxes. When $\bar{X}'_3$ of fox biomass is sacrificed to predators, an input of X_1 mice requires metabolism of X'_2. But when $\bar{X}''_3 > \bar{X}'_3$ is lost to predators, the function shifts downward and a greater metabolical level, X''_2, is required for the same input of mice. Basically, the greater metabolical level is needed to support the additional fox biomass taken by predators.

Where there is no direct interaction between species i and j then $\bar{X}_{ij} = X_{ji} = 0$. If $X_{ij} > 0$ then $\bar{X}_{ij} = 0$; that is, if species i feeds on species j, then j does not feed on i. This is not universally true, however, it leads to less notation in the model. As in the previous section, the zero index in the first summation of (20) indicates incoming solar energy, and the n+1 index indicates output, such as heat loss to the physical environment and not an input to another species.

The E's are energy prices as discussed in the previous section. In the case where predator in species i captures prey in species j, X_{ji} units of biomass are transferred to the predator. This biomass contains $E_{ji}X_{ji}$ energy units. Since the predator must also expend energy in the capture, $E_{ji}X_{ji}$ is the net energy gained by the predator or as in the last section

$$E_{ji}X_{ji} = (E'_{ji} - E''_{ji})X_{ji} \tag{21}$$

All energy prices *are* parametric in that every species takes the prices as given.

A natural equilibrium of the ecosystem, where natural refers to no human intervention, is provided by the simultaneous solution of all species' first order conditions. Each species provides at most n+2 equations from its n+l input variables (X_{0i}, X_{1i}, ... , X_{ni}) and one input variable ($X_{i,n+1}$). There may be fewer if there is no direct interaction with some species. In total, there are at most n x (n+2) equations and variables. In the long-run, all species will have zero stored energy. The driving force for this outcome is the change in prices that occur when stored energies are nonzero. For example, suppose $R_i > 0$. Then E_{ij} for j = 1, . . . , n will decrease, since species i is bountiful and more easily preyed upon. As more predation occurs, R_i will tend towards zero. A similar but *reverse* story can be told for $R_i < 0$.

This ecosystem can be likened to an economic system. A storage maximizing species is like a profit maximizing firm, and the firm sells outputs to other firms and buys inputs from other firms. The physiological function is like the firm's production function. One distinction is the presence of the $\bar{X}$ terms which have no counterparts in economic models. But this is because economic models deal with voluntary trades, involuntary trades are largely ignored. Involuntary trades are an essential part of the ecosystem. Mice do not volunteer themselves as inputs to the fox.

Provided certain conditions are met on species' physiology functions (i.e., strict quasi-concavity), the first-order conditions for stored energy maximization (conditions comparable to (8), (9), and (10)) can be inverted to obtain continuous, differentiable input demand functions. Species i's demand for biomass from organism j is

$$X_{ji}(E, \bar{X}) \tag{22}$$

Where E represects all the energy prices as defined above and $\bar{X}$ are the exogenous outputs supplied by i to other species. Using comparative static analysis, it can be shown that

$$\frac{\partial X_{ji}}{\partial E_{ji}} > 0 \tag{23}$$

for j = 1, ... , n. Thus, an increase in the energy content per unit of j's biomass (E'_{ji}) or a decrease in the energy spent to obtain a unit of j's biomass (E''_{ij}) will result in an increase in demand for species j by species i. Other comparative statics results will have signs dependent upon the complementarity between inputs and outputs in the physiological function. These signs are not unequivocal without placing further restrictions on the function.

Finally, as was done for (16) and the individual organism, the demands can be substituted into the original objective function for each species to obtain a stored energy function. Thus, for species i, i = 1, ... , n;

$$R_i(E, \bar{X}) = \sum_{j=0}^{n} E_{ji}X_{ji}(E, \bar{X}) - \sum_{j=1}^{n} E_{ij}\bar{X}_{ij} - E_{i,n+1}X_{i,n+1}(E, \bar{X}) \tag{24}$$

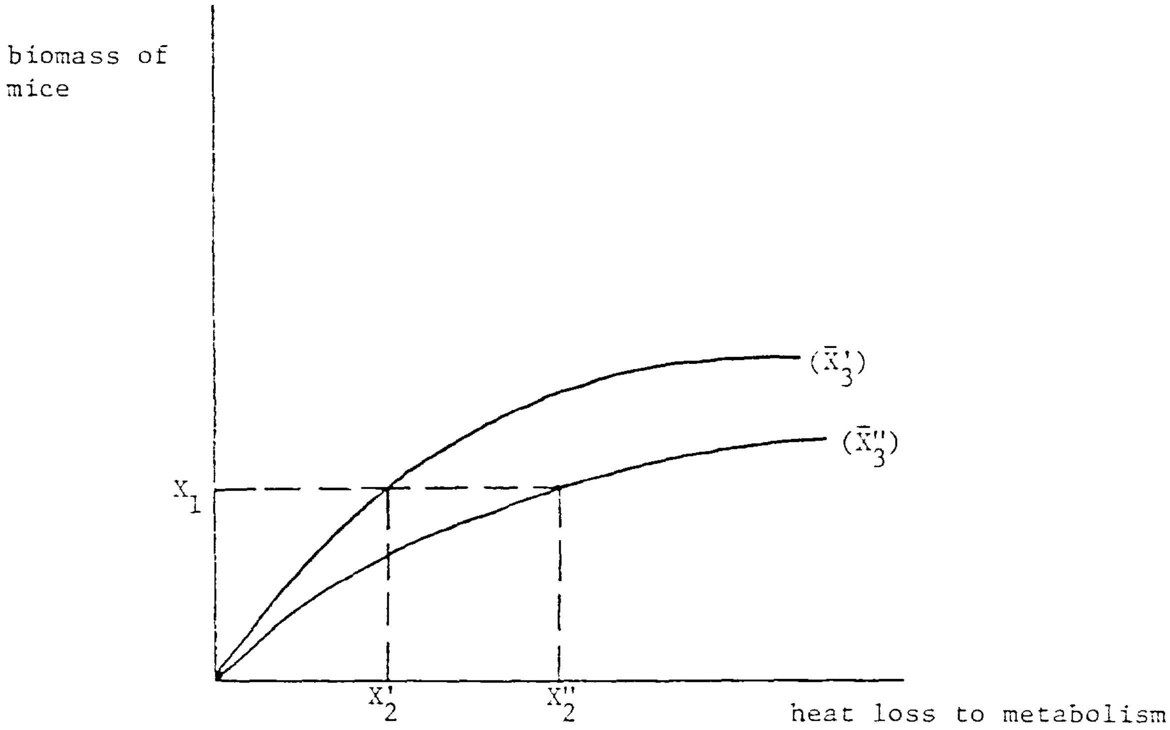
The function R_i gives the maximum stored energy possible for species i over all values of input/output prices and outputs. The envelope theorem can be used to show

$$\frac{\partial R_i}{\partial E'_{ji}} = - \frac{\partial R_i}{\partial E''_{ji}} = X_{ji} > 0, \quad \frac{\partial R_i}{\partial E_{ij}} = -\bar{X}_{ij} < 0 \tag{25}$$

Thus, if species i and j interact, increased energy content per unit of biomass of input species j, or decreased energy expenditures for obtaining units of biomass from species j, or decreased energy content of biomass yielded to species j will result in increased stored energy. Additionally,

$$\frac{\partial R_i}{\partial X_{ij}} = -Eij + \frac{\lambda \partial F^i}{\partial X_{ij}} < 0 \tag{26}$$

Figure 6



so that increases in exogenous outputs to predators have negative effects on stored energy. This follows from Figure 6 where increased predation always decreases the feasible region for the species.[5] As noted below, this is a short-run effect; that is, increased predation immediately lowers stored energy of the species. In the long run, as the ecosystem seeks a new equilibrium, certain prices may adjust and stored energy may increase. Witness the human practice of culling species to increase stability and productivity.

SECTION 4

EMPIRICAL SUPPORT FOR THE ECOSYSTEM MODEL

A central result in the previous Section is the derivation of the input demand function of one species for another. That is, $X_{ij}(E,\bar{X})$ is the ith species demand for the biomass of organism j. Moreover (23) showed that the partial of X_{ji} with respect to E_{ji} is positive (inequality (23)). This result constitutes a testable hypothesis which, if verified, lends support for the theory developed above. In economics, one would test equivalent hypothesis about consumer demand by gathering primarily price, quantity, and income data, and using econometric techniques to estimate a demand function. Testing the ecosystem hypothesis given by (23) requires gathering the appropriate data and, if the data is adequate, using econometric techniques to estimate the demand function of one species for another. In this Section, the data requirements are discussed, and shortfalls in data cited. However, a number of biological studies are cited which do lend support for the ecosystem model.

Result (23) implies that an increase in the energy content per unit of species j's biomass (E'_{ji}) or a decrease in the energy spent to obtain a unit of j's biomass (E''_{ji}) will result in an increase in demand for species j by species i. Thus data requirements include; i) the energy content per unit of all prey species' biomass; ii) the energy spent to obtain a unit of all prey species' biomass. The former requires studies to determine how the energy content varies over measures of biomass for the prey species. A reasonable proxy here might simply be to use a measure of weight such as pounds of the prey. The latter data is more vexing. However, a reasonable proxy here would be some measure of the availability of the prey. An abundant prey species would require less energy to be spent in capture than a nonabundant prey species, assuming both species have similar escape responses. One possibility is to use the reciprocal of the abundance of biomass per unit area as a measure of the energy price.

In addition to the price, (22) shows that the exogenous outputs are also variables in the demand function. This would require obtaining a measure of the biomass loss of the predator species to its own predators.

These various data are not always readily available or in a useful form. Some studies provide information on the quantities of various foods consumed by certain species, but do not indicate the relative abundance of these foods. An example would be a study by Baker and Hobbs (1982) which tabulated various plant species consumed by elk in Colorado. A study that does collect the correct type of data is one by Wallmo et al. (1977). They examine deer diet and habitat in Colorado. They list the different forage consumed; they tabulate the relative abundance of the forage consumed; and they then document how the forage breaks down into crude protein, carbohydrates, cellulose, etc. While this qualitatively satisfies the data requirements, the quantity of data is too scanty for an econometric analysis. Kufeld (1973) documents forty eight papers that study food habits of elk, and ranks the various foods in the elk's diet according to their value of the elk. This borders on the type of data requirements useful to economists, and may be adequate for econometric analysis.

A number of papers have used laboratory experiments to test hypothesis of the type given by (23). On one hand, laboratory experiments have an advantage in that other variables (weather, age of organisms, etc.) can be held constant. On the other hand, this is no guarantee that behavior is not modified in a laboratory setting.

Rapport (1971) uses microeconomic techniques to examine the foraging behavior of certain protozoan. His purpose is to show that the "fundamental theorem" of foraging theory, that predators rank order single prey species, can be improved upon using economic techniques. In particular, he argues that predators choose among alternative <u>bundles</u> of prey. Moreover, while the "fundamental theorem" implies that changes in relative abundance of less desired prey has no effect on foraging, Rapport shows that changes in relative abundance of any prey species effects foraging. His experiments consisted of allowing protozoan to feed for one hour in the presence of varying densities of two algae prey species. A clear pattern emerged whereby greater densities of a species led to greater consumption of that species as (23) would dictate.

In another laboratory experiment, Kagel et al. (1975) observed the behavior of white rats. Specifically, the rats were allowed to push one of two levers, where one lever delivered rootbeer and the other Collins mix. Each rat was allowed so many pushes on the levers and initially 20 pushes were required on either lever to obtain a unit of liquid. At these prices, different rats chose different combinations of rootbeer and Collins mix. Then the prices were changes and 40 pushes were required for rootbeer and 10 for Collins mix. Each rat was provided with enough total pushes so that the original consumption bundle was possible. The result was as (23) would predict. All rats increased consumption of Collins mix and decreased consumption of rootbeer. Thus, goods are not ranked one at a time, but rather bundles of goods are ranked and the highest ranked bundle in the opportunity set is consumed.

Finally, there have been nonlaboratory studies that also lend support to the hypothesis presented above. Menge (1972) observed the foraging strategy of starfish. The observations were conducted over a period of about two years in the San Juan Islands off Washington. Menge analyzed the starfish diet by both numerical and caloric consumption and he observed that they consumed more of a type of cirripede in the summer and autumn when the cirripede was more abundant. The increased abundance results in a reduction in the expended energy of the starfish and an increase in demand. Menge also found that the starfish consumed large amounts of a certain gastropod which can be explained by the ease with which the gastropod is captured. Generally, he found that prey species with less effective escape responses were consumed more often than those with more effective escape responses.

In another study, Werner and Hall (1974) examined bluegill sunfish predation on three different size groups of daphinea. The authors observed that an the density of prey increased for all groups, the sunfish began to select only the largest prey. Goss-Custard (1977) had similar findings with the foraging habits of redshark.

Bar-tailed godwits were studied by Evans (1976) who observed that the birds used less costly foraging methods when prey was scarce, thereby reducing expended energy. In fact, he found that foraging may completely stop when prey is very scarce, presumably because net energy from preying may actually be negative.

SECTION 5

HUMAN INTERVENTION

The natural ecosystem is characterized by inputs, outputs, energy prices, and phsyiology functions. Humans intervene in the ecosystem by directly or indirectly effecting all of these characteristics. Humans also change in the overall energy equation, since total energy into the ecosystem does not originate only with the sun. Instead, stored energy or fossil fuels are another source.

Examples of human intervention are given in Table 1. In fact, virtually any human action will have some influence on the ecosystem either directly or indirectly through one or more of the listed characteristics. The objective here is to capture this influence by augmenting the natural ecosystem model.

Initially, the analysis will be confined to the effects of human inputs and outputs. Humans have initial endowments of s raw materials to be used in the production of ecosystem goods and m manufactured goods. In turn, these ecosystem goods are also used in the production of manufactured

Table 1

	Physiology Functions	Energy Prices	Inputs/Outputs
Agriculture, Ranching	Developing new breeds of domestic plants and animals	Tilling the soil to make nutrients more accessible	Adding fertilizer
Timber	Breeding faster growing trees	Creating monocultures that decrease diversity and alter prices of food search	Cropping the forests
Hunting, Fishing	Fish hatcheries developing new breeds of wild fish	Creates higher prices for predators of the hunted species	Cropping and stocking
Pesticides	Interfering with birds' of prey ability to produce	Raising energy prices of food search by insect predators	Eliminating insect species

goods. Let $Z = (Z_1, \ldots, Z_m)$ be manufactured goods, and let Y^z_{pq} be the amount of raw input p used in the production of Z_q. Furthermore, let Y^h_{pi} be the amount of raw input p used as an input to the ith species. Then, if $\bar{Y}_p$ is the initial endowment of raw input p, it follows that

$$\sum_{q=1}^{m} Y^z_{pq} + \sum_{i=1}^{n} Y^h_{pi} = \bar{Y}_p \tag{27}$$

for p = 1, ... , s.

The problem for the ith species given by (20) can now be rewritten as

$$\text{Maximize } R^h_i = R_i + \sum_{p=1}^{s} E^h_{pi}\bar{Y}^h_{pi} \tag{28}$$

$$\text{s.t. } F^i(X_i, \bar{X}_i, \bar{Y}_i) = 0 \tag{29}$$

The stored energy in the interventionist state is rewritten as R^h_i to denote human presence. The inputs, Y^h_{pi}, that have been appended to the objective function are fixed for every species. This is to say that species have no control over how humans supply inputs, as the oak tree has no control over squirrels pilfering acorns.

Humans export biomass from the ecosystem to be used as inputs in the production of manufactured goods. Agriculture is a good example. A manufactured good may be a tomato in the supermarket. The ecosystem provides a tomato on the vine which is ten combined with other resources (labor, transportation, etc.) to produce the manufactured good. This exportation or cropping is done from stored energy. "...cropping from storage (is) removing from the system a constant fraction of that energy which is being diverted into storage" [Hannon (1976), p. 260]. The species continues to maximize stored energy which is modified as

$$R^h_i = (1 - c_i)[R_i + \sum_{p=1}^{s} E^h_{pi}\bar{Y}^h_{pi}] \tag{28'}$$

In (28'), c_i is the fraction of stored energy being cropped. Also, $0 \leq c_i \leq 1$ where $c_i = 1$ implies all stored energy is diverted to humans as in some agricultural products (wheat, vegetables, and other annuals) and $c_i = 0$ implies no human cropping. The actual amount of cropped stored energy from the ith species is denoted by

$$c_i [R_i + \sum_{p=1}^{s} E^h_{pi} \bar{Y}^h_{pi}] = c_i A_i \tag{30}$$

The c_i are fixed at levels that maintain the viability of the species. In other words, too much cropping may lead to instability in the species, but this possibility will be ignored at this point.

Species' demand for biomass are now dependent on the human inputs as well. Thus, (22) becomes

$$X_{ji}(E,\ E^h,\ \bar{X},\ \bar{Y}^h) \tag{31}$$

where the human associated energy price vector E^h and input vector $\bar{Y}^h$ are additional arguments. The maximum stored energy function of species i becomes

$$R_i^h(E,\ E^h,\ \bar{X},\ \bar{Y}^h) = (1 - c_i)A_i(E,\ E^h,\ \bar{X},\ \bar{Y}^h) \tag{32}$$

And by the envelope theorem,

$$\frac{\partial R_i^h}{\partial \bar{Y}_{pi}^h} = (1 - c_i)[E_{pi}^h + \lambda \frac{\partial F^i}{\partial \bar{Y}_{pi}^h}] \gtreqless 0 \tag{33}$$

so that changes in human inputs to a species have ambiguous effects on stored energy. The ambiguity arises because humans may be supplying too much or too little input given the species' objective of storage maximization.

SECTION 6

THE ECONOMIC PROBLEM

The economics problem is to allocate the raw inputs among manufactured goods and the ecosystem to maximize human welfare. A community welfare function will be used to represent human preferences. The function is written as

$$U(Z_1,\ldots Z_m,\ R^h_1,\ldots,R^h_n) \tag{34}$$

Humans derive utility from manufactured goods and directly from the species in the ecosystem. The latter sources of utility refer to enjoying (or not enjoying) nonconsumptive qualities of the ecosystem. Included are aesthetics, studying plants and animals, camping, photography, and so on (not enjoying refers to insect attacks, aversion to snakes, etc.). These activities are enhanced by 2 healthy ecosystem, and stored energy is assumed to be a reasonable proxy for health. Let $U_q = \partial U/\partial Z_q$ for $q = 1,..,m$ and $U_{hi} = \partial U/\partial R^h_i$ for $i = 1,\ldots,n$. Nonsatiation for manufactured goods implies $U_q > 0$ for $q = 1,.$. For the ecosystem, however $U_{hi} > 0$ for species providing nonconsumptive enjoyment (maple trees, deer, etc.), $U_{hi} = 0$ for species that are virtually unnoticed (soil microbes, lichens: etc.), and $U_{hi} < 0$ for pest species (weeds, mosquitoes, etc.).

For species that are used as inputs to manufacturing, humans essentially view the output from those species (c_iA_i) as a production function that depends on the raw inputs supplied to these species. That is, raw inputs are supplied, the species solves its stored energy maximization problem, and then yields output to the humans. While the humans are not cognizant of the intricacies involved in stored energy maximization, they are aware of the approximate amount of species output available for a given raw input. A farmer knows reasonably well the yield of corn from a given amount of fertilizer, although knowledge of the corn's physiology set and other inputs and outputs is unnecessary. That humans do not know precisely the species' output from a given input can be attributed to uncertainties (e.g., weather in agriculture) and lack of knowledge about ecosystem interactions. Uncertainties are beyond the scope of this work, but the lack of knowledge will be discussed below as ecosystem externalities. One further simplification is made to avoid notational complexity. The ecosystem is comprised of n species that form a very simple food chain. Species i, $i = 1, \ldots, n$, receives inputs, or demands outputs, from species $i - 1$ only. Where $i = 1$, the species only obtains input from the sun. Although this masks much of the richness of the ecosystem interactions, it suffices to show how human intervention can reverberate through the ecosystem. Given this assumption, the stored energy for species i can be written

$$R_i^h = E_{i-1,i}X_{i-1,i} - E_{i,i+1}\bar{X}_{i,i+1} - E_{i,n+1}X_{i,n+1} \tag{35}$$

Manufactured goods are produced using raw inputs and ecosystem inputs. Production of the qth good is given by the function

$$Z_q = G^q(Y_{1q}^z, \ldots, Y_{pq}^z, c_{iq}A_{iq}, \ldots, c_{nq}A_{nq}) \tag{36}$$

where $c_{iq}A_{iq}$ is the cropped stored energy from species i used in the production of the qth good.

The human problem can now be stated as maximizing welfare given by (34) subject to the functional relations given by (32) and (36) and endowment conditions from (27). Maximization is over all raw inputs. The maximum is characterized by the following expression which shows the case where $Y_{pi}^h > 0$ and $Y_{pq}^a > 0$, that is, positive amounts of raw input p are used as input for species i and for manufactured good q:

$$U_q \frac{\partial G^q}{\partial Y_{pq}^z} = U_{hi} \frac{\partial R_i^h}{\partial Y_{pi}^h} + \left\{ \sum_{j=1}^{i} U_{hj} \frac{\partial R_j^h}{\partial X_{j-1,j}} \prod_{k=j}^{i-1} \frac{\partial X_{k-1,k}}{\partial X_{k,k+1}} \right\} \frac{\partial X_{i-1,i}}{\partial Y_{pi}^h} +$$

$$\left\{ \sum_{q=1}^{n} U_q \sum_{j=1}^{i} \frac{\partial G^q}{\partial c_{jq}A_{jq}} \frac{\partial c_{jq}A_{jq}}{\partial X_{j-1,j}} \prod_{k=j}^{i-1} \frac{\partial X_{k-1,k}}{\partial X_{k,k+1}} \right\} \frac{\partial X_{i-1,i}}{\partial Y_{pi}^h}$$

(37)

Basically, (37) states that raw input p should be distributed in such a way that the marginal benefits of its use in manufacturing (left hand side (l.h.s.)) should equal the marginal benefits of its use as an ecosystem input (right hand side (r.h.s.)). Specifically, the first term on the l.h.s. is the marginal utility from the change in the qth manufactured good as the pth raw input to this good is changed. The first term on the r.h.s. is the marginal utility of a change in the ith species' stored energy due to changing the pth raw input to this species. The second term on the r.h.s. is the marginal utility of a change in stored energy of all lower species due to changing the pth raw input to the ith species. For example, if the food chain consists of three species, mayflies (1), trout (2), and eagles (3), then a human input to the eagles will effect eagle stored energy and the associated utility - the first term on the r.h.s. In turn, the eagles' demand for trout, the trout's demand for mayflies, and the mayflies' use of solar energy are all effected. Thus, the stored energy in all three species is effected which is then reflected in utility changes. All of these effects are captured in the second term. The third term is the sum of marginal utilities for all manufactured goods as the production of these goods is altered by the stored energy changes in all the species lower than i in the food chain. The stored energy changes imply that cropping for use in these manufactured goods is effected. If input p is used as an input for either more than one species or more than one manufactured good, additional terms would be appended to (35).

There is a first order condition for each input used in each manufactured good and in each species. In total, there are m P + n P + s first order conditions. The s is for the constraints in (27).

The raw inputs or resources are decision variables for the humans as they are allocated between manufacturing and the ecosystem. For the species, however, those resources are the parameters, since species have no control over them. Thus, as humans manipulate a resource to find its optimal use, comparative static changes are occurring in the ecosystem as it responds to the exogenous changes. The ecosystem seeks a new equilibrium which may not be what humans have in mind. An ecosystem externality, discussed below, is created.

At this juncture, a much simplified version of this model may be useful. Suppose there is a single raw input, one species, and one manufactured good. The raw input is divided between the manufactured good and the ecosystem so that

$$\bar{Y} = Y^z + Y^h \tag{38}$$

The manufactured good is produced according to

$$Z = G(Y^z, cA) \tag{39}$$

where cA is the cropped stored energy.

The stored energy of the species is

$$R^h = (1 - c)A(E, E^h, Y^h) \tag{40}$$

The human problem is to maximize $U(Z, R^h)$ subject to (38) - (40). If both Y^z and Y^h are positive at the maximum, then first order conditions require

$$\frac{U_h}{U_z} = \left[\frac{\partial G}{\partial Y^z} - c \frac{\partial G}{\partial cA} \frac{\partial A}{\partial Y^h} \right] / \left[(1 - c) \frac{\partial A}{\partial Y^h} \right] \tag{41}$$

This is a tangency condition between the human's marginal rate of substitution and the rate of product transformation between ecosystem amenities and the manufactured good. The numerator on the r.h.s. of (41) is the manufactured good's marginal product. It accounts for the fact that while manufactured output may tend to increase with increased raw input, this also means less raw input to the ecosystem and less ecosystem output into manufacturing which tends to decrease output. The denominator is the stored energy marginal output from changes in raw inputs.

Noninterior solutions are also possible and can be illustrated diagramatically. Figures 7 and 8 show the production possibility frontiers in $R^h Z$ space (abc in Figure 7 and ab in Figure 8) and several possible

Figure 7

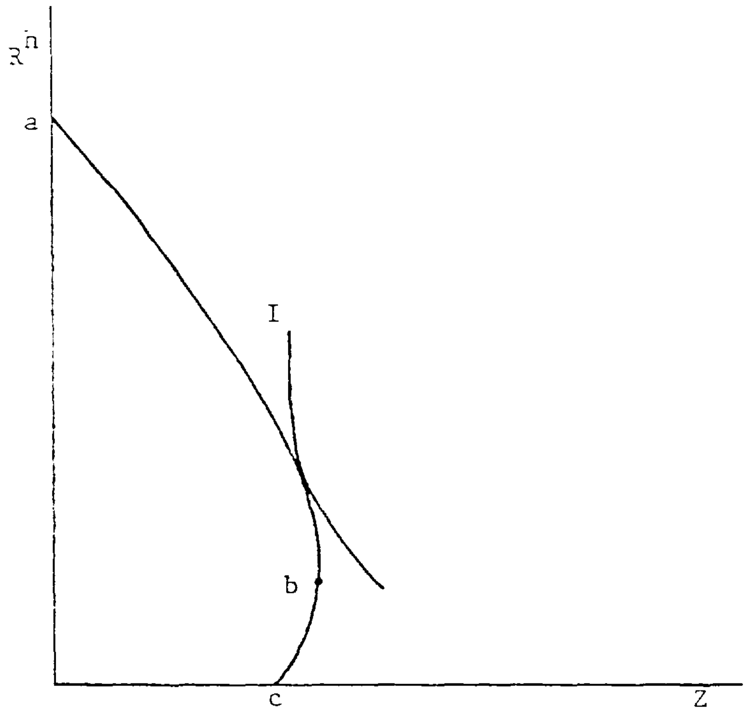
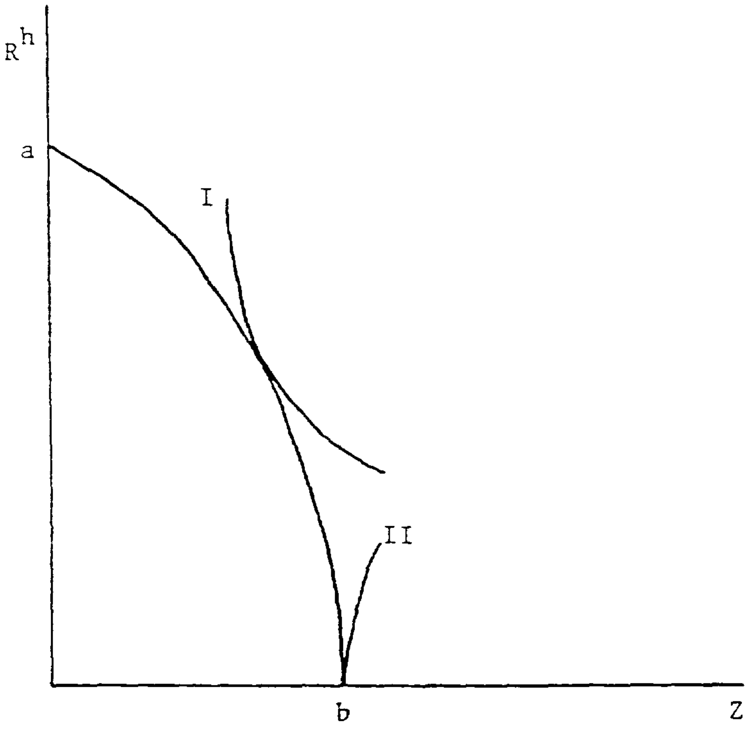


Figure 8



indifference curves. In Figure 7, the positively sloped portion, cb, indicates that raw input to the ecosystem creates higher stored energy in addition to more manufactured goods, since the stored energy can be cropped for inputs to the manufactured goods. Negatively sloped portions indicate a direct tradeoff between the use of raw inputs for manufacturing and ecosystems. Which shape obtains crucially depends on the term $\partial A/\partial Y^h$. The greater is this term then the more productive the ecosystem is in providing inputs to manufacturing from raw inputs. This then increases the possibility of a positive slope in the production possibility frontier, since the ecosystem can provide both inputs to manufacturing and to stored energy.

Indifference curve I in both Figures yield interior solutions. Indifference curve II in Figure 8 yields a solution where the ecosystem experiences no human intervention.

SECTION 7

ECOSYSTEM EXTERNALITIES

Above, the conditions which characterize an optimum distribution of resources among manufacturing and the ecosystem are presented. Resources are used as inputs for certain species, and these inputs can then enhance outputs from the species to humans. Inserting inputs to and cropping outputs from certain species will change stored energy levels and the availability of inputs and outputs to other species in the ecosystem. That is, $R_i^n \neq R_i$. Consequently, human intervention into any one species will have effects on many other species, as the intervention dictates a different ecosystem equilibrium. To the extent that stored energy levels differ in the new equilibrium in unexpected ways, an ecosystem externality is created. The stored energy levels may be expected to change, changed in unexpected ways, or certain species whose were not expected to change, did so.

The ecosystem externality can be contrasted to conventional externalities. An air polluting firm directly effects an argument in a consumer's utility function, that argument being clean air. The decrement in utility is clearly traceable to the externality source (although acid deposition may be an exception), but solutions to the problem are complicated because clean air is outside the market system. Human intervention into the ecosystem is an exogenous shock which causes that system to seek a new equilibrium. This gives rise to new stored energy levels, where these levels are arguments in a consumer's utility function. The intervention, which is tantamount to polluting in this example, must work its way through a complex general equilibrium system that is wholly external to the economic system. Thus, the effect on utility arguments are less direct for ecosystem externalities. And when links among species are unknown or poorly understood, the decrement (or increment) to utility due to an ecosystem externality may be untraceable to the original human intervention.

The following story provides a simple example of an ecosystem externality. Around the turn of the century, the citizens of Kern County, California, a rural area of farms and small towns, decided to do away with various predators that killed domestic animals and frightened children. Armed with shotguns, traps, and strychnine, they were very effective in decimating populations of skunks, foxes, badgers, weasels, snakes, owls, and hawks. In addition, they hired a team from the Department of Agriculture to exterminate all coyotes in the county. This was also successful. The myopic campaign took place over a period of two decades. Then, during a year when farmers were enjoying a bumper crop, hordes of mice appeared where they were not wanted. Their vast numbers, unchecked by natural predators, were too much for the usual wild grains to feed; and the mice began *to* encroach on silos, barns, and homes. In places, the mice were ankle-deep, and people were killing them by the thousands. Distributing poisoned grain subdued the mice for a few months, but they eventually regrouped and descended on the villages. U.S. Highway 399 became so slippery from squashed mice that cars ran into ditches and "go slow" signs were erected. The affair was labelled by the U.S. Biological Survey as the greatest rodent infestation in U.S. history. One particular school had mice in every classroom, in all the waste paper baskets, and in some desks.

The infestation attracted owls, hawks, ravens, and vultures from other areas, but they were quickly done away with by the citizenry. The mice were continually in search of new food supplies, and, in 1926, occupied an area of 96 square miles. Finally, an expert from Washington in the U.S. Biological Survey, whose name was actually Piper, was given the exterminating duties. By counting burrows, he estimated his foe at 100 million strong. Using 40 tons of strategically situated strychnine alfalfa, he succeeded in his assignment. But not before Kern County lost over one million dollars in crops and property damage and spent $5000 on poison.

The essence of this misadventure can be captured by the model herein. To the world of one raw input, one manufactured good, and one species, add two species. Species 1 can be a type of grain, species 2 mice, and species 3 a member of the owl family. The interaction among the species is a simple food chain with grain on the bottom and owls at the top. The societal utility function is

$$U(Z,\ R_1^h,\ R_2^h,\ R_3^h) \tag{42}$$

where grain is an intermediate good and not an argument. For the citizens of Kern County, it must have been the case that

$$U_{h2} < 0, \text{ and } U_{h3} < 0 \tag{43}$$

Of course, if a diverse citizenry is considered, and U^i is the utility function for the ith individual, $U^i_{h2} > 0$ and $U^i_{h3} > 0$ are reasonable possibilities, say for naturalists or birders. Nevertheless, (43) is assumed to hold for this example. Also, grain is assumed to provide no utility in and of itself, but is useful only in producing food or manufactured goods. Thus,

$$U_{hi} = 0 \tag{44}$$

Total raw inputs are accounted for by

$$\bar{Y} = Y^z + Y_1^h + Y_2^h + Y_3^h \tag{45}$$

where Y_i^h is the input to the ith species, i = 1, 2, 3. Since there is only one raw input, double subscripting is unnecessary. The manufactured good is produced according to

$$Z = G(Y^z, c_1A_1) \tag{46}$$

where c_1A_1 is grain output. For the mice, $Y_2^h = 0$, at least until the time that strychnine is used. Y_3^h is the input to the owls, but in this case where the input is destructive (poison, shotgun pellets) nothing is contributed to stored energy. Thus the associated energy price, ($E_3^h - E_3^h$), is negative or $E_3^h < 0$. The stored energy functions from (32) are

$$R_1^h = (1 - c_1)A_1(E, E^h, X_{12}, Y_1^h) = (1 - c_1)\{E_{01} X_{01}(E, E^h, X_{12}(X_{23}(Y_3^h)), \tag{47}$$

$$R_2^h = (1 - c_2)A_2(E, E^h, X_{23}) = (1 - c_2)\{E_{12} X_{12}(E, E^h, X_{23}(Y_3^h)) - E_{23}X_{23}(Y_3^h)\} \tag{48}$$

$$R_3^h = (1 - c_3)A_3(E, E^h, Y_3^h) = (1 - c_3)\{E_{23} X_{23}(E, E^h, Y_3^h) - E_{34}X_{34} - E_3^h Y_3^h\} \tag{49}$$

interactions occurring external to the sphere of human influence and knowledge. While (48) is an ecosystem link between (47) and (49), that is, mice consume grain and are consumed by owls, it is not part of the human calculus. The energy prices, E, are unknown as well as how these prices adjust to exogenous shocks (human intervention) to the ecosystem; and the demand for grain by mice and the demand for mice by owls given by (31) in the general case are another unknown. Consequently, the feedback effects from the ecosystem seeking a new equilibrium will not be part of the human calculations.

Maximization yields the following condition:

$$U_z \frac{\partial G}{\partial Y^z} = U_z \frac{\partial G}{\partial c_1A_1} \frac{\partial A_1}{\partial Y_1^h} c_1 = U_z \frac{\partial G}{\partial c_1A_1} \frac{\partial A_1}{\partial Y_3^h} c_1 + U_{h2} \frac{\partial R_2^h}{\partial Y_3^h} + U_{h3} \frac{\partial R_3^h}{\partial Y_3^h} \tag{50}$$

The first term is the manufactured good's marginal product weighted by the marginal utility for the good; the second term is the manufactured good's marginal product of ecosystem input (grain) weighted by the marginal utility; and the third, fourth, and fifth terms are the marginal utility of the manufactured good's marginal product of grain input which is effected by the change in owls, the marginal utility of mice times the change in the stored energy of mice due to the change in owls, and the marginal utility of owls times the change in the Owls' stored energy due to their slaughter.

The values of Y^z, Y_1^h, and Y_3^h that satisfy (50) provide the optimum solution for the citizenry of Kern County. The optimum is thwarted, however, because of a lack of information. The first two terms in (50) are accounted for by the citizens; that is, they are aware of how inputs of Y^z and grain contribute to the production of manufactured good Z. Presumably, they also account for the last term, since they know that killing off owls will ostensibly improve their situation. Their knowledge ends here, however, and the County did not taken into account the effects represented by the third and fourth terms. These terms capture the ecosystem externality, as they form a wedge between marginal rates of substitution in consumption and the rates of product transformation. Examining these terms in more detail,

$$U_z \frac{\partial G}{\partial c_1 A_1} \frac{\partial A_1}{\partial Y_3^h} c_1 \equiv U_z \frac{\partial G}{\partial c_1 A_1} c_1 [E_{01} \frac{\partial X_{02}}{\partial X_{12}} \frac{\partial X_{12}}{\partial X_{23}} \frac{\partial X_{23}}{\partial Y_3^h} - E_{12} \frac{\partial X_{12}}{\partial X_{23}} \frac{\partial X_{23}}{\partial Y_3^h}] \tag{51}$$

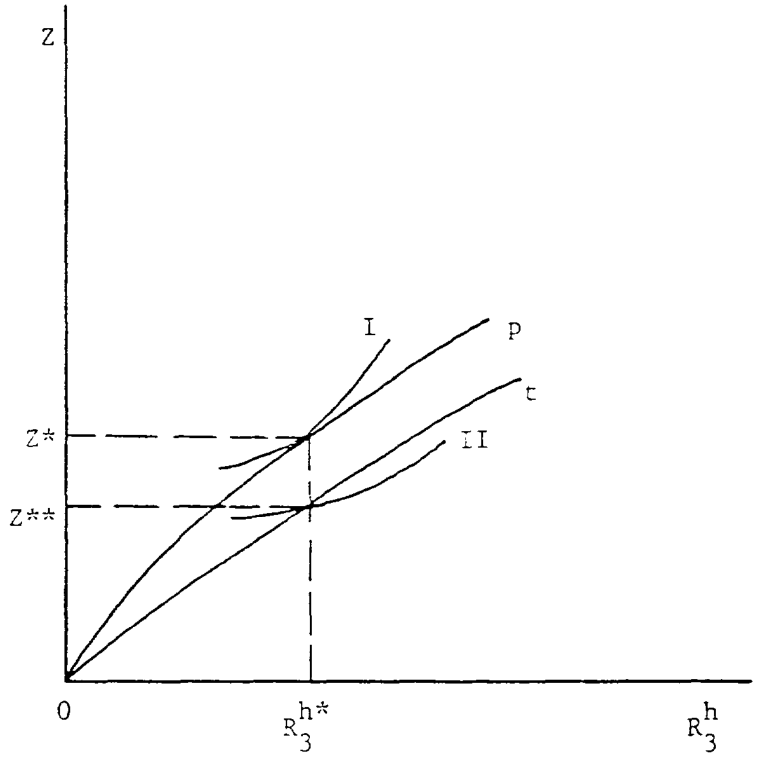
$$U_{h2} \frac{\partial R_2^h}{\partial Y_3^h} \equiv U_{h2} (1 - c_2) [E_{12} \frac{\partial X_{12}}{\partial X_{23}} \frac{\partial X_{23}}{\partial Y_3^h} - E_{23} \frac{\partial X_{23}}{\partial Y_3^h}] \tag{52}$$

Expression (51) is the effect that killing owls has on the grain available for the manufactured good weighted by the marginal utility of Z. Inside the brackets are the chain of events in the ecosystem leading to less grain. More owls destroyed means less predation of mice and then more mice leads to less grain available. The first string of partials within the brackets accounts for grain's changed use of solar energy. Expression (52) is the effect that killing owls has on the mice and this is weighted by the marginal utility for mice.

All of the partials within the brackets in (51) and (52) were negative for Kern County. Moreover, $U_z > 0$ and $U_{h2} < 0$ which means that both (51) and (52) are negative. Returning to (50), negative third and fourth terms, along with diminishing marginal utility and marginal product of Y^z imply that too little of the raw input is being used directly in the product of the manufactured good, and too much is being used to destroy owls. This is reminiscent of the standard case of negative externalities. If production of a good produces negative externalities, the market will produce too much of this good from a welfare standpoint. In Kern County, there was too much production of a good (dead owls) that caused negative externalities in the form of too many mice and too little grain.

Graphically, Figure 9 depicts the situation. In Z, R_3^h space, and for a given level of R_1^h, the perceived production possibility curve is Op. It is positively sloped, since more resources devoted directly to Z imply more Z and fewer resources for destroying owls, thus more owls, Curves I and II are community indifference curves with the direction of preference being north-west. The citizenry, using the perceived curve Op, kill off enough owls to attain R_3^{h*} which presumably leaves Z* available and satisfies the usual tangency conditions. However, accounting for the negative externalities means that the true curve is Ot. Thus, when R_3^{h*} is attained, only Z** is available: mice devour Z* - Z**. Utility is lower than expected, and a larger value for owl stored energy, or fewer resources devoted to killing owls, would be an improvement.

Figure 9



SECTION 8

EVALUATING ECOSYSTEM OUTPUTS

At the outset, the purpose of this report was stated to be the development of a means by which ecosystems and the organisms that comprise ecosystems can be evaluated. To accomplish this, it was necessary to mathematically model the behavior of ecosystem species using constructs that are similar to those used in economic models. In this way, it was possible to integrate the ecosystem into existing economic frameworks which allowed species to be placed alongside other economic goods that are often evaluated. A novel result was that some species are on the one hand goods in a consumer's utility function, but on the other hand, they are entities that follow certain optimizing behavior themselves. Moreover there may be many species that do not enter directly into consumer's utility functions, but do indirectly effect utility because they are linked via a food chain to those species that enter directly. Thus, to evaluate all ecosystem species, the links among species must be well understood.

In the remainder of this Section, a methodology is outlined that uses the results from the previous Sections to evaluate various species. Since the results are woven into familiar economic models the evaluation process appeals to techniques already derived in other contexts. In particular, the literature that deals with welfare measures for goods in intermediate markets is applied [see, e.g., Schmalensee (1976) and especially Just and Hueth (1979)]. The basic idea is as follows. A food chain is comprised of numerous species; each one provides food for the next highest species in the chain and preys on the next lowest species. Only the highest species enters directly into consumers' utility functions. All lower species are basically then intermediate goods iron the consumers' perspective. Hence, the value of these lower species is assessed in the same way that the value of intermediate goods is assessed in standard markets.

Again, for notational convenience, the analysis will deal with a single food chain of n species where only the nth species directly enters the human's utility function. The ith species provides $\bar{X}_{i,i+1}$ input to the i+1 species and demands $\bar{X}_{i-1,i}$ output from the i-1 species There may also be other inputs and outputs to and from species outside the food chain. The stored energy function for species i is given by a simplification of (24) as

$$R_i(E,\bar{X}) = E_{i-1,i}X_{i-1,i}(E,\bar{X}) - E_{i,i+1}\bar{X}_{i,i+1} \tag{53}$$

This function is not complete in the sense that the species may also be part of other food chains not shown here. But (53) is adequate for present purposes, because only changes in one particular food chain are considered. Furthermore, the assumption here is that other food chains are not appreciably effected by changes in this food chain.

Now consider the impact of changing an energy price, say $E_{j,j+1}$, on species i, where j<i. This could come about for many reasons including a change in availability of species j due to increased human intervention in the ecosystem. As this price changes, species will adjust their behavior so as to maximize stored energy given the new price. This leads to other price changes throughout the food chain as species alter prey patterns and thereby alter availabilities. Assume that prices change according to a well-behaved monotonic function. Again, changes outside this food chain are ignored or assumed small.

Then the effects on species i by changes in the availability of the jth species can be written using the envelope theorem as

$$\frac{\partial R_i(\bar{E},X)}{\partial E_{j,j+1}} = \frac{\partial E_{i-1,i}}{\partial E_{j,j+1}} X_{i-1,i} - \frac{\partial E_{i,i+1}}{\partial E_{j,j+1}} \bar{X}_{i,i+1} \tag{54}$$

Integrating (54) for a specific price change, say $\tilde{E}_{j,j+1}$ to $\ddot{E}_{j,j+1}$, yields the change in stored energy for species i denoted ΔR_i.

$$\Delta R_i = \int_{\tilde{E}_{j,j+1}}^{\hat{E}_{j,j+1}} \frac{\partial R_i(E,\bar{X})}{\partial E_{j,j+1}} \, dE =$$

$$\int_{\tilde{E}_{j,j+1}}^{\hat{E}_{j,j+1}} \frac{\partial E_{i-1,i}}{\partial E_{j,j+1}} X_{i-1,i} \, dE - \int_{\tilde{E}_{j,j+1}}^{\hat{E}_{j,j+1}} \frac{\partial E_{i,i+1}}{\partial E_{j,j+1}} \bar{X}_{i,i+1} \, dE \tag{55}$$

These terms can be interpreted in the same way that Just and Hueth (1979) interpret their results for economic sectors. The first term on the right-hand side of (55) is the change in area behind the demand curve of species i for species i-1 as a result of the energy price change in $E_{j,j+1}$. A positive or negative area change for species i represents a real gain or loss in terms of stored energy in the sane way as the area changes behind a standard demand curve represent consumer surplus changes. This change will be denoted as

$$\Delta S_i = \int_{\tilde{E}_{j,j+1}}^{\hat{E}_{j,j+1}} \frac{\partial E_{i-1,i}}{\partial E_{j,j+1}} X_{i-1,i} \, dE$$

$$= \int_{E_{i-1,i}(\tilde{E}_{j,j+1})}^{E_{i-1,i}(\hat{E}_{j,j+1})} X_{i-1,i} \, dE \qquad (56)$$

Equation (56) follows since, paraphrasing Just and Hueth, integration in (55) is along equilibrium biomass for species i as the supply of biomass is shifted. The ΔS_i term is a demand curve for biomass that accounts for adjustments in other species in the food chain. Similarly, the second term in (55) is

$$\Delta S_{i+1} = \int_{\tilde{E}_{j,j+1}}^{\hat{E}_{j,j+1}} \frac{\partial E_{i,i+1}}{\partial E_{j,j+1}} \bar{X}_{i,i+1} \, dE$$

$$= \int_{E_{i,i+1}(\tilde{E}_{j,j+1})}^{E_{i,i+1}(\hat{E}_{j,j+1})} \bar{X}_{i,i+1} \, dE \qquad (57)$$

This is the change in the area behind species i+1's demand for species i. Again, it represents a real gain or loss to species i+1.

Combining (55), (56), and (57) yields

$$\Delta R_i = \Delta S_i - \Delta S_{i+1} \qquad i = 1, \ldots . n-1 \qquad (58)$$

and after solving the difference equation,

$$\Delta S_n = \sum_{j=0}^{n-i-1} \Delta R_{i+j} + \Delta S_i \qquad (59)$$

The first term in (59) represents the change in consumers surplus behind the humans' demand curve for the n^{th} species. This term is the ultimate goal of the analysis, for it provides a measure of the value of lower order species, or species that have no direct value to humans. Equation (59) states the welfare loss or gain to humans (measured by a change in consumers surplus) due to a change in an energy price somewhere in the ecosystem food chain equals the change in stored energy of the i^{th} species where the energy price change originated, plus all the stored energy changes for species between the i^{th} species and the n^{th} species.

By way of example, suppose grizzly bears entered directly into human utility functions as a photographic subject when shot at a safe distance. Then suppose a pollutant, say ozone, has a deleterious effect on a species of plant that provides food for elk. There will be a change in stored energy for the plant, a change in stored energy for the elk and, finally, a change in the grizzly bears' stored energy since they may from time to time feed on elk. The loss to humans is accounted for by summing all these stored energy changes as (59) suggests. Thus, the value of the plant species can be calculated via its role in the ecosystem's food chain.

Calculating the actual welfare gains or losses in these situations will be complicated by several factors which can be explained by extending the example. First, the initial species on the food chain may also be a link in other food chains. The plant that is adversely affected by ozone may also provide sustenance for deer and insects. In one food chain, there is a change in stored energy of deer which can also be traced to a change in the grizzlies' stored energy; and in another food chain, the insects are food for rodents, which are food for golden eagles, where the latter may be a variable in the human utility function as are grizzlies. In this extended example, then, there are three equations of the type shown in (59), two for food chains with grizzlies at the top and one for a food chain with eagles at the top; all three must be utilized to assess the welfare losses due to ozone. In a complex ecosystem, the number and interactions among food chains may be substantial. One cannot expect to account for all these complexities; therefore, isolating the most important in terms of potential welfare losses is crucial.

A second complication in the analysis is that some species are not directly in the utility function, but do show up as species cropped by humans and used as inputs to manufactured goods. In these instances, the approach is similar except that the final welfare loss or gain shows up in the manufactured good's market. Basically, there is an extra link at the top of the food chain that must be added into an equation of the type given in (59). Referring back to the grizzly bear example, suppose grizzlies were still hunted for sport. They then represent an input into a manufactured good, that is, hunting, as well as providing direct utility for humans through photography. The loss of the plant species now leads to losses because grizzlies are more scarce and both more difficult to photograph and more difficult to hunt. Thus, a fourth equation representing losses must be recognized. To summarize, the ozone-induced loss to the plant species causes losses to humans as follows: a) 2 loss of photographic opportunities because there are fewer grizzlies due to fewer elk; b) 2 loss of photographic opportunities because there are fewer grizzlies due to fewer deer; c) a loss of opportunities to observe eagles because they are fewer in number due to fewer rodents; and d) a loss in grizzly hunting opportunities because, again, they are fewer in number.

One additional note on welfare losses and gains is that they may arise from sources other than energy price changes. In particular, they may arise because physiology functions or human-supplied inputs to the ecosystem are altered (refer to Table 1). The analysis would need to be modified to account for these other types of parameter shifts.

The original goal was to place an ecosystem within an economic framework and assign values to ecosystem components. In economic models, this can be done because humans have demands for the goods that are manufactured, and these goods can be valued by observing how much of one good must be given up to obtain more of another. This is precisely what has been done with the ecosystem components. How must grizzly bears be sacrified to obtain more of a manufactured good or vice versa? To answer this question, an appeal was made to measure grizzly bears, and all other species, in terms of stored energy. Thus, stored energy has played a key role throughout the theory. It has been a common denominator across all species, and a unit of measurement for the ecosystem. it has also been used directly in the human utility function as a proxy for whatever appeals to people about wildlife. If stored energy is not a good proxy for this appeal, then something else such as number of individuals may be appropriate. But this does not detract from the methodology used here, since one could obtain a conversion factor to transform stored energy into numbers of individuals. In other words, placing stored energy directly into the utility function is a matter of convenience and not essential to the analysis. The convenience is due to the ability to measure all species in this common denominator as well as what it is about species that appeals to humans. The common denominator provides a measurement link between ecosystems and economics, and as indicated in the introductory remarks, it is a concept accepted by ecologists.

The model development in this section leading to (59) suggests the type of data and approaches needed to apply the theory to actual problems. Because of the complexity of the ecosystem and the interwoven nature of the many food chains, any applied work will inevitably be confined to a few or even one food chain. This is, however, no more heroic than assumptions used by economists that allow partial equilibrium models to approximate general equilibrium changes. The data requirements for the right-hand side of (59) are essentially those outlined in Section IV and they need not be discussed further.

The left-hand side of (59) requires estimating human demands for species that are directly in the utility function. Attempts have been made to do this for species that are hunted (see Sorg, e.g.) but little evidence exists for species that provide only aesthetics. Moreover, hunted species may also provide aesthetic values, and again there is a dearth of evidence.

Nevertheless, the theory does provide a framework for formalizing the evaluation of ecosystems and their components. It provides, as well, directions for future research by indicating the data requirements for the evaluation process. Furthermore, by studying the links that comprise (59) in any one food chain, negative ecosystem externalities like those discussed in Section VII can be identified and avoided.

SECTION 9

A DIVERGENCE ON DIVERSITY

Watt (1973, p. 34) sets forth the following as a fundamental principle of ecological science: the diversity of any ecosystem is directly proportional to its biomass divided by its productivity. That is:

$$D = k\left(\frac{B}{P}\right) , \tag{60}$$

where D is a diversity measure directly related (Pielou, 1977, Chap. 19) to the number of species in a given habitat and the relative abundances of each species;[6/] B is the total weight or standing biomass of living organisms in a habitat; P is the amount of new living tissue produced per unit time; and k is a constant differing from one habitat to another. Thus, for a given biomass, system diversity and system productivity are inversely related.

Within a given habitat, $d(B/P)/dt > 0$, implying that in the early life of an ecosystem, the production of new tissue is very large compared to the amount of biomass. This high relative productivity is the source of biomass growth. It is achieved by introducing into an abiotic or stressed environment a small number of pioneer species (e.g., weeds) with rapid growth rates, short and simple life cycles, and high rates of reproduction. In the mature stages of an ecosystem, a wider variety of organisms that grow more slowly and have longer life spans is present. Net production or "yield" is lower in a mature system because most energy is invested in maintenance of the standing biomass. Thus, whereas energy in the pioneer stage is used to increase biomass, so that a relatively empty habitat can be filled, all the captured energy coming into a fully mature system is employed to maintain and operate the existing biomass, which already occupies all the habitat territory available.

Ecosystems that must live under intermittent or continued severe stress exhibit the attributes of immature systems: they have relatively low diversity and biomass but high throughputs of energy and thus high yields.

Ecologists traditionally prefer ecosystems with large biomass and diversity. This preference for mature ecosystems appears to rest on two positions: the maximization of system energy capture; and the maximization of system stability. In the first case, more energy is captured per unit biomass in a mature system because less energy has to be "wasted" in growth and reproduction activities. The distinction is similar to Boulding's (1966) description of the "cowboy economy" and "the spaceship economy", where the former maximizes throughput and therefore energy diffusion, while the latter maximizes incoming energy concentration and fixation. According to Margalef (1968), the immature or stressed system expends more energy per unit biomass in reproduction in order to make up for its more frequent loss of individuals. In addition, because of its relatively small energy recycling capacity and its relative inability to alter and to renew its environment in ways favorable to its sustenance, it must expend relatively more energy per unit biomass in food gathering activities. The immature system thus expends relatively more energy in producing new tissue to replace that which has disappeared (depreciated). In contrast, the mature system expends most of its incoming energy in keeping what it has already developed: it is durable. Because it sustains a greater biomass per unit energy, the mature system is frequently said to be more "efficient" (B.P. Odom, 1971, p. 76).

Although exceptions appear to exist [May (1971), Jorgensen and Mejer, (1979)], the greater efficiency of mature ecosystems is associated in ecological thought with greater stability, where stability is variously interpreted to mean system resiliency to exogenous shocks or infrequent fluctuations in standing stock. This stability is thought to originate in a set of homeostatic controls present in greater number and variety in mature systems, thus providing a greater number of avenues through which the system can recover from damages to one or more of its components. The greater simplicity of the immature system is thought to increase the likelihood that if anything goes wrong, everything goes wrong. Thus monocultures, which are by definition the simplest and least diverse of ecosystems, are susceptible to being wiped out by any single pest or event to which they are sensitive. Incoming energy flows only through one or a small number of pathways; when this pathway is degraded, no means to capture energy remains. The system therefore collapses unless energy subsidies (e.g., fertilizers) are provided from outside. These subsidies are of course a further source of the low biomass supported per unit incoming energy that is characteristic of immature ecosystems.

The human dilemma posed by the ecologists then involves a tradeoff between high yield but risky immature systems with undifferentiated components, and low yield, reasonably secure systems with a variety of components. Even if the requisite energy subsidies were usually available, an earth covered with cornfields would be dangerous. Moreover, given, as Scitovsky (1976) convincingly argues, the human taste for variety and novelty, a world of cornfields would be exceedingly dull. Nevertheless, flowers and butterflies nourish only the human psyche; they provide little relief to an empty stomach. Human activities increase biological yields by accelerating energy flows through ecosystems. In terms of the model of the previous two sections, these activities increase overall energy prices. To accomplish this, they simplify ecosystem structures, either by keeping them in a perpetual state of immaturity or by impoverishing the energy flows their habitats can produce.

In the context of the above perspective, pollution, such as acid precipitation, harms human welfare by reducing yields of the material scaffold of wood, fish, and corn and by increasing ecosystem simplicity: yields are reduced and monotony is increased. Woodwell (1970) notes that by elimination of sensitive species, SO_2 air pollution around the Sudbury smelter in Ontario first resulted in a reduction in the diversity and biomass of the surrounding forest. Finally the canopy was eliminated with only resistant shrubs and herbs surviving the assault. He also notes that chronic pollution reduces plant photosynthesis without having much effect upon respiration requirements. As a result, large plants, which have high respiration requirements, are placed at a disadvantage relative to small plants. In a vivid image, he posits the replacement of the great variety of phytoplankton of the open ocean by the algae of the sewage plants that are insensitive to just about any stress.

A. Valuing Diversity and Yield

In accordance with the treatments of Hannon (1979), Mauersberger (1979), and sections two and three of this chapter, the ecosystems refered to in the following development are long-run equilibria sustainable with various combinations of energy from solar, biogeochemical, and subsidy sources. Contrary to much of the ecological literature, day-to-day transient states in the relative abundances of various species are disregarded. This permits us to concentrate upon a small number of key expressions and basic principles, thereby avoiding the bewildering black-box flow diagrams often used by ecologists. We wish to gain insight into two questions. First, what is the economic value of the quantity of each species that a location is producing? For our purposes, a location is simply a set of map coordinates. Second, what is the economic value of the assortment or bundle of species that the location is producing? That is, what is the value of a particular ecosystem design? For a particular species assortment, the first question is usually answerable, given that market (not energy) prices of each species unit are readily observed or inferred.[7] However, the second question, whether treated singly or in combination with the first, has not yet been grappled with insofar as ecological questions are concerned. We adapt a model of Lancaster's (1975) to deal simultaneously with the two questions.

To analyze these two questions, we need a model permitting us to trace through the impact upon the economic benefits derived from ecosystems of changes in specie quantities and assortments caused by changes in energy flows. The first step in doing this is to define an ecosystem, e_i, as a set of species, where these species are in fixed proportions to one another. Expression (61) identifies ecosystem i with n species and

$$e_i \equiv (r_1^i, r_2^i, \ldots, r_n^i) \tag{61}$$

where r_j^i is the quantity of species j. Biomass is used to normalize the measure of different species. An ecosystem thus contains different species in a particular proportion at a single location. Ecosystems that contain species in different proportions are considered to be different ecosystems. Given the linearity of (61), the species content of x units of an ecosystem is simply x times the content of each species in an ecosystem unit.

Allow some time interval sufficiently long to permit each feasible ecosystem to attain a long-run equilibrium defined in accordance with the model of sections two and three. Assume that a given amount of energy, $\bar{E}$, from solar, biogeochemical, and subsidy sources is available for this time interval at the location in question. Included in the biogeochemical energy source is the energy currently stored in the standing biomass. With $\bar{E}$, a variety of ecosystems can be established, the range of the variety being determined by the physiology sets of each species and the ways in which the species interact with each other.

Note that our notion of long-run equilibrium need <u>not</u> be a climax biological equilibrium; that is, it includes other sustainable states as well. In particular, by including energy subsidies and biogeochemical energy in available energy, we allow immature ecosystems to be formed and sustained. For example, an energy subsidy is being provided a vegetable garden when it is weeded and when it is harvested. The weeding prevents the garden from "reverting" to field, woods or prairie; the harvesting prevents the standing stock of vegetable plants from suffering the effects of congestion. This standing stock will produce, period after period, a unique sustainable flow of new biomass or yield as long as the requisite biogeochemical energy and energy subsidies are provided. Similarly, with enough of an energy subsidy (as with a greenhouse) in Wyoming, one can sustain a banana-mango ecosystem with its associated flow of bananas and mangoes. We assume, whether reference is to an entire ecosystem or to a particular species within that system, that the sustainable yield measure is an order preserving transformation of the standing stock measure.

For a particular quantity of incoming energy, there will be some maximum amount of each ecosystem that a particular location can produce.[8/] Let the minimum energy requirements for producing an ecosystem be given by:

$$E = E(e(r)) = \phi(r), \qquad (62)$$

where the elements of the r-vector are sustainable yields per unit time. $\phi(r)$ will be called a diversity possibilities function. It shows the maximum quantities of various species combinations that a location can sustain with given available energy each period. We assume that $\phi(r)$ is homothetic and convex, and that $\phi' > 0$. For a given energy flow at a particular location. Figure 10 illustrates a diversity possibilities function for grass and corn.

In Figure 10, four ecosystems are depicted, one of which, e_1, contains only grass, and another of which e_4, contains only cows. Two ecosystems, e_2, and e_3, containing grass and cows in different combinations, are also depicted. If enough alternative ecosystems are possible, a continuous diversity possibilities frontier, E, can be formed, as we assumed in (62). For given energy availability, each point on the frontier, E, represents the maximum quantity of one species that can be produced with a particular quantity of the other species being produced. Since cows probably use relatively less, if any, solar radiation directly, a progressively greater proportion of biogeochemical energy and energy subsidies will be included in E as one moves from the vertical axis to the horizontal axis.

The convexity of the frontier follows from an ecological version of the economic law of diminishing returns known as Mitscherlich's law [Watt (1973, p. 21)]. As progressively more energy is diverted from grass production to cow production at the location in question, the increment to the latter will decline. Similarly, the diversion of energy from cows to grass will result in declining increments to grass production. Since in Figure 10, the cows could feed upon the grass, the convexity of the feasible region is also attributable to the less biologically efficient use of the given available energy by cows than by grass. As a food chain lengthens, the amount of original energy used for production by species distant from the original energy input tends to decrease at an increasing rate (E.P. Odom, 1971, Chap. 3). Of course, as Tullock (1971) recognizes, the croppings and droppings of the cows may recycle some of the energy originally embodied in the grass and cause both grass and yields to increase over some portion of the frontier. However, as grass becomes scarce, the cows must expend progressively more energy in search for it, if it is to remain a part of their food supply. Finally any cow grazing whatsoever might be so harmful to grass that the frontier bows inward, causing a nonconvexity problem for applications of economic optimization techniques.

The assumptions of homotheticity and $\phi' > 0$ for (62) imply that: $\phi(\lambda, r) = F(\lambda)\phi(r)$ for all λ, $r > 0$. In terms of Figure 10, these assumptions mean that there could exist a series of similar diversity possibility frontiers, one for each level of energy availability. The greater the level of energy availability, the farther would be the associated frontier from the origin. Therefore the biomass of any species obtained in a particular ecosystem to which greater quantities of energy are made available will increase but not necessarily on a one-to-one basis with the increase in available energy.

To make different ecosystems comparable, we define the solar radiation to which the location in question is exposed per period as the unit amount of energy, E_o. Each of the ecosystems that can be produced by this unit energy are therefore comparable in terms of the biomasses of each species embodied in them. We shall call them unit ecosystems. Keeping in mind that an ecosystem is defined as embodying species in fixed proportions, an altered quantity of an ecosystem is a simple multiple of the quantity of any species appearing to some positive degree in the unit ecosystem.

To complete the most fundamental parts of our analytical apparatus, we introduce a well-behaved utility function, U(r), for a representative person. Assuming others, energy subsidies to the relevant location to be predetermined, the Lagrangian of this individual's decision problem then can be stated as:

$$L = U(r) + \mu(\bar{E} - \phi(r)). \qquad (63)$$

The first-order necessary conditions for a maximum of (63) are,

$$\frac{\partial U}{\partial r} - \mu \frac{\partial d}{\partial r} = 0 \tag{64}$$

and the constraint expressing the available energy. Expression (64) states that the individual will equate the marginal utility he obtains from an additional unit of a species to the marginal cost of expending the energy to acquire that additional unit. Figure 11 is a diagrammatic representation of (64) for two types of ecosystems, e_1, and e_2, and two indifference curves U_1, and U_2. With available energy, $\bar{E}$, the individual's utility-maximizing choice is clearly at A, which corresponds to (64). We shall therefore call any ecosystem which conforms to (64) the ideal ecosystem. This is the ecosystem having that species assortment most preferred by the individual.

Assume that our representative individual, perhaps because he is unable to exercise enough influence over land use, cannot have the e_1 ecosystem. Instead, he must face the e_2 system, a system containing substantially more cows and less grass. The latter system may be considered to be less "natural" since its maintenance likely requires substantial man-supplied energy subsidies. With the available energy, $\bar{E}$, the individual will be worse off with the e_2 system since the highest utility level he will be able to reach is U_1 at C. If he were to be as well off with the e_2 system as he would be with the ideal system at A, he would have to be at B. The attainment of B, however, requires more input energy as indicated by the diversity possibilities frontier, E*. Since OA and OC both require $\bar{E}$ units of energy, while OB requires E* energy units, the energy quantity required to compensate the individual for the fact of the e_2 system is $E^* - \bar{E}$ along the e_2-ray. The compensating ratio, $OB/OC \geq 1$, is then the quantity of the existing system relative to the quantity of the ideal system that keeps the individual at the original utility level. Since OB and OC are each defined in energy units, the compensating ratio is a pure number. A glance at Figure 11 makes it obvious that this compensating ratio will be greater, the less substitutable the two systems are for one another, the steeper the slopes of the diversity possibility frontiers, and the wider the difference between the ideal ecosystem and the actual ecosystem. In addition to depending upon underlying preferences and production conditions, this ratio is obviously a function $h(e,e^*)$, where e^* is the species ratio in the ideal ecosystem and e is the species ratio in the existing system. Lancaster (1975, p. 57) describes the properties of this compensating function, which must be convex.

If all existing ecosystems are not to be ideal ecosystems, the preceding framework implies that in the real world there are some ecosystems produced under conditions of increasing returns-to-scale. If decreasing returns-to- scale were universal, less energy would be used by producing fewer units of a greater variety of ecosystems. In the extreme, each individual would have his ideal ecosystem available to him. Similarly, under constant returns-to-scale, the quantity of energy used to produce a quantity of an ecosystem is directly proportional. Thus, with decreasing or constant returns-to-scale, any individual who does not have his ideal ecosystem available is using more input energy to attain a particular utility level than would be required with his ideal ecosystem. Casual observation suggests that everyone is not happy with the ecosystems they have available. One plausible reason for this is the presence of increasing returns-to-scale in the production of ecosystems.[9] That is, the presence of increasing returns-to-scale for some ecosystems may force the individual to choose between an ideal diversity of ecosystem components and reduced energy consumption per unit of production for some smaller set of these components.

Let us momentarily return to (62), which gives the amount of input energy required to produce some amount of a particular ecosystem. Because of our use of energy *to* bring the unit quantities of different ecosystems to the same measure, and because of the properties we have assigned to the diversity possibilities frontier, if Q_1, and Q_2 represent quantities of different ecosystems, e_1 and e_2, then $f_1(Q_1) = f_2(Q_2)$ when $Q_1 = Q_2$. This allows us to perform the analysis in terms of a single input function:

$$E = f(Q) \tag{65}$$

The energy required to produce quantity Q_1 of e_1 and quantity Q_2 of e_2 is given by the sum of the two input functions:

$$E = f_1(Q_1) + f_2(Q_2), \tag{66}$$

and not the sum of the quantities of $(Q_1 + Q_2)$. If $f_1(Q_1) + f_2(Q_2) = f(Q_1 \quad Q_2)$, then constant returns-to-scale would exist. As usual, we assume $f(Q) > 0$, and $f'(Q) > 0$, but we need not assume that all incoming energy results in additional biomass, nor need we attach any sign to $f''(Q)$.

Now define a degree of economies-of-scale parameter, $\theta(Q)$, which is the ratio of the average energy input requirement to the marginal energy input requirement. This is simply the inverse of the elasticity of (65), or:

$$\theta(Q) = \frac{f(Q)}{Qf'(Q)} = \frac{f}{Q} f' \tag{67}$$

If θ is a constant, $f(Q)$ will then have the form:

(68)

the inverse of which is

$$Q = aE^{\theta} \tag{69}$$

This last expression is immediately recongizable as a homogeneous function of degree θ. If $\theta > 1$, there are increasing returns-to-scale; if $\theta = 1$, there are constant returns-to-scale, and if $\theta < 1$, there are decreasing returns-to-scale.

In expressions (63) - (64), we derived the representative individual's ideal diversity of ecosystem components, assuming that he faced no tradeoffs between this ideal and lowered unit energy costs of ecosystem production. We are now prepared to consider this question of the optimal deviation of the actual ecosystem available to the individual from the individual's ideal ecosystem.

Assume we wish to enable the individual to reach some predetermined arbitrary utility level with minimum use of energy. [10] Let Q^* be the quantity of an ideal ecosystem, e^*, that is required for the individual to reach this predetermined utility level. If the available ecosystem. e, is nonideal, the individual will have to be compensated by being provided more than Q^* of the available system. According to our previous definition of the compensating function, $h(e, e^*)$, the amount of the available eco-system required to bring the individual up to the predetermined utility level will be $Q^*h(e, e^*)$. Since the input function (65) is independent of the species ratios (by the assumed homotheticity of production and the definition of unit quantities), the optimal ecosystem is that which minimizes the quantity, Q, required to reach the predetermined utility level. That is, we wish to minimize:

$$Q = Q^*h(e, e^*) \tag{70}$$

This minimum is given by:

$$Q^* \frac{\partial h}{\partial e} = 0 \tag{71}$$

which obviously corresponds to (64). This result is relatively trivial but it does serve as a necessary prelude to determination of the optimal deviation of the available ecosystem from the ideal ecosystem.

Suppose there are n-1 less-than-ideal feasible ecosystems, the deviation of each less-than-ideal system from the ideal system being given by $x_i = e^* - e_i$. Then the quantity of the ith ecosystem required to reach the predetermined utility level is given by: $Q_i = Q^*h(x_i)$. The total energy inputs required to reach this utility level for all systems, whether ideal or not, are then:

$$E = f[Q^*h(x_i)], \tag{72}$$

where the x_i are the variables of the problem. From (72) is obtained:

$$\frac{dE}{dx_i} = Q^* \frac{df}{dh}\frac{dh}{dx_i} = Q^*f'h' \tag{73}$$

or

$$Q^*h' = \frac{1}{f'}, \tag{74}$$

for a minimum expenditure of energy.

The interpretation of (74) in economic terms is quite easy. The l.h.s. of the expression shows the increase in the quantity of the ith ecosystem required to maintain the predetermined utility level if there is a one unit biomass increase in the deviation of the available ecosystem from the ideal ecosystem. The denominator of the term on the r.h.s. shows the increase in the available quantity of the ith ecosystem to be obtained with a one unit increase in input energy. Thus (74) says that the optimal deviation of the available ecosystem from the ideal ecosystem occurs when the change in the compensating ratio is equal to the reciprocal of the additional energy required to produce more of the ith ecosystem. As the available ecosystem deviates less from the ideal system, the compensating ratio decreases. If the energy inputs required to reach the predetermined utility level also decrease, then the ideal system would clearly be optimal. However, if the compensating ratio increases and, due perhaps to economies-of-scale in production with simplified ecosystems, energy inputs per unit of yield decrease, then the achievement of an optimum requires that the tradeoff between the two be recognized.

The optimum condition (74) can be clarified when stated in elasticity terms. Upon defining the elasticity of compensating function as $\eta_h = xh'/h$ and substituting this and the elasticity, (65), of the input function into (74), we have

$$\eta_h \left(\frac{h}{x}\right) = \frac{Q^*\theta}{f} , \qquad (75)$$

which if f, h, and Q are fixed is simply

$$h_h(x) = r. \qquad (76)$$

Thus the optimal deviation of the available ecosystem from the ideal ecosystem occurs where the elasticity of the compensating function, $\eta_h(x)$, is equal to the degree, θ, of economics of scale in production. If x were such that $\eta_h(x) > \theta$, a one percent decrease in deviation of the available ecosystem would require η_h percent less in ecosystem quantity (remembering that all ecosystems are measured in the same units because they are defined relative to a unit ecosystem) and require $\eta_h(x)/\theta > 1$ percent less energy resources, so that energy inputs would be made smaller by reducing the extent of deviation from the ideal system. However, if $\eta_h(x)/\theta < 1$, an increase in the extent of deviation would reduce energy inputs. Thus when $\eta_h(x) = \theta$, the deviation is optimal. The welfare loss from an increase in the deviation of the available ecosystem from the ideal ecosystem is balanced by the increased ecosystem quantity obtained for a given energy input.

B. The Impact of Pollution

In the previous section, we have presumed that over some interval of the input function, (65), there exists increasing returns-to-scale: that is, as more energy is devoted to the production of a particular ecosystem, the ecosystem yield per unit of energy is increasing. When there are feasible monocultural ecosystems that yield an output (e.g. beef) highly valued for consumptive purposes, or as an input (e.g., sawtimber) for a fabricated good, and if these ecosystems exhibit increasing returns-to-scale, then some deviation of the available ecosystem from the ideal ecosystem may he optimal. The condition for optimality is $Q^*h'=(f')^{-1}$ or, in elasticity terms, $\eta_h(x) = \theta$. It is thus apparent that the extent of optimal deviation will vary with the parameters that influence the above conditions. The elasticity, η_h, is determined by the properties of the compensating function, h. The economies-of-scale parameter, θ, is either an exogenous parameter (with homogenous production) or is a function of yield, and thus of the compensating function.

Consider a pollutant, α, which might, in principle, effect h', f', or both. For example, a pollutant stresses ecosystems, making them immature, and thus less diverse. In addition, for at least some of the ecosystems remaining viable after the introduction of a pollutant, their yields are less than they would be without the presence of the pollutant, i.e., the level of ecosystem yield obtainable with any given provision of energy is reduced. Thus, in terms of Figure 11, the diversity-reduction would he reflected in a rotation of the available ecosystem toward one or the other axes, while the reduction of yield of whatever ecosystem was ultimately available would register in a shift of the diversity possibility frontiers toward the origin. If the ideal ecosystem is unchanged, and if the reduction in diversity represents a movement away from this ideal system, then the individual will require additional compensation if he is to remain at the original utility level. A similar result occurs if f' (the additional energy input required to obtain an additional unit of an ecosystem) increases. In both cases, an increase in the deviation of the optimal from the ideal ecosystem occurs. The effect of a variation in a on the optimal deviation is easily found by differentiating either (74) or (76).

Upon differentiating (76) with respect to α, we get:

$$\frac{dx}{d\alpha} = \frac{(d\theta/d\alpha) - (d\eta_h/d\alpha)}{(d\eta_h/dx) - (d\theta^{\eta}/dQ)} \qquad (77)$$

Given the convexity of the indifference curves, the $d\eta_h/dx$ term in the denominator must be positive. If the degree of economies-of-scale is fixed or declines with increases in the level of output, the $d\theta/dQ$ term in the denominator must be negative. Thus the denominator in (77) will be unambiguously positive. The sign for (77) will therefore depend solely upon the terns of the numerator. If the ideal ecosystem has high diversity, the sign of $d\eta_h/d\alpha$ will be positive since the convexity of the indifference curve requires that reduced ecosystem simplification imply increased responsiveness of the necessary compensation to further simplification.

The sign of $d\theta/d\alpha$ in (77) is less easily determined. Remembering that $\theta = (f)f'/(Q)$, it is plausible that increases in a would increase only f', implying that de/da would be positive, but leaving the sign of the numerator in (77) dependent on the relative magnitudes of $d\theta/d\alpha$ and $d\eta_h/d\alpha$. It is of course possible that pollution would reduce the yields obtainable for every ecosystem for all output levels. This event would be reflected in a reduction in f, implying that $d\theta/d\alpha < 0$, for a given f' and Q. In this case, the increase in pollution would reduce rather than increase the optimal deviation of the available ecosystem from the ideal ecosystem!

These results obviously imply that economic analyses which concentrate only on the ecosystem yield effects of pollution can be seriously misleading. In cases where pollution reduces both yields and diversity, the analyses will tend to underestimate the economic losses from the effects. Similarly, if there exist cases where diversity is decreased while yields are increased, the usual analyses might not perceive any losses. However, in some cases, the usual analyses will exaggerate the severity of the losses. Harkov and Brennan (1979 pp. 157-158) conclude, for example, "... that slower growing trees, which often typify late successional communities, are less susceptible to oxidant damage than rapid-growing tree species, which are commonly early successional species." Assuming that the ideal ecosystem is more diverse than was the available ecosystem before the increase in pollution, the increase in pollution could reduce f', θ, or both. In either circumstance, more incoming energy would be required than before to obtain a given yield with the immature ecosystem. The pollution may therefore reduce the optimal deviation of the available ecosystem from the ideal system. In short, pollution can enhance rather than hinder the willingness of individuals to live with mature biological communities! Obviously, in this case, any economic analysis which neglected the increase in diversity would overestimate the economic damages attributable to the pollution.

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[1] This ignores other possibilities like geothermal systems or tides.

[2] Lotka likens the development of this model to the work of Jevons and the marginalist school of economists. He recognizes that this maximal is not appropriate for humans. Borrowing from Pareto, he describes humans as maximizers of pleasure. This is consistent with maximizing species growth only if the marginal pleasures (i.e., marginal utilities) are proportional to the marginal productivities of the physical needs. Thus, Lotka essentially denies the validity of an energy theory of value which, as pointed out earlier, has been propounded by many modern-day ecologists.

[3] The physiology set is analogous to the firm's technology set often used in economics. The development of the model presented here closely parallels the development of the economic model in Russell and Wilkinson (1979, Chapter 7).

[4] Conditions (11) and (13) characterize the solutions shown graphically by Rapport (1971, Figure 2) in a model of one predator and two prey species. Although he has quantities of the prey species on his axes, he refers to the predator obtaining assimilated energy. Along each indifference curve in his figure, output energy is constant; or x_{n+1} is constant along each curve.

[5] The sign of (62) follows from Figure 10. The signs of the partials of F with respect to inputs i=0, ..., n, and output n+l will be opposite. The sign of F with respect to the X outputs, however, will be the same as input signs. To relate to an economic production function, the species is always operating in the uneconomic region of its physiological function for any positive values of the X's.

[6] The numbers of a particular species are capable of interbreeding.

[7] See Freeman (1979) for a thorough survey of available techniques for answering this question.

[8] The work of Bigelow and his colleagues (1977) is a detailed account of the ecosystem possibilities in a Dutch estuary. Odom (1971) and other ecology texts are replete with other examples.

[9] Other plausible reasons exist. For example, a process through which the individual can register his ecosystem preferences may be lacking.

[10] The envelope theorem (Shephard's lemma) assures us that the solution to this problem is equivalent to the solution of the utility maximization problem.

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CHAPTER 2

ON THE VALUE OF THE CONDITION OF A FOREST STOCK

by

Thomas D. Crocker

SECTION 1

INTRODUCTION

Any economic approach to the efficient provision of nonmarketed goods requires knowledge of individual preferences. As is well-known, if preferences are transitive so that the Slutsky terms are symmetric, observations on usages of the good across price and income settings can be employed to construct demand functions from which unique inferences about underlying preferences can be drawn. Several specialized techniques such as travel cost and hedonic pricing methods have been developed to assess preferences for nonmarketed environmental assets. The premises on which these and similar observed behavior techniques rest have by no means been immune from criticism. However, the appropriateness of the transitivity axiom, which these techniques invoke without exception, has been exempt from questioning. In this paper, I report a set of empirical results, obtained by a contingent valuation method, that, for the aesthetic features of environemental assets, cast doubt upon the validity of this axiom. Because the axiom is necessary to the uniqueness of the preference measures generated by techniques that employ observed behavior, one's confidence is weakened in those measures which represent the values of the aesthetic features of environmental assets.

It is possible, of course, that the pattern of results to be reported here is simply a creature of the contingent valuation technique. No assurance can be provided that this alternative hypothesis is false. The likelihood of it being acceptable, however, is reduced by the fact that the questionnaire used to produce the contingent valuations was built upon a number of published findings in experimental economics and psychology. Ideally, one would construct a contingent valuation questionnaire by initially inducing values in the usual manner of experimental economics [Smith (1982)], and then testing alternative questionnaires in a fully controlled setting until a version was discovered that generated the already known valuations. If the test setting does not permit this, one should at least use as prior information the findings of other controlled studies.

SECTION 2

THE SETTING

Even a cursory review of the technical literature dealing with the biological impacts of air pollution soon turns up expressions of concern about the impact upon forests of oxidants, primarily ozone, and sulfur compounds. Nearly always mentioned as the leading exhibit of what has been happening and what could happen on a far larger scale is the San Bernardino National Forest of southern California.

Some 30 years ago, observers first noticed 2 yellow mottling of the needles and extensive needle drops on the ponderosa and Jeffry pines that dominate much of the Forest. It has since been conclusively demonstrated that the malady is caused by ambient oxidants, the precursors for which are emitted in the vast upwind Los Angeles urban complex lying beneath and as much as 80 miles to the west [Miller and McBride (1975)]. Among the forest ecosystem stresses that the needle mottlings and drops represent are declines in conifer reproduction [Kichert and Gemmill (1980)], reduced resistance to fungal [James, et al. (1980)] and beetle [Taylor, et al. (1980)] attacks, mortality rates that are 3 times greater than normal [Miller (1973)], and reductions of up to 84 percent in standing average wood volume [Miller, et al. (1977)]. In addition, greater fire frequencies and intensities, reduced water storage capacities, and substitutions of deciduous and shrub species for pines and firs have been occurring [Killer, et al. (1982)]. Attention here is limited to an economic assessment for self-selected current outdoor recreators of the oxidant-induced damages to the existing stock of ponderosa and Jeffry pine trees that comprise the dominant vegetation types in the most popular areas of the Forest.[1]

Assuming that the marginal utility of money, λ, is constant, the formal content of the valuation problem can be represented by an individual's continuous, differentiable objective function U(v(q), q(x)), where v is his annual number of visits to the forest, and q is a forest quality index that is a decreasing function of actual biological injury. For a particular forest visit to which he is already committed, the individual's marginal loss from more injury is then:

$$\frac{dU}{dx} = -\frac{1}{\lambda}\left(\frac{dU}{dq}\right)\left(\frac{dq}{dx}\right) \qquad (1)$$

given that he is unable to influence the levels of x or q. Upon applying the chain rule to (1), the change in his marginal loss from a change in injury is seen to be:

$$\frac{d^2U}{dx^2} = - \frac{1}{\lambda} \left[\left(\frac{d^2U}{dq^2} \right) \left(\frac{dq}{dx} \right)^2 \quad \left(\frac{dU}{dq} \right) \left(\frac{d^2q}{dx^2} \right) \right] \tag{2}$$

Certaintly no one would object to $dU/dq > 0$. The sign of d^2U/dx^2 thus depends upon the signs of d^2q/dx^2 and d^2U/dq^2. If $q(x)$ is linear, then the second set of terms in the brackets of (2) disappears, and d^2U/dq^2 is left to determine the sing of the entire expression. The focus of the paper is upon the magnitude of dU/dq in (1) and the sign of d^2U/dq^2 in (2).

SECTION 3

THE DESIGN

The questionnaire that was employed is in the Appendix. It was built around three 6x8-inch color photographs of near-identical large ponderosa and Jeffry pine stands similar in size and configuration to those present in the most popular areas of the Forest. Each photograph was taken at ground level from a distance of 30 to 40 feet. The 3 photographs were simultaneously presented to respondents in the left-to-right ordering shown in the questionnaire. In terms of the linear injury scoring system developed by Miller (1973, p. 104), *A* represents "very slight injury" with a score of 1 to 8, *B* depicts "very severe injury" having a score of 29 to 35, and *C* shows "moderate injury" with a score of 15 to 21.[2] The photgraphs used to represent the forest environments are thus tied to a cardinal and linear index that biologists have frequently used to characterize oxidant damages, e.g., Taylor et al. (1980).

The purpose of the questionnaire is to generate truthful respondent messages that can then be compared to the aforementioned environments when the insitutional rules, times, and locations to which the messages refer are held constant. As Brookshire, et al. (1982) note, the air pollution problem in southern California is well understood by local residents. So as to enhance the likelihood that this knowledge would be applied and to provide among respondents the common frame and editing whose importance Tversky and Kahneman (1981) emphasize, each respondent was initially told that air pollution was the source of any differences he perceived in the health states of the depicted forest environments. In order to temper their subjective costs of participating, respondents were also told that the interview would take no more than 5 or 10 minutes. The questionnaire had to be brief because all respondents were engaged in outdoor recreation at the time. Moreover, it was expected that nearly all respondents would be daytrippers or overnight campers having severly limited opportunities to adapt their schedules to the time demands of an interview.

Interview brevity was possible because detailed explanations of hypothetical problems removed in time, space, and institutional detail from the respondent's immediate experience were unnecessary. He was asked to state his maximum willingness-to-pay in terms of a fee to be added to a daily $6.00 or $7.00 access fee he had, in fact, already paid on the interview day. Much of the environmental and preference information the respondent had to process in order to arrive at his additional willingness-to-pay had therefore already been used by him in his decision to pay the original access fee. Smith (1982) refers to an experiment of Siegal's (1961) in which increases in information processing requirements, holding reward levels constant, reduced the proportion of reward-maximizing choices. Recent experimental studies of auction processes; such as Cox, et al. (1982), demonstrate that bids reflect full willingness-to-pay only after the participant has had considerable experience with the commodity and the process. Basically, the close accord between the respondent's hypothetical and real situations reduced the likelihood of substantial discrepancies between the expected and the realized consequences of his choices [Aizen and Fishbein (1977); Brookshire and Crocker (1981)], and allowed a degree of control to be exercised over the respondent's total valuations.

A further attempt was made to ease the respondent's information processing burden by asking him initially to rank-order the depicted environments from his most to his least preferred. This had the further advantage of allowing the respondent to frame as well as to solve his decision problem. The separation of the ordering and the bidding process conforms to the Tversky and Kahneman (1981) view of decision-making in which the editing or framing phase precedes the evaluation phase.

The sequence in which the respondent was asked to bid on the environments corresponded to the rank-ordering he had already assigned. Since the respondent has no information on the other respondent's bids and since each bid referred only to one visit in a particular environment, the process had the privacy features of a sealed bid solicitation. Engelbrecht-Wiggans (1980) has shown that when values for more than one unit per person of a commodity are solicited in this fashion, willingness-to-pay for the initial unit is not fully revealed.

Given that the respondent's stated maximum willingness-to-pay for access declined as his perception of the quality of the depicted environment fell, his bids are compensating surplus measures.[3] The iterative bidding procedure was applied only to the respondent's most preferred environment. In order to reduce the arduousness of the process, it was presumed that once the respondent has settled upon this maximum payment, he had enough prior information about his preferences to allow him to state without further prodding his maximum willingness-to-pay for a visit to his next most preferred and his least preferred environments.

Following the bidding exercise, the respondent was asked whether he would be willing to go to his least preferred environment if doing so were the only way to avoid crowds in his most preferred environment. A substantial number of positive (yes) answers to this question would suggest that the bids were at least partly due to an association between the respondent's most preferred environment and his individualized perspective of what constitutes "crowding."

There is an additional feature worthy of note in the fact that the respondent's bid explicitly refers to an increment to an access fee for his current visit. The respondent did not confront the problem of deciding to which of his possible several visits over a tine period his bids would refer. Moreover, the emphasis on the current visit did not allow some respondents to adjust visit frequencies and bids simultaneously while others adjusted only their bids. The introduction of an element of noncomparability across the valuations of different respondents was thus avoided.

Nevertheless, there are at least two reasons why the acquisition of information on visit frequency and its changes and cost consequences is useful. First, the adoption of substitute activities, with consequent alterations in visit frequencey, is a major means by which respondents expand their opportunities to minimize their losses or maximize their gains from a changed forest enviornment. A failure to account for alterations in visit frequency will therefore lead to overestimates of the losses suffered in degraded environments and to underestimates of the gains acquired in improved environments. Second, this information provides a crude check on the consistency of stated economic bids with standard economic logic.[4]

SECTION 4

EMPIRICAL RESULTS

A. Data Properties

Some features of the data obtained from interviews of 36 respondents during a June 1983 weekday, and to 64 respondents over one day of a July 1983 weekend, are reviewed in Table 1. The interviews for both samples were conducted at the same set of Forest locations.[5] The heavy local day trip and overnight camping use of the Forest that Rausser and Oliveira (1976) remark upon is evident in both samples. Twenty-four of the 36 respondents in the weekday sample had a one-way trip shorter than the arithmetic mean trip of 82 miles. In th weekend sample, however, exactly half of the 64 respondents had one-way travel less than the sample arithemetic mean of 73 miles. Given the heavy preponderance of single day trip lengths of local origin, it does not seem unreasonable to assume that the sample represents single purpose recreational visits.

The average annual visits entry for each sample in Table 1 makes plausible the conclusion that the two samples are drawn from distinct populations. This plausibility was enhanced when the hypothesis of equality of the mean bids for <u>A</u>, <u>C</u>, and <u>B</u> between samples was statistically tested. At the 95-percent confidence level, only the mean bids for <u>B</u>, the representation of the most severe damage, could be statistically considered as equal between samples. Retirees, schoolteachers, students, and the unemployed dominate the weekday sample. They appear much less frequently in the weekend sample.

In the weekday sample, only one respondent reported a household annual income exceeding $50,000. The weekend sample had 6 such respondents. One can only conclude that the break-point for the binary income question was placed at too high a level.[6] This conclusion is reenforced by those respondents in the combined samples who said they could have worked on the day of the interview. Only 3 of these 23 respondents who could have worked reported an opportunity cost sufficient to exceed $50,000 annually.

Fifteen weekday and 33 weekend respondents stated they would have stayed home if they had not visited the Forest on their respective interview day. The remaining 52 respondents in the combined samples would have chosen to engage in a variety of activities ranging from going to the beach (19), visiting regional fresh water bodies (11), going to another forested area (12), or to the desert (5), to playing golf and visiting friends. Even though indoor and outdoor commercial activities are plentiful in the Los Angeles area, only one lonely individual volunteered that he would substitute such an activity, an

TABLE 1

SAMPLE ATTRIBUTES

	Weekday	Weekend
Sample Size (n)	36	64
Daytrippers	5	--
Overnight campers	31	64
Southern California residents	34	64
Average one-way distance (miles)	81.78(10.71)*	72.77(3.92)*
Average annual visits now	3.69(0.48)*	5.97(1.03)*
Average annual visits if only least preferred environment available	3.06(0.53)*	5.31(1.18)*
Usually visits sites resembling <u>A</u>	18	39
Usually visits sites resembling <u>C</u>	11	16
Usually visits sites resembling <u>B</u>	4	3
No resemblances to usual sites	3	6
Earnings > $50,000	1	6
Could have worked today	8	15
Average earnings for those who could work	$93.13(18.83)*	$173.21(17.86)*
Average expenditures on substitute activity	$35.14($9.47)*	$25.31(8.50)*
Substitute to avoid crowding	29	48

*Standard Error

amusement park visit.

Twenty-nine of the 36 weekday respondents and 48 of the 64 weekend respondents said they would go to their least preferred site if their most preferred site were congested. It seem that respondents' willingness-to-pay to avoid "crowding" is at least equal to their willingness-to-pay to be without the oxidant-induced environmental damages that the differences between A and C or B represent. This result is consistent with the statistically significant higher mean bids obtained for the weekday sample. As Daubert and Young (1981) point out, willingness-to-pay will be higher for those who participate in the presumedly less-congested weekday periods.

B. Preference Expressions

Table 2 is a frequency count of respondent rank-orderings across the environments. A, which is the "very slight injury" obviously rules respondent preferences. However, the nearly equal frequencies of A > B > C and A > C > B, along with the 10 people who expressed A > (BC), imply that the sample respondents are unable to express a clear preference when asked to choose between B and C.

The preference pattern that emerges in Table 2 also appears with respect to the respondents' cardinal evaluations. Tables 3a and 3b include the mean and the median willingness-to-pay additional access fees to each of the 3 depicted environments.[7] The willingness-to-pay for the A environment in each sample is more than twice the willingness-to-pay for either the C or the B environments. The hypothesis of bid equality of the elements in the three possible pairs of the depicted environments in each of the samples was tested statistically. At the 95 percent confidence level, the hypothesis was rejected for all pairs except for the C and B mean bids in the weekend sample. Equality of the mean bids for this same pair in the weekday sample could not be rejected at the 70 percent confidence level.

No respondents exhibited differences between the place they assigned A in the rank-ordering and the cardinal ordering of their bids; however, 12 respondents who stated B > C, or C > B, stated identical positive bids for C and B.

Bradford (1970) has demonstrated that marginal bid functions can be interpreted as indifference curves whose slopes represent marginal rates of substitution between an income equivalent and the good of interest. His demonstration does not require that the indifference curves exhibit a diminishing marginal rate of substitution, a requirement that indifference curves underlying Tables 3a and 3b would clearly fail. Moreover, the convex form of the total willingness-to-pay functions in these tables cannot have originated in the biological damage index since Taylor, et al. (1980) state that it is linear. Any monotonic transformation of this index will continue to yield a convex total willingness-to-pay function. The source of the patterns displayed in Tables 2 and 3 must therefore reside in the underlying preferences for the depicted environments.

TABLE 2

RANK-ORDERING OF ENVIRONMENTS

Rank-Ordering	Incidence	
	Weekday	Weekend
A > B > C	12	20
A > C > B	12	22
A > (BC)	4	6
(ABC)	5	13
B > C > A	2	1
C > A > B	1	-
C > B > A	-	1
B > (AC)	-	1

Note:

(BC) is indifference between _B_ and _C_.
(ABC) is indifference among _A_, _B_, and _C_.
(AC) is indifference between _A_ and _C_.

TABLE 3a

WILLINGNESS-TO-PAY (Weekday Sample, n=36)

	A	B	C
Injury score midpoint	4.5	18	32
Arithmetic mean bid (Standard Error)	$2.51. (.604)	$1.07 (.337)	$0.69 (.202)
Median Bid	$1.00	-	-

TALBE 3b

WILLINGNESS-TO-PAY (Weekend Sample, n=64)

	A	B	C
Injury Score midpoint	4.5	18	32
Arithmetic mean bid (Standard Error)	$1.84 (.257)	$0.55 (.102)	$0.65 (.102)
Median Bid	$1.00	-	-

There are abundant arguments that nonconvexities reflect systematic and regular features of individual preferences. May (1954) showed that if the alternatives being considered are multidimensional, intransitivities may arise, unless in a lexical fashion, one dimension always dictate choice. Other arguments are built upon either the unavailability of information about the consequences of alternative acts, or unwillingness or inability to process this information. The result is a "threshold of sensitivity" [Georgescu-Roegen (1936, 1958)] or a "zone of indifference" [Luce (1956); March (1978)] within which choices are randomly made or an "inerta of choice" prevails [Devletoglou (1971)]. The existence of these thresholds or zones has been supported for more than 100 years by psychophysical experiments involving human perceptions of sensory phenomena such as heat, light, and sound. Weber proposed in 1846 that a just noticeable increment in a stimulus would be proportional to the magnitude of the stimulus [Baird and Noma (1978)]. Fechner (1966) in 1860 refine? Weber so that the strength of a sensation is proportional to the logarithm of the stimulus.

C. Explaining the Bids

When explaining the bids, the semi-logarithmic form to be used for the relation between the total bid and the damage index can be justified by appeal to Fechner's proposition. In general, the threshold of sensitivity or zone of indifference arguments are consistent with the presence of 153 zero bids in a total of 300, where each of the 100 respondents had 3 bids.[8] These 153 zero bids mean that the sample of bids is censored at a lower bound of zero. More broadly, one observes a positive bid only when oxidant-induced damages cross a threshold, and the placement of this threshold differs according to observable individual respondent attributes and the sets of relative prices that respondents confront [Maddala (1983)]. At least in principle, there was no upper bound to the bid a respondent could make. However, the high frequency of zero bids makes it unlikely that the sample of bids is normally or log-normally distributed. All of these facts justify the application of the Tobit transformation if unbiased and consistent parameter estimates are to be obtained for the following expression: Bid = $\alpha + \beta_1 \ln$ (Damage) + β_2 (Foregone income) + β_3 (Substitute activity expenditures) + β_4 (Current visits) + β_5 (Travel cost + On-site cost) + β_6 (Weekend sample) + β_7 (Avoid crowds) + β (Depicted environment exhibits more damage than commonly visited environment? + ε, where α is a constant and ε is now a normally distributed error term. The results of applying the Tobit estimator to this expression are set forth in Table 4.[9] Travel costs were assumed to be 20 cents a mile, and on-site costs were either \$6.00 or \$7.00.

When considering the signs of the coefficients in Table 4, one must remember that Bid represents the respondent's maximum willingness-to-pay over and above what he is currently paying for current day ("today") of access to a particular forest environment. Thus, whether oxidant damages reduce the utility of the current visit, or increase the cost of attaining a particular level of visit quality, the sign of β_1, the damage index will be negative. Three rationales can be offered for the

TABLE 4

MAXIMUM-LIKELIHOOD (TOBIT) ESTIMATES OF BIDS

Parameter	Unit	Expected Sign	Normalized Coefficient	Asymptotic Standard Error
α	Dollars	+	-.0790	.3212
β_1	Damage index	-	-.4271*	.0807
β_2	Dollars	+	.0020*	.0009
β_3	Dollars	-	-.0012	.0011
β_4	Annual	+	.0120	.0078
β_5	Dollars	?	.0066**	.0034
β_6	Dummy Weekend = 1	?	-.0808	.1428
β_7	Dummy Yes = 1	+	1.0543*	.1925
β_8	Dummy Yes = 1	+	.0647	.1786

Log-likelihood function	-452.2018
Observations at limit	153
Observations not at limit	147
Standard error of estimate	2.9724
R^2	.1810

* Significant at least at the .05 level of the one-tailed t-test.

** Significant at least at the .05 level of the two-tailed t-test.

positive sign attached to β_2, foregone income. First, for those who could have worked on the interview day, their earnings are likely to be proportional to their annual incomes. Alternatively, if foregone income also represents the opportunity costs of choosing to recreate on the interview day, the higher this cost, the higher the surplus over and above access costs that must accrue to the respondent. Finally, if the respondent's work time is unrationed, he is better able to exploit any opportunities for gain that a particular forest visit offers him.

Given that the respondent equates the marginal rate of substitution between his forest activity and his named substitute activity to their relative prices, a lower price for the substitute activity implies a lower maximum willingness-to-pay for the forest activity, and a negative β_3. Ability to perceive oxidant-induced forest damages can reasonably be expected to increase with increased visits. Frequent visitors are more finely calibrated. β_4 should therefore be positive. The sign attached to β_6, the dummy for the weekend sample is ambiguous, even though a simple comparison of mean bids showed a significant difference between the weekend and weekday samples. Other factors now taken into account could account for this change. A desire to avoid crowds, β_7, is consistent with a heightened sensitivity to differences among the "qualities" of forest environments, whatever the sources of these differences. The variable to which β_8 is attached is intended to account for a proposition initially put forth by Kahneman and Tversky (1979). Although originally developed in the context of an argument for the state-dependence of decisions under risk, the proposition implies that the respondent will value a loss of what he already has more highly than the equivalent foregone gain. The proposition thus implies that the β_8 coefficient will be positive.

At first glance, the proper sign for β_5, the travel cost variable, would seem obvious. Higher travel and on-site costs result in a smaller appropriable surplus, implying a negative β_5. In the context of the problem with which these sample respondents were confronted, another interpretation is plausible, however. As already emphasized, respondent bids refer to an access fee on the very day of the interview. Failure to pay the access fee would result in exclusion from the forest environment. Given that all respondents would return home within one day, those who had travelled longer distances would have less time to adapt and thus plausibly fewer and more costly opportunities to do so. Their losses from being denied access would be correspondingly greater. The expected sign of β_5 is therefore ambiguous.

All the coefficients of Table 4 possess the expected signs. Only the coefficients for "1n (Damage)' -- β_5, and "Avoid crowds" -- β_7, are significant at the 95 percent level or better. The relatively low t-value for "Substitute activity expenditures" -- β_3, is probably due to the fact that this variable was set at zero for all respondents who would choose to stay home.

D. Checking for Inconsistencies

The above nonconvex preference ordering results are discredited if

TABLE 5

CONSISTENY CHECKS

	Unaltered Visit Frecuencies	Altered Visit Frequencies
Weekday Samples		
Sample size	17	7
Average expenditures	$ 53.79	$ 40.33
Access costs	$ 35.00	$ 38.97
Loss in surplus	$ 1.00	$ 6.92
Weekend Samples		
Sample size	20	8
Average expenditures	$ 41.26	$ 21.25
Access costs	$ 36.37	$ 40.75
Loss in surplus	$ 1.95	$ 2.25

they fail to conform to the minimal requisites of consumer theory. Because the 48 respondents who would have remained at home were not asked how much money they would spend at home, there is no information on the "prices" of their named substitute activities. Table 5 allows comparisons of arithmetic mean substitute activity prices and differences in bids of most and least preferred environments for subsets of the remaining 52 respondents. The discussion of Table 5 presumes that the bids for the visit on the day of the interview correspond exactly to the bids for any visit throughout the year. In addition, if annual visit frequency is to be reduced because of having access only to the least preferred environment, it is assumed that the named substitute activity would be adopted to replace the marginal visit. Finally, the forest activity and the named substitute activity are considered to be perfect substitutes.

If a representative respondent is not to alter his visit frequency, then the sum of his access costs and his loss in surplus must be no greater than his expenditures in his most preferred substitute recreational activity. Otherwise, the respondent would adopt the substitute activity. The first column of Table 5 obviously conforms to this proposition, where $53.79 > $35.00 + $1.00 for the weekday sample, and $41.26 > $36.37 + $1.95 for the other sample. Similarly, if a representative respondent is to reduce his visit frequency, his access costs plus his loss of surplus must exceed his expenditures on the substitute activity. Again, the second column of Table 5 is consistent with this proposition.

SECTION 5

AGGREGATE VALUES

Provided that the character and the value of each potential and actual visit is identical to the interview day visit, that the actual visit is identical to the interview day visit, that the independence of irrelevant alternatives axiom is applicable here, and given appropriate separability and linearity assumptions [Forster (1981)], the bid results can be used to estimate the aggregate annual gains that small changes in the existing pattern of oxidant-induced damages would cause to accrue to current outdoor recreational users of the Forest.

In 1982, the Forest had 6,446,000 recreational visitor-days of which approximately 90 percent were day or overnight trips [Personal Communication (1983)]. Presume in the following calculations that at least some part of each of these visitor-days was spent in the 161,000 acres composing the ponderosa-Jeffry pine portion of the Forest. Miller (1973) remarks that 46,000 acres, 54,000 acres, and 61,000 acres of this forest type have respectively been heavily, moderately, and lightly or not at all damaged by ambient oxidants. Treat these categories as corresponding to our *A*, *C*, and *B* representations.

In Table 2, it was noted the 34 of cur 100 respondents perceive that they currently recreate in *C*- and *B*-type environments. If we assume that the remaining 66 respondents are indifferent to damage reductions in *C*- and *B*-environments, then only the aforementioned 34 sample respondents will benefit from a shift of all Forest environments to A. The respective mean bids for *A*, *C*, and *B* of the 15 weekday individuals among these 34 respondents were $2.53, $0.87, and $0.33; for the weekend individuals, the respective mean bids were $1.22, $0.53, and $0.60. Of the 515 annual visitor days in the combined 100 respondent sample, these 34 individuals accounted for 199 days, or 39 percent. If adjustments in visitor days are disallowed, and if visitor days are assumed to be distributed equally between weekdays and weekends, the aggregate annual willingness-to-pay of those Forest visitors who do not now recreate in *A*-environemtns is readily calculated. For example, the aggregate annual willingness-to-pay for the *C* environment is:

$$\frac{\$0.87}{2} + \frac{\$0.53}{2} \quad (0.39)(6{,}446{,}000) = \$1{,}760{,}000$$

Similar calculations performed for the *A*- and *B*-environments yield annual values of $4,714,000 and $1,169,000, respectively.

Assuming that the willingness-to-pay for the various environments are independent of the acreage in any particular environment, the aggregate annual willingness-to-pay by those who do not now recreate in the *A*-environment for the existing mix of *A*, *C*, and *B*-environments is:

$$\frac{61{,}000 \text{ acres}}{161{,}000 \text{ acres}} (\$4{,}714{,}000) + \frac{54{,}000 \text{ acres}}{161{,}000 \text{ acres}} (\$1{,}760{,}000) +$$

$$\frac{46{,}000 \text{ acres}}{161{,}000 \text{ acres}} (\$1{,}169{,}000) = \$2{,}716{,}000,$$

or $16.87 per acre per year. If the entire 161,000 acres were in the *A*-environment, the per acre annual mean bid of these same individuals would be $4,714,000/161,000 acres = $28.63. Similarly, the annual mean per acre bid for a completely *C*-environment Forest would be $10.93, and for a wholly *B*-environment Forest, it would be $7.26. Thus, for those individuals who currently do not recreat in *A*-environments, the shift of an acre-from the *C*-environment to the *A*-environment would, on average, generate $28.63 - $10.93 = $17.70 in additional annual surplus, while a shift of an acre from the *B*- to the *A*-environemtn would, on average, generate $28.63 - $7.26 = $21.37 in additional annual surplus for the recreator.

The immediately preceding calculations presume that the number of daily visits would not change as the forest environment changes.[10] In fact, the 100 respondents state that the sum of their individual annual visits would decline from 515 days to 479 days if they always had to retreat in the *C* or *B* environments. Moreover, these calculations dismiss the very real possibility that those who already recreate in *A* environments might acquire surpluses from having additional acreages shifted from *C* and *B* into *A*. Additional *A* acreages expand their choice sets, and they may simply prefer that more *A*-environments *exist* [Miller and Menz (1979)].

When the above calculations are redone to account for changes in visits and for the bids of all respondents for all environments, the shift of an acre from *C* to *A* generates an annual average surplus of $93.80 - $32.05 = $61.75, while a shift of an acre from *B* to *A* provides an annual average surplus of $93.80 - $26.09 = $67.71.

SECTION 6

CONCLUSIONS

With the single exception of Calish, et al. (1978), the literature is devoid of empirical work relating the condition of forest stocks to measures of economic values. Forest managers will nonetheless make decisions of economic value. This and similar studies can assist in giving empirical form to the economic content of these decision problems.

The marginal value function of this study increases with reductions in oxidant-induced damages. The result is not idiosyncratic. Even though they usually fail to note it, many other contingent valuation studies of environmental questions have found the same phenomenon. None of these studies have forced a form upon the objective function. Crocker and Forster (forthcoming) review 5 frequently cited studies of atmospheric visibility and conclude that each finds an increasing marginal benefit function. Daubert and Young (1981) state that shoreside users are "relatively indifferent" among all but extreme high or low stream flows. Table III of Loehman, et al. (1979) represents an increasing marginal benefit function for reductions in the health effects of air pollution. Underlying physical and biological relations or adjustments in some endogenous variable such as visit frequency could be the sources of these nonconvexities. The form of the present study rules out these sources. However, it can neither rule out nor distinguish between intervals of nonconvexity in preference orderings or the multidimensional character of its depicted environments as sources of the increasing marginal benefit functions it observes. Some implications nevertheless follow for future studies of the values of environmental goods having substantial aesthetic components.

Using the lucid phrases of Gensch and Svestka (1979), observed behavior studies might be well-advised when formulating propositions to devote more attention to "sequential noncompensatory" models of individual decision processes such as Tversky and Sattah (1979) rather than focusing only upon the "simultaneous compensatory" models that currently dominate. The former are able to incorporate randomness and inertia of choice; they do not insist that the individual be cognizant of all mathematically unequal utilities. The choice between the two classes of models could often amount to a subjective evaluation of the tradeoff between the biases introduced by a lack of descriptive reality and the inelegance caused by the absence of a unique mapping between demand and utility.

On the other hand, the immediately preceding conclusion may actually be offered little support by the present study. Its results may simply be a creature of the multidimensional character of the depicted environments. In particular, a multiplicative interdependence may be present in utility terms between healthy pine trees and other elements (bushes, resistant tree species, terrain) present in the packages of forest environments. The minimum value of a combination of the healthy pine trees and these other elements may be much greater than the sum of their values when treated separately; that is, the health of the pine trees must be some necessary minimal scale in order for the other elements to be valued. If so, the values obtained here, and perhaps in other contingent valuation studies as well, are relevant only to the entire environmental package. One could not then repackage particular elements in order to extrapolate their values to other settings.

APPENDIX

SBNF Oxidant Questionnaire

Interviewer ____________________; Location ____________________________;

Date ____________________

Hello. I am ________________________________ from the Univ., of California.

SECTION I

As you may know, the San Bernardino National Forest has been exposed to increasing annual dosages of air pollution in the last 3 or 4 decades. This air pollution is thought by many scientists to have damaged the health of the forest.

SECTION II

These photographs show 3 forest environments. Suppose you were to visit an environment like one of them today. Which environment would you most prefer to visit?

A B C No preference (Circle)

Is there a single environment you would least like to visit?

A B C (Circle)

Suppose that the only way you can enter any environment like the one you most prefer is by paying a daily fee additional to any you are now paying. This additional fee will be used to finance special programs designed to protect this forest. Would you be willing to pay an additional $3.00 to assure entrance today to the environment you most prefer?

If yes, increment by $2.00 until a negative response is obtained, then decrease by $1.00 until a positive response is again obtained. Record final bid $________. If no decrease by $.50 until a positive response is obtained, then increase by $.25 until a negative response is again obtained. Record final bid $_________.

How much additional would you be willing to pay to assure entrance today to your nest most preferred environment? Record bid $_________

How much additional would you be willing to pay to assure entrance today to your least preferred environment? Record bid $________

Would you be willing to go to your least preferred environment if it were the only way to avoid crowds present in your most preferred environment? ___________________________

SECTION III

Now I would like to ask a few other brief questions.

Where is your home? ____

How far did you travel today to get here? _________________________

Which environment in the photos most closely resembles the sites you usually visit?. ____

A B C None (Circle)

About how many days do you visit this forest each year? _________

If all the forest were similar to your least preferred environment, how many days each year would you visit? ____________________

If you wanted, could you have worked today?

Yes No (Circle)

If yes, about how much would you have earned? _____________________

If you hadn't come here today, and hadn't worked, what would you have done? ____

About how much would it have cost you including the cost of transportation, if any? _________________________________

Does your household's annual income exceed $50,000?

Yes No (Circle)

REFERENCES

1 According to Bolsinger (1980), these two species also comprise 59 percent of the Forest's sawtimber volume. Though little actual logging takes place, the Forest contains nearly 1.2 billion board feet of sawtimber. Originally established in 1925, "...primarily for the conservation of water resources" [U.S. Forest Service California District (1942)], the Forest has since become the most heavily used unit for outdoor recreation in the National Forest system [Hilb (1976)].

2 These color print enlargements were selected from among hundreds of 35 mm slides owned by Dr. Paul R. Miller of the Pacific Southwest Forest and Range Experiment Station. Buhyoff and Wellman (1980) cite numerous psychophysical studies which support the hypothesis that people evaluate photographs of landscapes "in the same manner" in which they evaluate the actual scenes. The injury scores were assigned by Dr. Miller on June 17, 1983.

3 This is not quite accurate, since the fee change measures the price change required to maintain the ex ante utility level. Hicksian compensating measures refer to the income required for such maintenance. However, as opposed to some unidentified visit, the fees in terms of which the bids were stated refer to a specific visit to which the respondent was already committed. The difference between the income equivalent of the fee change and the fee change is therefore likely to be trivial. Note also that if the individual is allowed to adjust his visits in response to a change in forest quality, (2) becomes very complex, implying that its sign will likely be ambiguous for reasons in addition to the ambiguity of the sign for $\partial^2 U/\partial q^2$. Many contingent valuation studies are less than clear as to whether the respondent was allowed to adjust his visits as he calculated his bid.

4 In the contingent valuation literature, tests for biases in bids have fallen into three classes: (1) tests for discrepancies between respondents' stated bids and the prices the investigator infers they have paid in a real market for the same good, e.g., Brookshire, et al. (1982); (2) tests for discrepancies between respondents' statements about the willingness-to-paid and their willingness-to-accept payments that are actually offered, e.g., Bishop and Heberlein (1979); and (3) various tests for the consistency with economic logic of the respondents' statements, e.g., Rowe, et al. (1981). Rowe and Chestnut (1983) provide a most useful commentary on the meaningfulness of many of the test results reported to date.

5 The interviews were supervised by Professor Henry J. Vaux, Jr. No more than 10 individuals refused to particpate. The two interviewers had conducted hundreds of interviews in another contingent valuation study involving forest fire damages.

6 The binary form of the annual income question was prompted by two considerations: (1) the fact that, when trying to explain bids for aesthetic environmental commodities, most contingent valuation studies have obtained small and statistically insignificant coefficients for annual income; and (2) serious doubt that one can define adequately within the confines of a 5 or 10 minute interview what is to constitute annual income. The binary measure enhances the likelihood that different respondents employed similar definitions.

7 All those who were not indifferent among the environments yet who refused to provide any positive bid replied with "We pay too much already," "Present fees are high enough," and similar sentiments. One weekday individual bid $20.00 for the *A* environment. This was the highest bid for any environment. There were 2 weekday and 2 weekend bids of $10.00. Both of the weekend $10.00 bids were for the *A* environment. One of the weekday $10.00 bids was for the *C* environment, while the other was for the *A* environment. Removal of these "outliers" does not alter monotonically increasing form of the marginal benefits functions.

8 Only 68 of these zeroes were for the *A* environment, and 54 of the 68 were by the 18 respondents who were indifferent among all the depicted environments.

9 As usual, the normalized coefficients of Table 4 represent the change in Bid with respect to a change in the explanatory variable. In this case, however, the change in Bid embodies two components: (1) the change in the probability of a bid being greater than zero weighted by the expected value of those bids which are greater than zero; plus (2) the change in the expected value of those bids greater than zero weighted by the probability of a bid being greater than zero. The Tobit estimator thus accounts for changes in the probability of making a positive bid as well as for changes in the magnitudes of the positive bids.

10 An ordinary-least-squares, linear in the original variables regression for explaining the variation in visits produced the following:

$$\begin{array}{l} \text{Visits} = \underset{(2.6099)}{1.7859} - \underset{(0.0704)}{0.1486}\,(\text{DAMG}) - \underset{(3.0585)}{4.9433}\,(\text{INCM}) \\ \qquad + \underset{(1.7366)}{3.3514}\,(\text{RTON}) + \underset{(0.0112)}{0.0246}\,(\text{SBST}) - \underset{(0.0377)}{0.0671}\,(\text{TRVL}) \end{array}$$

where DAMG is the pine tree damage index of Taylor, et al. (1980);

INCM is a dummy set equal to unity when the respondents stated that his annual income exceeds $50,000; RTON is a dummy set equal to unity when the respondent stated that his worktime was unrationed on the day of the interview; SBST is respondent expected dollar expenditures in his named substitute activity; and TRVL is the respondent's dollar amount of travel and on-site costs. Summary statistics for this expression were $R^2 = 0.15$, $F = 13.82$, and $n = 180$. Ten respondents who professed never to visit a site similar to those depicted excised from the sample. The parenthetic terms beneath the coefficients are standard errors. Six observations on the dependent variable were zeros.

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CHAPTER 3

THE VALUE OF YIELD RESPONSE INFORMATION IN ECONOMIC ASSESSMENTS OF POLLUTION IMPACTS ON MANAGED ECOSYSTEMS: A METHODOLOGY WITH ILLUSTRATIONS

by

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SECTION 1

INTRODUCTION

Consider a policymaker who must make a decision about altering an allowable ambient pollution level. Suppose that he tries only to maximize an economic measure of the difference between the benefits and costs of air pollution control. Control-induced improvements in agricultural yields contribute positively (and independently of other classes of benefits) to the net benefits he will realize, but he is uncertain about yield responses to various levels of control. He therefore supports biological dose-response (yield) research in order to reduce his uncertainty. However, a finite research budget forces him to ask how much this yield response uncertainty might be reduced before he makes a control decision. To answer this question, he must know the extent to which improved yield response information will affect net benefit estimates and therefore influence his policy choice. We try to provide answers to this question for exposures to ambient ozone of four major United States agricultural commodities: corn, cotton, soybeans, and wheat. Although our primary concern is methodological, we provide estimates of the gross economic benefits of ozone control for these four crops in order to show how the question can be answered.

The uncertainties the policymaker wishes his yield response researcher to confront arise from three sources: (1) natural uncertainty, or uncertainty about the stochastic process such as the exact manner in which a plant metabolizes each molecule of the toxin; (2) statistical uncertainty, or the doubts due to limited data, associated with estimation of the parameters of any particular model of the stochastic process; and (3) model uncertainty, or the misgivings about whether a particular model of the stochastic process is the "true" model. Only the advances in fundamental knowledge that basic research provides can overcome natural uncertainty. Model uncertainty refers to the researcher's inability to identify and unambiguously defend unique choices of the system of equations to be estimated, the functional form and dimensionality of the design matrix, the values to be assigned to each element of the design matrix, and the designation of the endogenous variables and their density functions. Gaver and Geisel (1973), Barry and Wildt (1977), and Klein, *et al*. (1978), among others, treat these issues, usually within a Bayesian framework. Our discussion, which is also Bayesian, is limited to statistical uncertainty, where this kind of uncertainty is interpreted as imprecision in biological estimates of yield responses. We want to know the consequences for pollution control benefits assessments of varying degrees of statistical imprecision in biological yield response estimates.[1] Though our problem and our treatment is somewhat different, our basic perspective is in the tradition of the line of work originating with Hayami and Peterson (1972).

Statements that the benefits of environmental pollution control are much more difficult to assess than the costs are commonplace, e.g., Eads (1981), although the arguments that support the conclusion are rarely provided. Jacobson (1981) and Olson (1982) argue that a major obstacle to benefits assessments springs from the difficulty of replicating the responses of complex natural systems having large geographical and temporal scopes. This presumes that benefits assessment methods requires difficult-to-acquire yield response information. When this presumption is combined with concerns about the compounding of measurement errors from the logical chain of pollution exposures to yield responses to economic benefits assessments, one can easily conclude that all yield response information has high marginal value. It readily follows that frequent and rigorous policy applications of benefits assessment techniques must wait upon the accumulation of extremely precise yield response information. Formal economic assessments of the benefits of environmental pollution control are then supposedly rendered intractable if the prior yield response information they are thought to require is ill-defined. Many economists have implicitly accepted the premises of this position by their recent advocacy and application of duality [e.g., Crocker, *et al*. (1981)], hedonic [e.g., Freeman (1979)], and survey [e.g., Brookshire, *et al*., (1982)] techniques which do not require explicit yield response information. We reject the ease with which the position has been accepted by natural scientists and some economists, and demonstrate how the value of more precise dose-response information to benefit-cost analysis can be estimated.

A premise of the above position is that more precise yield response information always contributes at least as much to benefits estimates as does a thorough representation of price responses and producer and consumer adaptations to an environmental change. Some recent empirical work of Adams, *et al*. (1982) casts doubt upon but does not deny this premise.[2] For the particular circumstances Adams *et al*. (1982) studied, price responses and producer adaptations played a *far* larger role in determining the predicted crop production adjustments resulting from an air quality improvement than did the biological predictions of yield changes triggering the economic reactions.[3] In short, at least in the case of Adams *et al*. (1982), the ultimate yield effects and consequent benefits estimates of air pollution hinged as much on an adequate representation of producer and consumer decision processes as they did upon any grasp of biological yield response functions.

In the next section, we derive the measures we will employ for assessing the worth of more precise yield response information. Worth is to be interpreted in terms of the differences this more precise information makes in estimates of the economic benefits of alternative ambient air quality levels. An example empirical application of the aforementioned measures to estimates of the value of controlling ozone impacts upon United States production of corn, cotton, soybeans, and wheat follow. All biological yield response data we use in these sections are drawn from recent information generated by USEPA's National Crop Loss Assessment Network (NCLAN), a coordinated multi-site, biological research program explicitly aimed at providing estimates of biological yield responses for use in economic assessments. A concluding section summarizes our findings and offers suggestions for future research directions. An appendix provides additional analytical and empirical support for the textual material.

SECTION 2

DECISION-MAKING UNDER UNCERTAINTY

In essence, the policymaker of the preceding section confronts a problem of decision-making under uncertainty. Yield response information is assumed to be the source of his uncertainty. Its consequence is error in the net benefits he associates with each of the alternative pollution control policies he is considering. The magnitude of this error will vary inversely with the precision of his yield response information. His basic problem then is to decide how many observations to acquire for each yield response relation of interest. To capture the policymaker's problem, we adopt a Bayesiar approach [Bayes (1764)] that allows the policymaker to revise in a statistically meaningful manner the means and variances of his net benefits estimates when he acquires additional yield response information. The structure of the Bayesian regression analysis we employ to specify the degree of uncertainty in the parameters and related statistics (e.g., mean response) of the yield response function is set forth in the Appendix.

In order to characterize our approach more fully, consider a situation in which a finite number, say I, of possible actions a_i, i = 0, 1, ... I - 1, is available: Action a consists of maintaining the current ambient standard, in which case the" resultant pollutant concentration is $X = X_o$. Action a_i, $i \geq 1$, consists of setting a new standard, in which case the pollutant concentration is $X = X_{(i)}$. The new standard, $X_{(i)}$, may be either less than or greater than X_o.

A. Expected Payoffs

The net benefits the policymaker expects to realize from any action he selects are the expected payoffs. He must estimate the expected payoffs corresponding to each possible action. The expectation of payoffs is used because actual payoffs depend on the unknown parameters of the yield response function and, consequently, are random variables. Letting R(i) denote the payoff when action a_i is taken,

$$R(i) = W(i) - c(i), \tag{1}$$

where W(i) represents the gross economic benefit to society when action a_i is taken, and c(i) represents the costs of implementing the same action. From a Bayesian viewpoint, W(i) is a random variable $(i \geq 1)$ and, hence, R(i) also is a random variable. Taking expectations,

$$E[R(i)] = E[W(i)] - c(i). \tag{2}$$

It remains to derive an expression for E[W(i)], the expected gross economic benefit when action a_i is taken.

We consider J different crops. Let Q_{oj} be the quantity of the jth crop (j = 1, 2, ..., J) produced under current air pollution concentration $X = X_o$. Similarly, Q_{ij} denotes the quantity of the jth crop produced under air pollution concentration $X = X_{(i)}$ (i.e., when action a_i is taken, $i \geq 1$). Then,

$$Q_{ij} = T_{ij} Q_{oj}, \quad i \geq 1, \tag{3}$$

where T_{ij} denotes the percentage adjustment in yield for the jth crop when $X = X(i)$. It is expressed as a fraction of the yield under the current standard [see (4) of the Appendix].

In this analysis, the gross societal benefit obtained from the agricultural system when quantity Q is produced is measured in terms of the mean level of consumption realized at time t. Following the specification of Bradford and Kelejian (1977), the societal benefit is given by the expected value of the Marshallian surplus, w(Q):

$$w(Q) = E\{\sum_{j=1}^{J} [\int_o^{Q_D} P_j^D(g)\,dg - \int_o^{Q_S} P_j^S(g)\,dg]\} \tag{4}$$

where E is the expectation operator, $Q_D = Q_S$ is the level of consumption at which quantity supplied and quantity demanded are equated, $P_j^D(g)$ is the demand price at time t for quantity g of the commodity j, and $P_j^S(g)$ is the analogous supply price. For simplicity, we disregard intertemporal questions and transfer costs. To implement the policy assessment that (4) represents, consider the following well-behaved general equilibrium, inverse linear demand and supply functions [Just, et al. (1982)]:

$$P_j = a_j^D - b_j g \tag{5}$$

$$P_j = d_j^S + e_j g \tag{6}$$

where a_i and d_j are constants incorporating the effect of other variables in the demand and supply structure. Under this structure, the integral defines w(Q) in (4) as a convex function of P.

The benefits measure, w(Q), reflects Marshallian surplus under a given set of economic and environmental conditions. The economic benefit to society when quantity Q of the jth crop is produced can be geometrically approximated as

$$w(Q) = \tfrac{1}{2} (b_j + e_j) Q^2, \tag{7}$$

where b_j is the absolute value of the slope of the demand equation (5) and e_j is the slope of the supply equation (6). Applying (3) and (7),

$$w(i) = \tfrac{1}{2} \sum_{j=1}^{J} (b_j + e_j)\,(T_{ij}Q_{oj})^2. \qquad (8)$$

With the convention that $T_{oj} = 1$, (8) still holds when $i = 0$.

Taking expectations,

$$E[W(i)] = \tfrac{1}{2} \sum_{j=1}^{J} (b_j + e_j)\, Q_{oj}^2\, E(T^2_{ij}). \qquad (9)$$

Using the fact that T_{ij} has a posterior distribution of the Student t form [see (9) of the Appendix],

$$E(T^2_{ij}) = \hat{T}^2_{ij} + [(n_j-2)/(n_j-4)]\; s^2\,(\hat{T}_{ij}), \qquad (10)$$

where the n_j refer to the number of experimental yield response observations or the jth crop. It follows that

$$E[W(i)] = \tfrac{1}{2} \sum_{j=1}^{J} (b_j+e_j)(\hat{T}_{ij}Q_{oj})^2 + \tfrac{1}{2} \sum_{j=1}^{J} (b_j+e_j)Q^2_{oj}[(n_j-2)/(n_j-4)] \qquad (11)$$

Here the $\hat{T}_{ij}$ and $s^2(\hat{T}_{ij})$ are computed from the yield response experiment for the jth crop [see (10) and (11) of the Appendix]. With the conventions that

$$\hat{T}_{oj} = 1, \; s^2(\hat{T}_{oj}) = 0, \qquad (12)$$

(11) still holds when $i = 0$.

This analytical expression (11) for the expected economic benefit when action a_i is taken shows explicitly the effect of uncertainty about the yield ratio for the jth crop, as measured by $s^2(T_{ij})$. The naive approach of substituting T_{ij} in place of T_{ij} in (8) yields only the first term on the right-hand side of (11), and would result in a negatively biased benefit value. Specifically, remembering that b_j is the absolute value of the slope of (5), such a benefit value would be smaller than the expected benefit, E[W(i)] by the quantity

$$\tfrac{1}{2} \sum^{J} (b_j + e_j)\, Q^2_{oj}\, [(n_j-2)/n_j-4)]\; s^2\,(\hat{T}_{ij}). \qquad (13)$$

B. Optimal Policy

Given the results of a yield response experiment, the expected payoffs, (2), associated with each possible action can be computed from the expected benefits function, (11). The optimal action" is the action with the highest expected payoff, and the decision making rule that specifies which action is optimal is called the "optimal policy." Action a_i* is optimal if

$$E[R(i*)] \geq E[R(i)], \qquad (14)$$

for every i, i = 1, 2, ..., I - 1; that is, if

$$E[W(i*)] - E[W(i)] \geq c(i*) - c(i). \qquad (15)$$

Using (11), action a_i* is optimal if

$$\frac{1}{2} \sum_{j=1}^{J} (b_j + e_j) (\hat{T}^2_{i*j} - \hat{T}^2_{ij}) Q^2_{oj} + \frac{1}{2} \sum_{j=1}^{J} (b_j + e_j) \qquad (16)$$

$$Q^2_{oj} [(n_j-2)/(n_j-4)] [s^2(\hat{T}_{i*j}) - s^2(\hat{T}_{ij})] \geq (c(i*) - c(i).$$

Condition (16) specifying the optimal policy simplifies if only one crop is considered (i.e., J = 1). In this case, action a_{i*} is optimal if

$$\hat{T}_{i*} \geq \{\hat{T}^2_i + [c(i*) - c(i)]/[(1/2) (b+e)Q^2_o] - \qquad (17)$$

$$[(n-2)/(n-4)] [s^2(\hat{T}_{i*}) - s^2(\hat{T}_i)]^{\frac{1}{2}}.$$

C. Probability Distribution of Benefits

The results just derived are based only on the criterion of maximizing expected return. As Klein, et al. (1978) demonstrate, other criteria may be more appropriate for some decision problems. It is therefore of interest to obtain the entire probability distribution of the benefits, W(i), when action a_i is taken, not just the expected benefits, E[W(i)]. Such an approach makes explicit that uncertainty in the benefits estimates for which imperfect information about the parameters of the yield response function is responsible.

We first derive an expression for the probability density function (p.d.f.) of the benefits attributable to action i for the jth crop, W(i,j) say, with

$$W(i,j) = \frac{1}{2} (b_j + e_j) (T_{ij} Q_{oj})^2, \qquad (18)$$

i = 1, 2, ..., I - 1. Now, by equation (9) of the Appendix, the standardized yield ratio random variable

$$T^*_{ij} = (T_{ij} - \hat{T}_{ij}) / s(\hat{T}_{ij}) \qquad (19)$$

has a Student t distribution with $n_j - 2$ degrees of freedom. That is, T^*_{ij} has p.d.f.

$$f_{T^*ij}(x) = \frac{\Gamma[(n_j - 1)/2]}{[(n_j - 2)\pi]^{\frac{1}{2}}\Gamma[(n_j - 2)/2]} \left(1 + \frac{x2}{n_j - 2}\right)^{-(n_j - 1)/2} \tag{20}$$

Using change of variable techniques, the benefits p.d.f., $f_{w(i,j)}$, for the jth crop when action a_i is taken to related to the p.d.f., f_{Tij}, for the yield ratio T_{ij} by

$$\begin{aligned} f_{w(i,j)}(w) &= \tfrac{1}{2}\,[\tfrac{1}{2}(b_j + e_j)\,Q^2_{oj}\,w]^{-\frac{1}{2}} \\ f_{Tij}(x) &= \left(\frac{w}{\frac{1}{2}(b_j + e_j)\,Q^2_{oj}}\right)^{\frac{1}{2}}, \quad w > 0. \end{aligned} \tag{21}$$

To evaluate (21), *we* note that (19) implies that f_{Tij} and f_{T^*ij} are related by

$$f_{Tij}(x) = \frac{1}{s(\hat{T}_{ij})}\, f_{T^*ij}\,[(x-\hat{T}_{ij})/s(\hat{T}_{ij})] \tag{22}$$

We now derive an expression for the p.d.f. of the benefits attributable to all J crops

$$w(i) = \sum_{j=1}^{J} w(i,j). \tag{23}$$

Since (23) expresses w(i) as a sum of independent random variables, its p.d.f. $f_{w(i)}$ say is a J-fold convolution [Feller (1950, pp. 214-216] of the p.d.f.'s $f_{w(i,j)}$, $j = 1, 2, \ldots, J$. Specifically, $f_{w(i)}$ can be obtained by the following recursion:

$$\text{(i)} \quad g_{w(i,1)}(w) = f_{w(i,1)}(w), \quad w > 0; \tag{24}$$

$$\text{(ii)} \quad g_{w(i,j)}(w) = \int_o^w g_{w(i,j-1)}(w-x)\, f_{w(i,j)}(x)dx, \quad w > 0, \qquad j = 2, 3, \ldots . j; \tag{25}$$

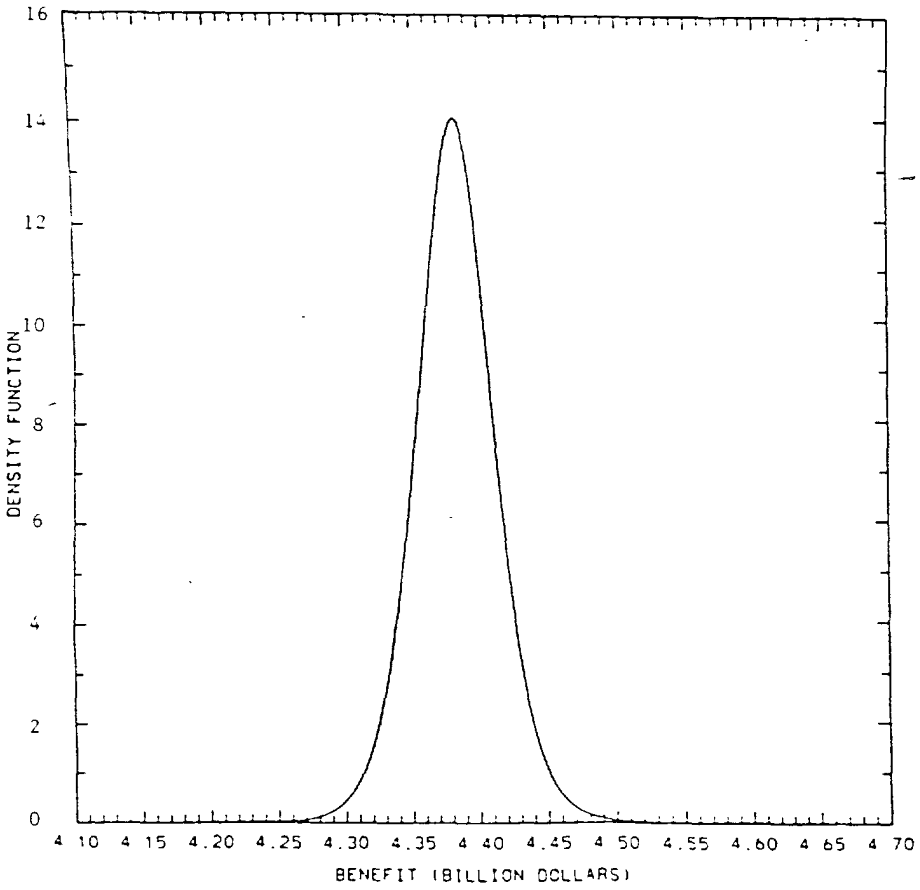
$$\text{(iii)} \quad f_{w(i)}(w) = g_{w(i,j)}(w), \quad w > 0. \tag{26}$$

If (21) is substituted into (25), it is difficult to obtain an analytical expression for $f_{w(i)}$. However, (25) can be evaluated by numerical methods to compute the p.d.f., $f_{w(i)}$.

Using a numerical algorithm, (25) is evaluated in Figure 1 for one crop, cotton, and one action, a_1. The appendix displays the mechanics of the calculation. As explained in Section III, action a_1 refers to meeting

FIGURE 1

Posterior Distribution of Economic Surplus for Cotton



a secondary standard of .10 ppm. The parameter values used to establish Figure 1 are also set forth in the nest section. Figure 1 portrays the uncertainty in the benefits calculation for action a_1 that is due to the statistical imprecision in the cotton yield response function. The latter is also presented in the next section. Finally, in the next section, the results of similar calculations are presented for each action-crop combination. However, the figures of Section III are in terms of the differences in benefits attributable to meeting the existing ambient standard of .12 ppm and meeting each of three plausible alternative standards.

SECTION 3

AN EMPIRICAL EXAMPLE

The combined production of corn, soybeans, cotton, and wheat comprised 64 percent of 1980 cropped acreage, 70 percent of 1980 total crop value, and 65 percent of the value of 1980 agricultural exports for the United States [USDA (1980)]. The obvious economic importance of these crops has probably motivated the attention that USEPA's NCLAN research program on the yield response effects of air pollution has devoted to them. On the basis to date of the NCLAN and other-yield response research results, Heck, et al. (1982) conclude that ozone has the greatest crop production impact of the various air pollutants known to harm vegetation. Further, ozone in potentially damaging concentrations is thought to be the most widespread of these pollutants. In order to illustrate the methodology of the preceding section, we therefore chose to use as an example the contribution that more precise yield response information makes to estimates of the impact that meeting alternative ambient ozone standards would have upon the economic value of production for the four aforementioned crops. In principle, the same methodology is applicable to other pollutants, such as SO_2, and other classes of crops, such as vegetables.

Specific parameters are required to implement the methodology of Section II. To calculate the benefits function, the parameters of the supply and demand relations must be available. Parameters of the yield response function are necessary for estimates of how benefits are altered under alternative ambient ozone concentrations. Clearly, assumed and actual (current ambient) concentrations by regions are needed. The demand and supply relations are estimated via standard econometric procedures. The yield response information, with regionalization where possible, is taken from NCLAN's Annual Reports for 1980 and 1981; USEPA's SAROAD data base is the source of the ambient ozone information. Each of these required bits of information is discussed in more detail below.

A. Supply and Demand Relations

We employ changes in Marshallian surpluses to measure the differences in economic benefits across alternative ambient ozone concentrations. For each of the four crops, a set of semi-equilibrium market relations is estimated. Given that each crop is an intermediate product, full general equilibrium properties cannot be invoked [Just and Hueth (1979)]. This can affect the meaning of the benefits measures. The semi-equilibrium market relations are specified as:

$$P_c^D = f(Q_c, R, T, WP, OSM) \quad (27)$$

$$Q^s = f(P_c, S, P_j, T, QL) \quad (28)$$

$$Q^s = Q^D \quad (29)$$

where P_c is crop price, Q^D and Q^s are, respectively, supply and consumption levels in equilibrium, R is per capita disposal income, T is time, WP is a weighted price of other feed grains, CSM is oilseed meal price, S are stocks, P_j is an index of production prices (costs), and QL is lagged production.[3] Prices and income are expressed in actual dollars. The markets are assumed to be well-ordered. For estimation, each expression was assumed to be linear in the original variables.

The system (27)-(29) was estimated for corn, soybeans, and wheat by the Zellner (1962) seemingly unrelated regression (SUR) procedure. Two-stage least squares, with the Cochrane-Orcutt (1949) iterative procedure for serial correlation, was used for the cotton system. The supply and demand parameters for corn, wheat, and soybeans were taken from SUR supply and demand blocks for major livestock feeds and feed grains. Simultaneities involving cotton stocks required 2SLS estimation for that crop. Data cover the period 1960 to 1980, and are from the USDA Agricultural Statistics annuals, The estimated supply and demand parameters are presented in Table 1. As is evident from the table, the statistical results are consistent with expectations concerning signs and significance of the relevant variables. These are the supply and demand parameters (the b and e coefficients of (4) in Section II) that we use to calculate the economic benefits associated with meeting alternative ambient ozone standards.

B. Yield Response Information

The magnitudes of the yield response parameters used for the empirical version of expression (A1) in the Appendix are reported in Table 2. They were derived from data reported in the 1980 and 1981 annual NCLAN reports [Research Management Committee (1981, 1982)], and were estimated by ordinary-least-squares for an expression linear in the original variables. Regional differences in responses were accounted for by testing for the homogeneity of slopes across regions. For those crops where regionalization was statistically justified, regional yield response was weighted by the sane region's market share in arriving at the overall yield response.

The yield reductions predicted by the estimated yield response functions are parameters in the model of Section II. They serve to drive the benefits assessment. Table 3 reports, in the form of yield ratio statistics, the yields occurring under the current SNAAQS standard for ozone of 0.12 ppm not to be exceeded more than once a year.[4] These relative yields thus represent the biological consequences of alternative regulatory options. They trigger the economic consequences. In

TABLE 1

Supply and Demand Parameters

Prices are in actual dollars. Corn, soybean, and wheat quantities are in bushels. Cotton quantities are in 500-pound bales.

Crops	Supply Coefficients Own Price	 Elasticity[a]	Demand Coefficients Own Price	 Price Flexibility[a]
Corn[b]	654.75 (3.211)[d]	0.31	-0.000089 (1.850)	0.24
Cotton[c]	1.002 (1.821)	0.47	-0.1306 (1.602)	0.50
Soybeans[b]	272.44 (4.662)	0.48	-0.0015 (2.296)	0.38
Wheat[b]	226.66 (3.743)	0.59	-0.00081 (1.810)	0.52

[a] Evaluated at mean quantity and price for 1960-1980 period.

[b] Estimates from Seemingly Unrelated Regression (SUR) supply and demand blocks for four feed grains (corn, barley, wheat, and grain sorghum) and soybeans.

[c] Estimates from two-stage least squares and Cochrane-Orcutt iterative procedure applied to expressions which were linear in the original variables.

[d] Values in parentheses are "t" statistics.

TABLE 2

ESTIMATED VALUES OF YIELD RESPONSE PARAMETERS

Yield is in grams per harvested plant. Ozone is in parts per million by volume.

Crop j	Sample size n	Intercept $\hat{\alpha}$	Slope $\hat{\beta}$	Standard error $s(\hat{\beta})$
Corn[a]	24	174.0	- 685.0	128.0
Cotton[a]	12	1098.4	-3708.0	228.52
Soybeans[a]	16	21.4	- 93.1	7.6
Wheat[a]	16	5.0	- 12.0	2.6

---

[a] Estimated from data reported in NCLAN Annual Reports (1981, 1982). Estimates were obtained by ordinary-least-squares for an expression linear in the orginal variables.

TABLE 3

YIELD RATIO STATISTICS

Units are identical to Table 2. Ozone is in ppm.

Crop j	Action (ozone standard) i	Estimated yield ratio[a] $\hat{T}_{ij}$	Standard error of ratio $s(\hat{T}_{ij})$
Corn	0.10	1.052	0.00963
	0.08	1.103	0.01926
	0.14	0.948	0.00963
Cotton	0.10	1.042	0.00329
	0.08	1.085	0.00659
	0.14	0.958	0.00329
Soybeans	0.10	1.059	0.00481
	0.08	1.118	0.00961
	0.14	0.941	0.00481
Wheat	0.10	1.028	0.00329
	0.08	1.056	0.00659
	0.14	0.972	0.00329

[a] The yield ratio is the estimated yield for the action i relative to the current standard of 0.12 ppm. These ratios were calculated from the information in Table 2.

biological yield terms, they match or exceed the losses that Boyer (1982) attributes to insects, diseases, and weeds.

In addition to the biological and economic consequences of the ozone exposures that result from meeting the current ambient standard, the consequences of alternative SNAAQS for ozone of 0.8 ppm, 0.10 ppm, and 0.14 ppm are evaluated. By manipulating the equilibrium supply condition of expression (4) for each crop, one can give economic meaning to the biological consequences of the alternative hypothetical ambient standards. The supply shifts that the biological consequences induce are registered in movements of the economic surplus (gross benefit) measures. Thus, by comparing changes in economic surplus across successful attainments of the alternative ambient standards, we are able to assess the differences in societal benefit across standards, including the current standard of 0.12 ppm.

C. Calculation of Expected Economic Surplus

Integration of the areas under the crop supply and demand functions at relevant price and quantity equilibria provides measures of the economic surplus associated with each ambient standard. Given the assumed linear nature of the market relations, the integration can be accomplished by using the geometric approximation set forth in expression (7). Table 4 reports these surpluses, where the consumption level for each crop is taken to be the 1978-80 arithmetic mean. The table states that the total economic surplus for the national consumption of the four crops is $51 billion when the ambient ozone standard is 0.12 ppm; it does not say that this standard is responsible for the entire $51 billion. The last column labelled "Change in Economic Surplus" is the feature of interest. Its entries represent the addition to or subtraction from economic surplus predicted to result from altering the current ambient standard of 0.12 ppm.[5]

The economic model in expressions (27)-(29) does not register the different cropping patterns growers might select as levels of ambient ozone change; that is, some of the ways in which the grower might maximize his gains from an ozone decrease and minimize his losses from an ozone increase have been omitted. This causes the estimated gains of economic surplus in Table 4 from an ozone decrease to be understated and the estimated losses from an ozone increase to be overstated. We do not know the extent of under- or overstatement the omission, causes. Its repair requires a more complete model of grower decision processes.

D. The Impact of Enhanced Precision in Yield Response Estimates

The empirical implementation of expression (25) is the real focus of our concern. For given yield response information, and when a particular ozone standard is to be enforced, we want to know the entire probability distribution of the economic surplus, not just the expected surplus. Rather than assuming that the estimated yield response parameters are the "true" ones, we wish to acknowledge statistical uncertainty explicitly by including it in the analysis. The inclusion provides insight into what can be gained by additional observations on

TABLE 4

Sum of Economic Surpluses for Four Crops with Alternative Secondary Ozone Standards

All values are in billions of 1980 dollars.
Assumes linear yield-response functions.

Ambient standard a_i	Expected Surplus E[W(i)]	Change in Expected Surplus E[W(i)] - E[W(o)]
0 (0.12 ppm)	51.286	-----
1 (0.10 ppm)	56.177	4.891
2 (0.08 ppm)	61.257	9.971
3 (0.14 ppm)	46.637	-5.349

SOURCE: Calculated from information in Tables 1 and 3.

the yield responses of corn, soybeans, wheat, and cotton to ambient ozone. Additional observations provide reductions in the variance of the yield response parameter, $\hat{\beta}$, ultimately causing it to converge on some stable magnitude which approaches the true but unknown magnitude, β.

The more precise yield response information afforded by additional experimental observations has policy worth only if it has the potential to alter a decision. We ask whether additional precision in the linear yield response results reported in the NCLAN Annual Reports (1981, 1982) and in Heck, et al. (1982) is likely to influence the economic surplus estimates that could form a basis for decisions about allowable ambient ozone concentrations.

Figures 2, 3, 4, and 5 display the uncertainties in economic surpluses caused by the estimated parameters of the yield responses of Tables 2 and 3. For each of the four crops, the figures represent the density functions of the differences in economic surpluses between the current ambient standard of 0.12 ppm and alternative standards (reading from left to right in the figures) of 0.14 ppm, and 0.10 ppm, and 0.08 ppm. The scales on the vertical axes are probabilities per unit of output. Two features of these functions are worthy of note, particularly when one remembers (recall Table 2) that the linear yield response estimates on which these surplus distributions are founded involved as few as 10 and no more than 22 degrees-of-freedom.

First, the mass of the surplus estimates at and in the immediate neighborhood of their means is very great for each crop-ambient ozone combination. Only the distributions for the 0.08 ppm standard lying on the far right of each figure exhibit much variability. Additional experiments using linear yield response functions for the four crops would increase the mass at the mean of each distribution, but it seems likely that this increase would contribute very little to any standard setting policy decisions based on these distributions. This judgement is reenforced by the lack of overlap between distributions, with the sole exceptions of the 0.10 and 0.08 ppm surplus distributions for corn and wheat, which display some overlap with one another. This lack of overlap between distributions implies that the common tradeoff between Types I and II statistical error need not be confronted, given that the surplus estimates are to be used to discriminate among the economic implications of the named alternative ambient ozone standards. Even for the two cases where overlap does occur, it happens in each case about one standard deviation (the inflection point) from the mean of at least one of the overlapping distributions. If, as is in fact done in Figure 6, one aggregates the surplus distributions for each ambient standard across the four crops, the force of any policy concerns about these two instances of overlapping is tempered simply because the extent of the overlapping nearly becomes nonexistent.

FIGURE 2

DISTRIBUTION OF NET BENEFITS, CORN

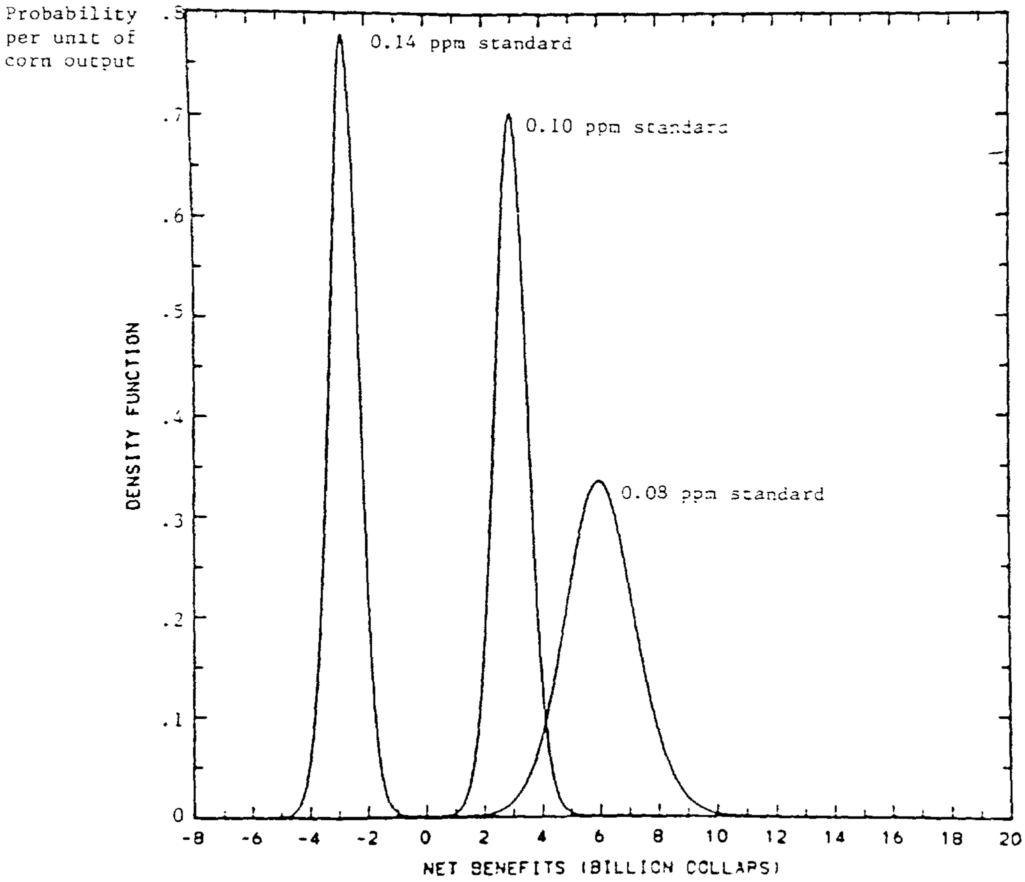


Figure 3

DISTRIBUTION OF NET BENEFITS, COTTON

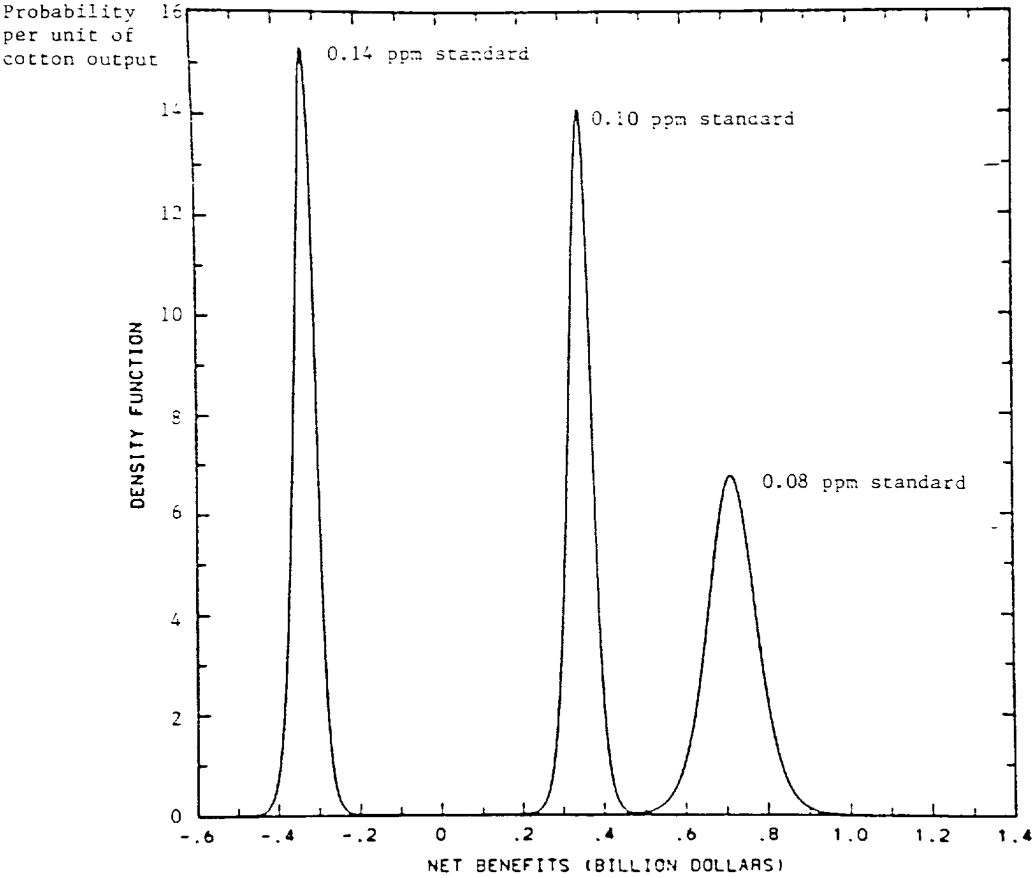


Figure 4

DISTRIBUTION OF NET BENEFITS, SOYBEANS

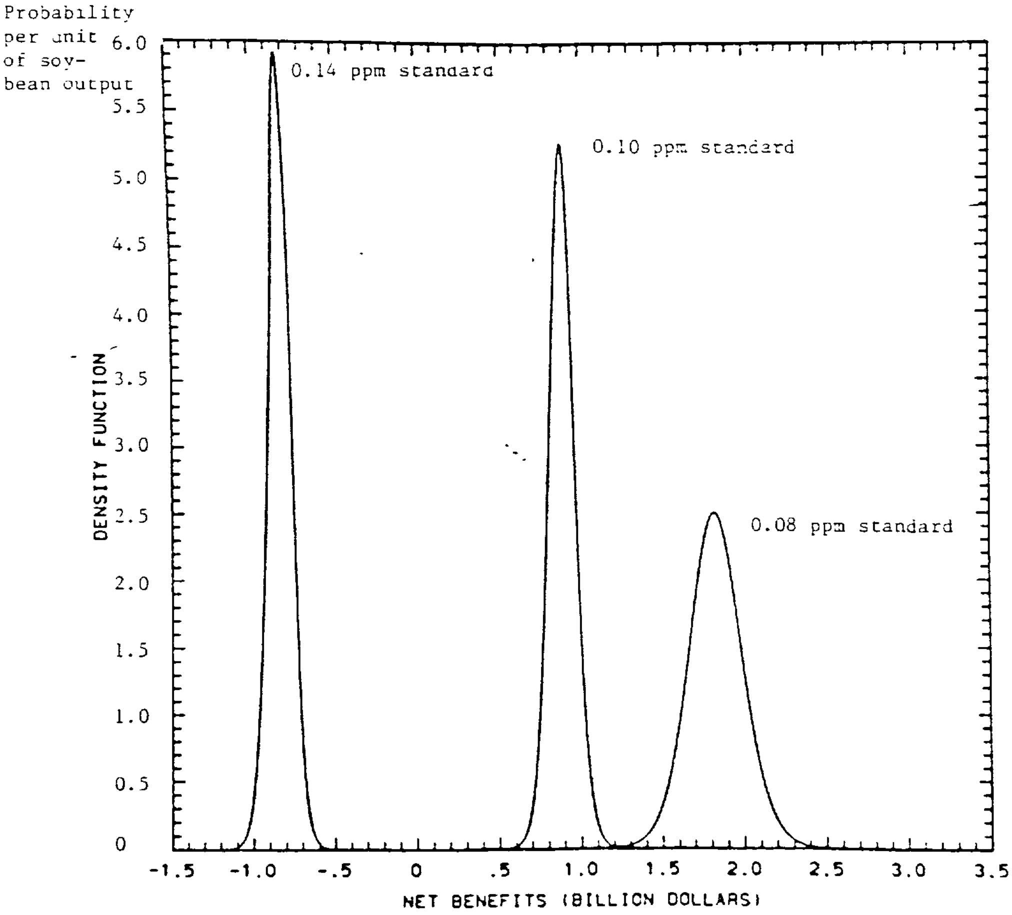
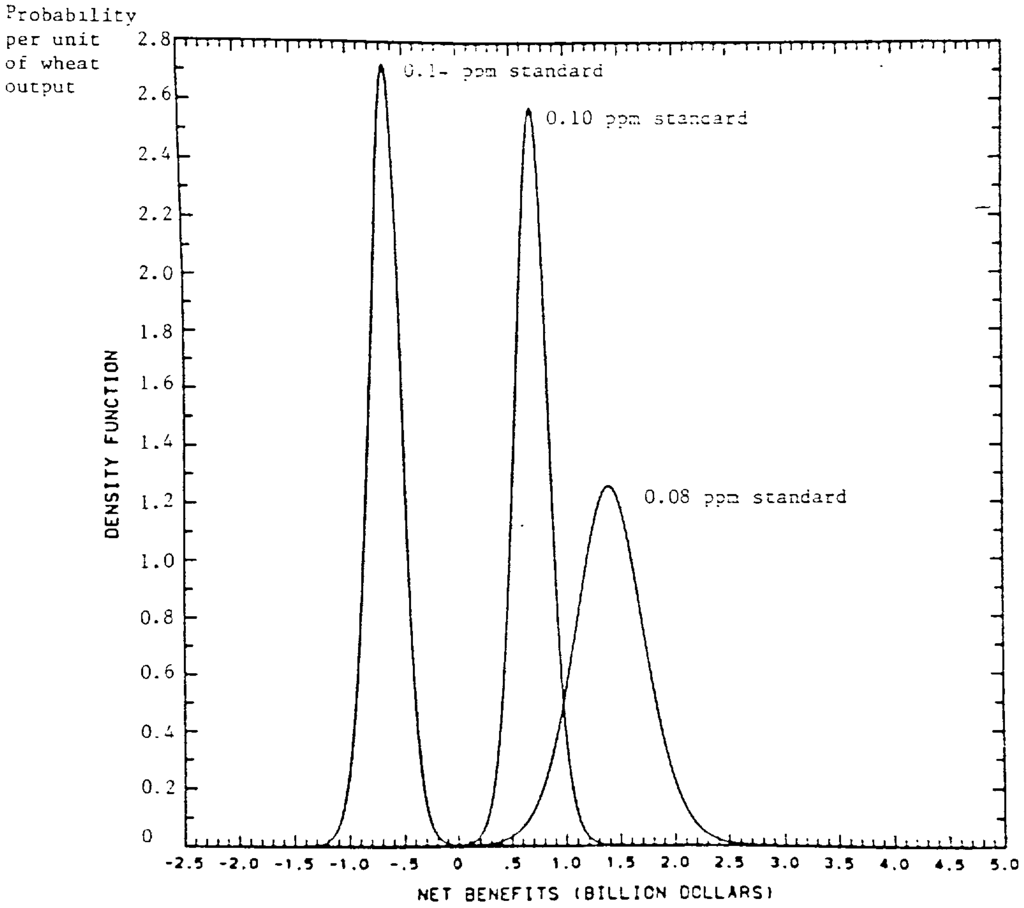


Figure 5

DISTRIBUTION OF NET BENEFITS, WHEAT



SECTION 4

CONCLUSIONS

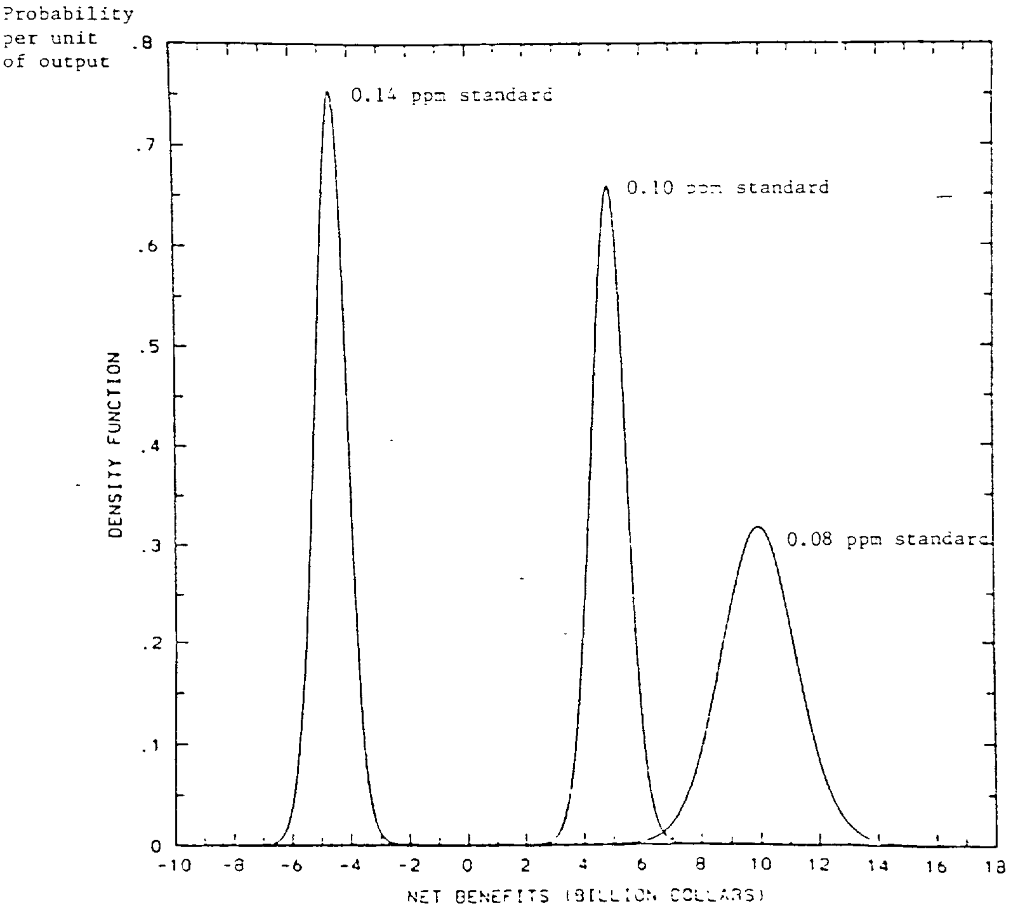
We have presented and empirically implemented an analytical framework in which the worth of more precise yield response information may be reckoned. Our framework decomposes into two parts. The first part depends on the statistics of the yield response function, while the second operates with the slopes of the supply and demand functions at their equilibrium points. Worth is dependent upon reductions in that variability of economic surplus estimates for which biological yield response estimates can be assigned responsibility. It is ultimately determined by the extent to which the variability affects the probabilities of overestimating ultimately realized economic surplus and thereby failing to plan for a more lax ambient standard, or by underestimating the realized surplus and thereby failing to plan for a stricter ambient standard. In effect, the framework explicitly captures statistical uncertainty caused by yield response estimates and, by penalizing alternative ambient standards which are possibly too conservative or too optimistic, allows this uncertainty to be incorporated directly into the decision process.

By way of illustration, framework has been applied to four different field crops having quite dissimilar growing requirements [Heck, et al. (1982)] and which, with the exceptions of corn and soybeans, are geographically concentrated in unlike regions. Moreover, as Table 1 illustrates, the market relations for the four crops are diverse. Finally the framework was used to evaluate discrete ambient ozone standards differing by as little as 17 percent and by no more than 33 percent from the current standard of 12 ppm. Relatively small variations in ozone levels should, in principle, enhance the relevance of good precision in yield response estimates. Better precision improves one's ability to discriminate among the economic consequences of the alternative standards. In short, substantial opportunities were provided for the yield response information to make a major difference in one's ability to distinguish among the economic effects of alternative air pollution levels. We have found for all four crops, if possibilities for the grower to alter his cropping patterns are ignored, that about 20 or fewer linear yield response observations similar to those found in Heck, et al. (1982) are quite adequate to discriminate among the differences in economic surplus that ambient ozone standards of 0.14, 0.12, 0.10, and 0.08 ppm generate.[6] This finding would seem to say as much for the success of the aforementioned linear yield response experimental designs as it does for the role of the economic analysis.

Our findings also provide information that can be used to choose among

Figure 6

OVERALL DISTRIBUTION OF NET BENEFITS: FOUR CROPS



future yield response experiments. In particular, yield response experimentation with a greater number of crops, rather than more experiments with those crops that have already been studied, would seem desirable. As Adams, et al. (1982) illustrate, economists possess analytically sound, empirically verifiable techniques allowing them to account for the shifts in cropping patterns as well as the market price effects that changes in ambient air pollution induce. However, these techniques presuppose knowledge of the differential yield responses to given air pollution levels of the substitute crops, that the representative grower would consider feasible to produce.[7]

In evaluating our conclusions, the reader will have remembered that our treatment employs linear yield response functions similar to those found in Heck, et al. (1982). The issue of model uncertainty has therefore been disregarded. When dealing with small perturbations in yield, linear forms can serve as reasonable and highly tractable approximations to actual nonlinear responses. However, some of the yield changes presented in Table 3 approach 10 percent or more of the base yields. One might doubt whether changes of this magnitude are properly viewed as "small." Nonlinear forms such as the quadratic could provide better fits. When censoring is present, as it is certainly likely to be when dealing with perennial crops such as citrus and alfalfa, the various time-to-failure models set forth in Kalbfleish and Prentice (1980) are deserving of attention. Our framework is equally applicable to nonlinear yield response functions. Nonetheless, if given precision is to be attained, most nonlinear models are more consumptive of degrees-of-freedom than is the linear form.

Finally, there are no grounds at this time to extrapolate our results on the worth of more yield response information on corn, cotton, soybeans, and wheat to other response functional forms, crops, or ecosystems. In order to judge when such an extrapolation would be proper, a formal analysis of the properties of yield response and demand and supply relations that are influential for economic surplus measures must be undertaken. This has not yet been done for the vegetative effects of pollution. For classes of vegetation effects involving many-decade time intervals and episodic events, the supply and demand portion of the judgement is unlikely to be available any time soon. In these circumstances, the worth of more precise yield response information will be greater because it will be the <u>only</u> technical information the policymaker has available about the potential nature of societal impacts.

APPENDIX

BAYESIAN REGRESSION ANALYSIS FOR YIELD-RESPONSE EXPERIMENTS

A. Nature of the Analysis

The purpose of this appendix is to describe how the observations obtained from a dose-response experiment can be modeled using Bayesian regression analysis. A Bayesian approach is necessary to provide inputs in a form appropriate for making a decision regarding an economically efficient level of environmental regulation.

Consider the following "simple normal linear" regression model [Zellner (1971)]:

$$Y_k = \alpha + \beta X_k + \varepsilon_k \qquad (A.1)$$

$k = 1, 2, \ldots, n$, with the error term (ε_k) being independently normally distributed with zero mean and constant variance σ^2, $[N(0,\sigma^2)]$. Here the X_k denote the level of pollutant applied to the kth plot of the experiment and Y_k denotes the corresponding observed crop yield for that plot. In keeping with the Bayesian approach, the parameters, α, β, and σ^2 of the regression model are viewed as random variables, rather than as unknown constants.

Assume for purposes of illustration that no prior information is available concerning the parameters of the regression model. In particular, not even the sign of the slope β of the regression (or yield response) function is assumed to be known. We are allowing for the possibility, *a priori,* that crop yield Y and pollutant concentration X have a positive association. Formally, it is mathematically convenient to assume that α, β, and $\log \sigma$ are uniformly and independently distributed, *a priori*. Such a "diffuse" prior probability distribution has probability density function

$$p\ (\alpha,\ \beta,\ \sigma) \propto \frac{1}{\sigma} \qquad (A.2)$$

$$-\infty < \alpha < \infty,\ -\infty < \beta < \infty,\ 0 < \sigma < \infty.$$

We wish to estimate the mean yield Y_h corresponding to setting a pollutant concentration standard X_h. For convenience, express this mean yield Y_h as a fraction, T_h say, of the mean yield Y associated with the current pollutant level X_o; that is,

$$T_k = Y_h/Y_o. \qquad (A.3)$$

The yield ratio (3) can be reexpressed as

$$T_h = 1 + \beta(X_h - X_o)/Y_o. \tag{A.4}$$

It is assumed that the current mean yield Y_o is known, so that by (4), the yield ratio T_h is simply a linear transformation of the slope β of the yield-response function.

We now obtain the posterior probability distribution of the yield ratio T_h given the sample of n observations $\{(X_k, Y_k): k = 1, 2, \ldots, n\}$ generated by the experiment. The slope β of the yield-response function has posterior probability distribution of the Student t form; specifically,

$$t_{n-2} = \frac{(\beta - \hat{\beta})}{s(\hat{\beta})} \tag{A.5}$$

is a random variable having the Student t distribution with n-2 degrees of freedom. Here

$$\hat{\beta} = \frac{\sum_{k=1}^{n} (X_k - \overline{X})(Y_k - \overline{Y})}{\sum_{k=1}^{n} (X_k - \overline{X})^2}, \text{ and } \hat{\alpha} = \overline{Y} - \hat{\beta}\,\overline{X}, \tag{A.6}$$

and

$$s^2(\hat{\beta}) = \frac{s^2}{\sum_{k=1}^{n} (X_k - \overline{X})^2} \tag{A.7}$$

with

$$s^2 = \frac{1}{n-2} \sum_{k=1}^{n} (Y_k - \hat{Y}_k)^2, \text{ and } \hat{Y}_k = \hat{\alpha} + \hat{\beta}X_k. \tag{A.8}$$

From the posterior distribution of the slope β of the yield response function, it follows that the posterior distribution of the yield ratio T_h is also the Student t form; specifically,

$$(T_h - \hat{T}_h)/s(\hat{T}_h) \tag{A.9}$$

is a random variable having the Student t distribution with n-2 degrees of freedom. Here

$$\hat{T}_h = 1 + \hat{\beta}(X_h - X_o)/Y_o \qquad (A.10)$$

and

$$s(\hat{T}) = s(\hat{\beta}) \mid X_h - X_o \mid /Y_o. \qquad (A.11)$$

This result concerning the form of posterior probability distribution of percent yield reduction, T_h, enables us to make probability statements (e.g., to determine the probability that T_h is greater than a certain specified value, given our sample). In particular, the posterior probability distribution of T_h will be used to compute expected benefits in the decision-making problem of setting a standard on pollutant concentration X.

B. Example: cotton-ozone data

We now demonstrate the application of the Bayesian regression methodology for estimating yield response functions. Data are taken from an agronomic experiment involving cotton plants which were exposed to different ozone concentrations. The 12 pairs of observations (i.e., n = 12) of mean seasonal ozone concentration X (ppm) and cotton yield Y (grams) per plot are listed in Table A1.

Employing the simple normal linear regression model with the diffuse prior probability distribution, (A.2), assumed for the parameters α, β, and σ, the following statistics were obtained:

$$\alpha = 1098.39 \text{ g}, \quad \beta = -3707.99 \text{ g/ppm}, \quad s(\hat{\beta}) = 288.52 \text{ g/ppm} \qquad (A.12)$$

The slope, β, of the cotton-ozone dose-response function has posterior probability distribution of the Student t form; namely,

$$t_{(10)} = [\beta - (-3707.99)] / 288.52 \qquad (A.13)$$

has a Student t distribution with n-2 = 10 degrees of freedom. Figure Al shows the posterior probability density function for β. Although the prior distribution allowed for the possibility that β is positive (i.e., a positive association between cotton yield and ozone concentration), _a posteriori_ the probability that β is positive is virtually zero (in fact, smaller than 0.005%).

We now wish to estimate the percent yield ratio T_j for various levels of ozone concentration X_h, relative to a current mean cotton yield of Y_o = 838.83 g corresponding to a current ozone concentration of 0.07 ppm. For convenience, the value of Y_o was obtained by using the regression coefficient estimates α and β, whereas the form of the posterior distribution of the yield ratio T_h, (A.9), requires that Y be known. Taking the case of ozone concentration X_h = 0.06 ppm, (A.10) and

TABLE A1

Mean Seasonal Ozone Concentration and Cotton Yield by Plot

Ozone is in ppm. Cotton yield is in grams.

Plot Number k	Ozone Concentration X_k	Cotton Yield Y_k
1	0.018 ppm	1030
2	0.032	1030
3	0.046	988
4	0.043	936
5	0.070	781
6	0.073	868
7	0.113	633
8	0.107	600
9	0.144	647
10	0.138	573
11	0.179	409
12	0.186	456

Figure A1

POSTERIOR DISTRIBUTION OF COTTON SLOPE

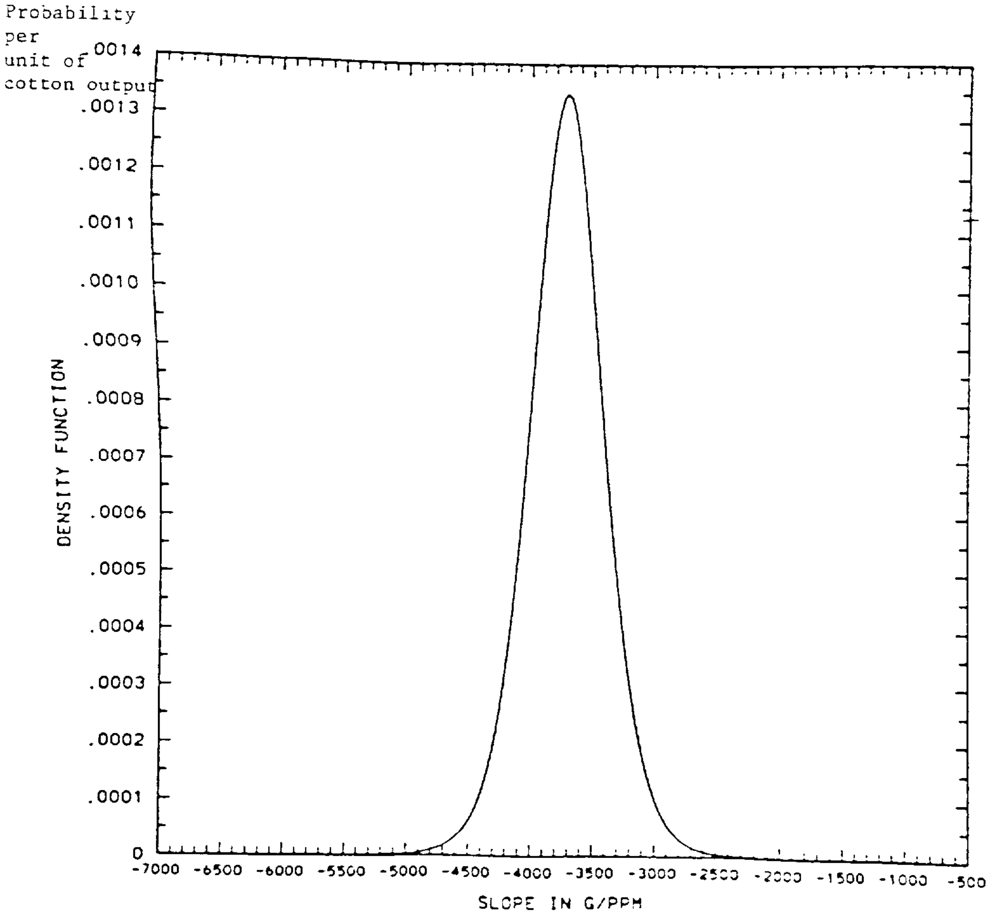
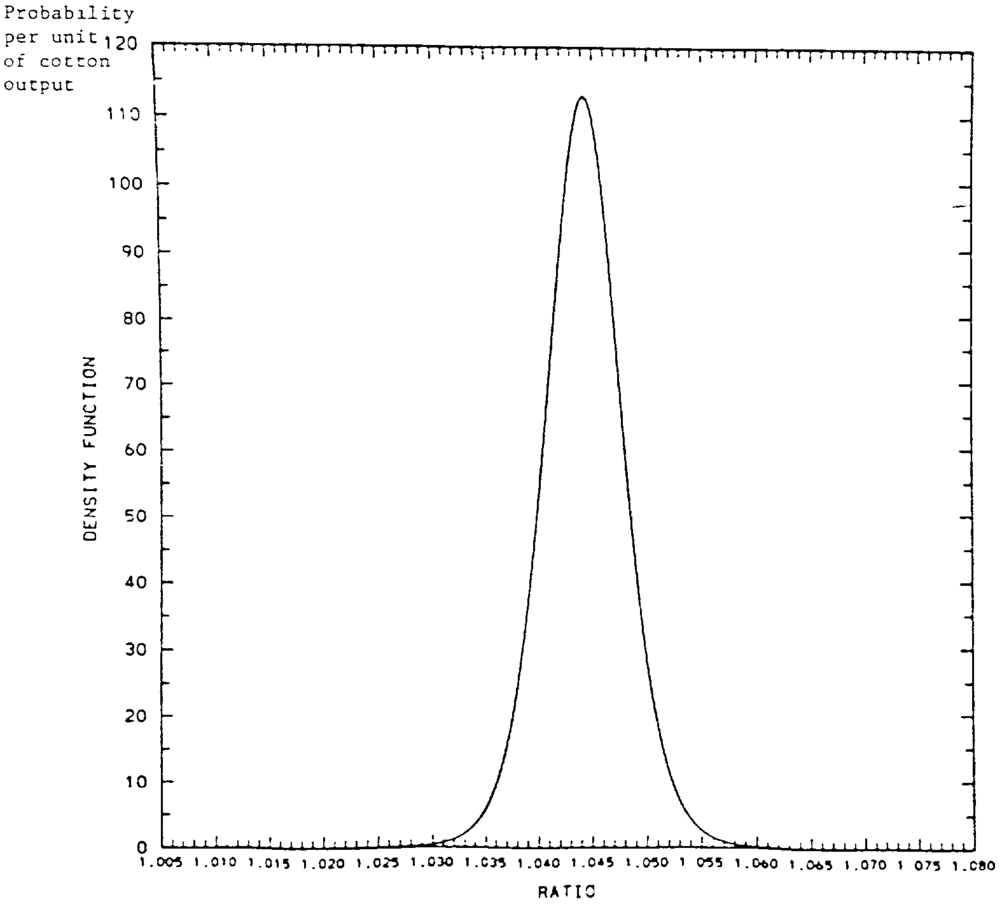


Figure A2

POSTERIOR DISTRIBUTION OF COTTON YIELD RATIO



(A.11) give:

$$\hat{T}_h = 1.0331, \; s(\hat{T}_h) = 0.003440. \qquad (A.14)$$

Thus the standardized yield ratio

$$(T_h - 1.0442)/(0.003440) \qquad (A.15)$$

has a Student t distribution with 10 degrees of freedom. Figure A2 shows the posterior probability density function for T_h. We note, for instance, that T_h falls between 1.0365 and 1.0519 with a 95% chance *a posteriori.*

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[1] We thus disregard the abundant sources of uncertainty residing in the economic propositions and empirical applications that support control benefits assessments.

[2] On the other hand, Smith and Vaughn (1980) and Kopp and Smith (1982) provide some empirical support on the cost side for the premise. In their studies of the costs of pollution control in the iron and steel industry, they found their cost estimates to be very sensitive to the engineering details embedded in their models.

[3] See Crocker (1982) for more details. Adams, *et al*. (1982) employed a price endogenous, quadratic programming model to examine the economic impact of ambient oxidants upon the 1976 production of 14 annual crops in four southern California subregions. For all but two the 56 possible region-crop combinations, the differences between estimated and actual levels of crop production were substantially less than ± 10 percent. In 29 of the 56 combinations, the predicted percentage yield change inclusive of the economic reactions differed from the triggering percentage yield change by a factor of 2 or more. Many, perhaps most, of these latter differences are accounted for by the propensity of farmers to take advantage of changes across crops in most favorable production opportunities. The errors in predicting ultimate yield responses that neglect of farmers' economic reactions will introduce can be rigorously shown to be inversely dependent on the absolute curvature of the production possibility surfaces and the price flexibility of crop supplies.

[4] The pollution exposure (dose) in each of the yield response expressions was measured as a seven-hour seasonal mean concentration of ozone. The seven-hour period is from 9:00 a.m. to 4:00 p.m., the period in which stomatal activity and hence plant sensitivity to pollution is greatest. In order to transform the mean seven-hour dose to the same basis as the SNAAQS, ambient ozone is assumed to be log-normally distributed. Thus, for example, a seasonal seven-hour concentration of .07 ppm is treated as being a SNAAQS concentration of 14 ppm.

[5] In accordance with expression (2) of the text, the expected payoffs of the alternative standards are the $E[W(i)] - E[W(o)]$ less the costs of implementing the alternatives. USEPA's Office of Air Quality Planning and Standards (1979) has estimated the costs of implementing a range of alternative ozone standards similar to those we consider at $3 billion to $9 billion annually. Crocker (1982) suggests that total agricultural benefits from all classes of improved air quality may not exceed 10-20 percent of total air pollution control benefits. *If* cost

responsibilities are assigned to agriculture in accordance with its supposed share of these total benefits, then the expected payoffs for the 0.10 ppm and the 0.08 ppm standards are positive. However, about half the gain in surplus associated with going from the 0.12 ppm standard to the 0.08 ppm standard is due to the estimated increase in corn yields. We have recently experimented with a quadratic form for the corn yield response function and have found that yield responses and consequent changes in economic surplus are somewhat lower in absolute magnitude than the corn surplus used to arrive at Table 4. In particular, with a quadratic yield response function for corn, Table 4 becomes:

Ambient Standard a_i	Expected Surplus $E[W(i)]$	Change in Expected Surplus $E[W(i)] - E[W(o)]$
0 (0.12 ppm)	51.3	---
1 (0.10 ppm)	54.6	3.3
2 (0.08 ppm)	57.8	6.5
3 (0.14 ppm)	47.5	-3.8

More significantly, the density functions for the quadratic version of Figure 2 now display no overlap. This suggests that biological model uncertainty may be as important a factor as sample size (precision) in the role that yield response information plays in benefit-cost analysis.

[6] The policymaker would have to possess a loss function putting extremely heavy emphasis on Type I error in order to be very concerned with the overlap between the 0.10 and 0.08 surplus distributions for corn and wheat.

[7] See Adams and Crocker (1982) for detail on the features of these differential yield responses that are of particular interest to economists. If research resources are limited, the decision problem of which crops are deserving of additional yield response observations resembles a portfolio problem. The crops are the kinds of securities and the observations are the number of units of each kind of security to be held.

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