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DEFORESTATION, BIOLOGICAL CONSERVATION, AND THE OPTIMAL PROVISION OF WILDLIFE RESERVES*

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Abstract. This paper uses the species-area relation to characterize the optimal deforestation program and to determine the optimal provision of wildlife reserves for tropical rain forest countries. These decisions, it is shown, must be taken jointly. The model constructed in this paper is more general than those used previously for analysis of the economics of environmental preservation. Provided a very simple inequality is satisfied, it will be optimal to set aside a greater quantity of wildlife reserves and to choose a slower rate of deforestation, even if the marginal returns to deforestation increase over time. Implications for policy are discussed.

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Concern about the extinction of wildlife species has grown to include not only specific species such as the blue whale but masses of species, many of which are entirely unknown to science. This wider concern reflects the increasing awareness that biological diversity *per se* contributes to social welfare. There are many reasons why this is so, but perhaps the most important is the potential contribution of genetic information embodied in the species stock to basic research, particularly in medicine and agriculture (see, e.g., Brown, 1985; Fisher and Krutilla, 1985; and Harrington and Fisher, 1982).

Of the many threatened ecosystems, tropical rain forests have the greatest potential for species extinction. While the rain forests cover only seven percent of the earth's surface, they are believed to harbor at least one-half of all wildlife species (Myers, 1986). The threat to these species is not overexploitation (on which much has already been written) but habitat destruction.[1] Deforestation is proceding at a rate so rapid that by the end of this century the only undisturbed tropical lowland forest left anywhere in the world may only be found in whatever wildlife reserves have been previously set aside. Conservation biologists estimate that the *minimum* quantity of reserves needed to conserve the *majority* of tropical species is ten percent of the total area.[2] But the existing quantity of reserves is only about one-third of this amount. Two questions arise for policy. One is whether the quantity of reserves set aside thus far is enough or whether more virgin territory should be protected. The other is whether the *rate* of deforestation is itself excessive. In this paper I ask, more generally: How should a society choose the quantity of virgin territory to set aside as wildlife reserves when biological diversity *per se*, or the number of species conserved, provides direct utility value? and At what rate should a society cut down its remaining primary rain forests, given that it may also want to set aside parts of these as wildlife reserves? It is self-evident that the answers to these questions must emerge from a single model.

The provision of natural environments such as wildlife reserves was first posed as an economic problem in a seminal essay by Krutilla (1967). Interestingly, although Krutilla's paper stimulated much research in this area, the first item on Krutilla's (1967, p. 785) research agenda has not been explored previously:

> "First, we need to consider what we need as a minimum reserve to avoid potentially grossly adverse consequences for human welfare. We may regard this as our scientific preserve of research materials required for advances in the life and earth sciences. While no careful evaluation of the size of this reserve has been undertaken by scientists, an educated guess has put the need in connection with terrestrial communities at about ten million acres for North America. Reservation of this amount of land--but a small fraction of one per cent of the total relevant area--is not likely to affect appreciably the supply or costs of material inputs to the manufacturing or agricultural sectors."

The costs of preservation may not be very large in North America. But in the tropics the conflict between preservation and development is more biting. Not only is the quantity of biological diversity at stake far greater, as noted earlier, but the tropics are also more vulnerable ecologically than temperate areas (see, e.g., Johns, 1985; and Wilcove *et al*., 1986). Furthermore, per capita incomes in tropical countries are much lower and depend to a greater extent on the development of wild areas. Protection of all remaining rain forests may well come at a cost that is too high for the current generation to be willing to bear.

0.1 Modeling Approach

In modeling this problem I take it that the tropical society's objectives are embodied in a social welfare function (SWF)--the integral of discounted social utilities.[3] One argument in the social utility function is the level of biological diversity, and the other is per capita consumption. I assume that the only way to conserve biological diversity is by preserving habitat--that is, by setting aside wildlife reserves.[4] I further assume that the appropriate measure of biological diversity is the *number of species* conserved.[6] I take it for granted that a competitive economy will protect too little habitat--and hence too few species--if only because the "nonextractive" value of habitat accrues to society at large and not to individuals. Decisions are therefore made by a central planner. The planner's problem is to choose the deforestation profile that maximizes the SWF subject to certain technical relations and ecological constraints. The technical relations translate deforestation profiles into consumption profiles. The ecological relations describe how deforestation depletes the stock of biological diversity.

The assumption that it is species diversity that matters and not the identity of species conserved may seem inappropriate. Brown (1985), for example, has argued that scientists entertain beliefs about which contemporary drugs, seeds, and livestock are most likely to require an infusion of genetically diverse wild strains in the future, and on that basis attach higher values to some wildlife species than to others (see also Brown and Goldstein, 1984). This may well be true. But examples abound where previously economically insignificant species have been found to be of great value. Furthermore, it is often the case, particularly in the tropics, that species entirely unknown to science may be lost. When these considerations are taken into account the case for focusing on the number of species conserved and not their identities would seem a strong one. As Harrington and Fisher (1982, p. 121) note:

> "One of the things that makes it difficult to formulate a policy for endangered species is the inability to determine on a species-by-species basis what mankind gives up if a species is forever lost. At the same time, we do know that the larger the number of

> species that are lost in a particular area..., the more likely it is that something of potential value will be lost. This is relevant since human activities, particularly tropical deforestation, can imperil large numbers of species at one time."

Since Krutilla (1967) first wrote on this topic, the feature that has come to characterize the economics of natural environments is the *irreversibility* of development. Irreversibility plays an important role here as well. One may well ask why cutting down a tree should be irreversible. Of course the original tree cannot be recovered. But a new tree can grow in its place. Ordinarily we would be content with this. But the tropics are a special case. Another tree may well grow where the original one once stood. But the time until maturity is likely to be very long, and in the meantime the habitat of species endemic to that forest is altered (in the case of select cutting) if not destroyed (as when forests are cleared for agriculture). One can predict with some accuracy the number of species that will be lost if the forest is felled and never replaced. Indeed, it is this relation I use in this paper. Of course if the soil is not harmed too much and if permanent development such as agriculture is prohibited in deforested areas, a new forest will grow where the original one once stood; and if one is willing to wait long enough a climax forest will once again serve as habitat to a number of species. But as one conservation biologist (Jordan, 1986, p. 426) has remarked:

> "The eventual growth of trees ... is not the same thing as reestablishing a tropical rain forest. The tropical rain forest is a highly diverse community, consisting of a large number of plant species and animal species which have coevolved with the plants. Reestablishment of the high species diversity and complex food webs of the predisturbance tropical forest may take much longer, or may never occur at all if disturbance have caused important extinctions."

Fisher and Krutilla (1985) maintain that irreversibility is a valid assumption for similar reasons.

The models presented in this paper are deterministic, and this may seem to overlook an important aspect of the problem. As noted earlier, biological diversity is valued partly because of its *potential* contribution to research. Importantly, whether the stock of species in a tropical forest is useful economically will generally not be known at the time the decision to fell or preserve the forest is taken. But does this uncertainty mean that replacing uncertain future benefits with their expected values will mislead policy? Arrow and Fisher (1974) have shown that under such circumstances the use of expected values will lead the social planner to preserve too small a quantity of a natural environment if development is irreversible.[6] The intuition behind this result is that there is a value to keeping options open when there is uncertainty about future benefits and when current decisions to develop cannot later be reversed. The implication of this to the analysis is that considerations of uncertainty serve only to reinforce my main conclusions.

0.2 Commentary on the Literature

Krutilla (1967) argued that future valuations are crucial to the problem of preserving natural environments when development is irreversible. Fisher, Krutilla and Cicchetti (1972; henceforth F-K-C) proved formally that if preservation benefits are increasing relative to development benefits, then the optimal level of development will be less than an analysis based on current valuations would suggest is optimal. Krautkraemer (1985), however, has shown that even when development values fall relative to preservation values it may nevertheless be optimal for an economy to exhaust its endowment of natural environments.

The models of F-K-C and Krautkraemer[7] are very different, and these differences are important to their conclusions. F-K-C model the benefits of development as depending on the *stock* of the resource in its developed state; Krautkraemer models development benefits as depending on the *flow* of the resource that is developed. The precise sense in which these assumptions matter will be made evident in this paper. In particular, Model 1 will generalize Krautkraemer's model and Model 2 the analysis of F-K-C. Model 3 contains elements of both approaches and thus provides the most general framework yet available for analysis of optimal environmental preservation.

What is the significance of this literature for the conservation of bilogical diversity? The analyses by Krautkraemer and even F-K-C are not very encouraging. Determination of the optimal rate of deforestation and the optimal provision of wildlife reserves is an exercise in *planning*, and it would not seem folly to expect that the returns to deforestation will increase over time due to technical progress in forestry and agriculture. Of course one could assume that the benefits of biological conservation will also increase because of changes in "tastes." Interest in conservation has indeed grown in tropical countries. But if possible one would like to build a case for conservation on something firmer than this.

I show that even if the returns to deforestation are increasing over time and "tastes" are constant, it may be optimal to set aside some virgin territory as wildlife reserves. In the context of the previously-cited literature, I show that Krautkraemer's conclusion is overly pessimistic; even when there is technical progress in resource extraction it may not be optimal to exhaust the resource. I also show that F-K-C's conclusion that the optimal level of development is less than would emerge from a purely myopic analysis holds under more general conditions than they analyzed. The reason is that cleared forest is a capital asset that can, if utilized properly, yield a never ending flow of income. With technical progress in forestry and agriculture, the benefit of clearing virgin forests that remain increases--but so too does the income derived from the land already under cultivation. While the marginal returns to deforestation increase over time, the marginal *benefit* of deforestation may fall because of the rising standard of living. Furthermore, this result may hold even if the returns to logging virgin forests increase faster than the returns to agriculture; the sufficiency condition for the provision of wildlife reserves depends on the ethical views of the planner as well as the rates of technical progress in forestry and agriculture.

I also show how these considerations affect the optimal rate of deforestation. In F-K-C's model, the optimal rate of exploitation is either infinite or zero. Krautkraemer did not derive this rate, focusing instead on the asymptotic properties of his model. In this paper F-K-C's optimal approach path emerges as a special case, and the optimal exploitation path corresponding to Krautkraemer's model is partially characterized. When there is technical progress in forestry and/or agriculture, I show that irreversibility not only alters the decision to preserve virgin territory but also the optimal rate of deforestation. Indeed, these decisions must be made jointly. I show that under these conditions planning that ignores technical progress is likely to set aside an area of wildlife reserves that is too small *and* to choose a rate of deforestation that is too rapid.

1. THE SPECIES AREA RELATION

It is an empirical observation that the number of species (within a given taxonomic group) found in an area tends to increase with the size of the area. Why? Williams (1964), among others, has argued that as the sample area is increased, the number of new habitats encountered should increase concomitantly. It follows that since new habitats harbor new species, the number of species found should depend positively on the size of the area sampled, all else being equal.

A more elegant hypothesis emerges from island biogeography theory (see Preston, 1962; and MacArthur and Wilson, 1967), which maintains that the number of species found within an area is determined by a dynamic balance between immigration and extinction rates. Consider an archipelago of islands. Suppose the species immigration rate for each island depends on the distance between the island and the mainland (the source of potential immigrants), but not on the size of the island. Suppose further that the species extinction rate for each island depends on the species population size, which in turn depends on the size of the island. Then if the distances between each island and the mainland were identical, the species extinction rate would be higher for small islands than large islands--that is, the number of species found would depend positively on island size. This hypothesis, like the first, extends naturally to wildlife reserves, which may be considered islands in a sea of altered habitat.

The species-area relation is usually expressed in the form

$$S = \alpha A^{\beta},$$

where S is the number of species, A is area, and α and β are parameters. The parameter α obviously depends on the units of area measurement. All else being equal, α will be larger the greater the species density. The parameter β is independent of the units of area measurement and can be interpreted as the elasticity of species diversity with respect to area. Estimates for β tend to fall in the range 0.18 – 0.35 (Diamond and May, 1981). Thus the empirical evidence points to diminishing returns (in species diversity) to increasing area.[8]

The value of this relation to biological conservation was first noticed in the mid-1970s (Diamond, 1976; May, 1975). The immediate implication is that we can predict with some accuracy the number of species that will be conserved if a wildlife reserve of given size is set aside. For example, a β of about 0.3 implies that if one percent of the Amazonian rain forest were set aside as a wildlife reserve, roughly 25 percent of the original species would be conserved.[9]

2. FELLING THE FOREST (MODEL 1)

In this model I take it that the forest is "mined" to produce a composite consumption good (say, GDP). By this I mean not only that habitat destruction is irreversible, but also that land, once deforested, lies forever fallow. This is a harsh assumption. But by working first with this assumption, and then (in Model 2) with the assumption that felled trees are of no value but that deforested land is itself productive, the solution to the more general and realistic case (Model 3), where both of these assumptions are dropped, will become easier to analyze.

2.1 The Model

Denote the rate of consumption obtained through deforestation by c_t and assume there is a level of consumption $\overline{C}$ that is available whether or not the forest is mined. Denoting C_t total consumption we have $C_t = \overline{C} + c_t$. If we assume zero population growth and normalize by setting the population at the start of the planning period equal to one, then C_t, $\overline{C}$ and c_t can be interpreted either in total or per capita terms.

$\overline{C}$ is included so that we may discover precisely how Krautkraemer's result depends on his assumption that the economy relies exclusively on exploitation of the resource for consumption. Rarely will it be the case that a natural environment is an economy's *only* source of consumption, and if there is technical progress in the resource extraction sector then there must surely be technical progress in the economy's other sectors as well. In Models 2 and 3 I assume that $\bar{C}$ equals zero, but I add an agricultural sector that makes consumption positive even when there is no deforestation. It will be seen then that our use of $\bar{C}$ here is not artificial. In all three models there is a steady state. The main difference is that in Model 1 the steady state is partly determined by $\bar{C}$, whereas in Models 2 and 3 the steady state is determined endogenously.

Let the instantaneous social utility function be given by $U(C_t,S_t)$, where S_t is the number of species conserved at date t. Assume: $U_C, U_S > 0$; $U_{CC}, U_{SS} < 0$; $U_{CS} = U_{SC} = 0 \ \forall \ C_t, S_t$; and $U_C(0) = U_S(0) = \infty$. These assumptions are fairly standard in the literature for control theoretic models where the state variable (in this case, S) enters the objective functional, and will assure us that when a higher per capita consumption leads to additional biological conservation, the reason is not that species are valued more at a higher consumption level but that instantaneous social utility is increased if in foregoing some consumption more species can be conserved.

We now need to describe how S_t changes over time. Differentiating the species-area relation with respect to time and writing A_t in terms of S_t yields

$$\dot{S}_t = aS_t^{-b}\dot{A}_t \text{ where } a = \beta\alpha^{1/\beta} > 0 \text{ and } b = -(\beta-1)/\beta. \tag{2.1}$$

Note that $0 < \beta < 1 \Rightarrow b > 0$.

The species-area relation pertains to an equilibrium situation. Eq. (2.1) thus tells us how the *equilibrium* value of S changes in response to a change in A. Adjustment to a new equilibrium value of S (following a shock--a change in A) will not be instantaneous and may in fact take centuries.[10] In using (2.1) I am therefore assuming that our concern is with the number of species conserved *permanently* and not the number that happen to be present at any particular moment in time.

We now need to relate $\dot{S}_t$ to consumption. Let

$$\dot{A}_t = -\sigma c_t, \ \sigma > 0, \tag{2.2}$$

where $1/\sigma$ is the consumption obtained per unit of land deforested. The value taken by $1/\sigma$

will depend not only on the volume of timber per hectare, but also on the logging technique. Clear-cutting of forests will destroy more habitat per unit of consumption than will selective logging. But damage caused by selective logging can also be severe. In West Malaysia the taking of three percent of the forest was found to result in an overall loss of 50 percent of the trees (Johns, 1985). On the island of Borneo, selective logging was found to leave about 30 percent of the ground bare and damaged; the extraction of one tree was found to result in the loss of 17 others (Abdulhadi *et al.*, 1981).

Substituting (2.2) into (2.1) we obtain

$$\mathring{S}_t = -aS_t^{-b}\sigma c_t. \tag{2.3}$$

Adding the irreversibility constraint, the planner's problem can now be stated formally as

$$\left.\begin{aligned} &\max_{\{c_t\}} \int_0^\infty U(C_t,S_t)e^{-\delta t}dt, \ \delta > 0 \\ &\text{s.t.} \quad \mathring{S}_t = -aS_t^{-b}\sigma c_t, \ S_0 > 0 \text{ given} \\ &\qquad\ C_t = \overline{C} + c_t \\ &\qquad\ c_t \geq 0. \end{aligned}\right\} \tag{2.4}$$

2.2 Necessary Conditions

The current value Hamiltonian (dropping time subscripts) is

$$H = U(C,S) - paS^{-b}\sigma c, \tag{2.5}$$

and the first order conditions are (2.3) and[11]

$$c \geq 0 \text{ if } U_C/aS^{-b}\sigma = p \tag{2.6a}$$

$$c = 0 \text{ if } U_C/aS^{-b}\sigma \leq p \tag{2.6b}$$

$$\mathring{p} = \delta p - U_S - pabS^{-(b+1)}\sigma c. \tag{2.7}$$

Eqs. (2.6) show that the optimal rate of deforestation depends on the marginal social utility of consumption obtained by depleting S by one unit and the shadow value of species diversity. Deforestation should take place only if the shadow value of S is less than the marginal consumption benefit associated with an incremental species extinction.

Eq. (2.7) can also be given an economic interpretation. Denote the social rate of discount by ρ_t. Assuming an interior solution we find that in this model ρ_t is given by

$$\rho_t = \delta - \overset{\circ}{p}/p - abS^{-(b+1)}\sigma c.$$

The term $\overset{\circ}{p}/p$ is the capital gains on investment in S, while the term $abS^{-(b+1)}\sigma c$ recognizes that in foregoing deforestation today, the loss in S due to any given positive level of c tomorrow will be smaller. These two terms when added together yield the own rate of return to investment in S. The social rate of return on investment is $U_S aS^{-b}\sigma/U_C$. Eq. (2.7) thus requires that the social rate of return on investment equal the social rate of discount.

2.3 The Solution to the Autonomous Case

If we have an interior solution, then (2.6a) must hold. Differentiating (3.10a) with respect to time and making the appropriate substitutions gives

$$\overset{\circ}{C}/C = [1/\eta(C)]\{(U_S/U_C)aS^{-b}\sigma - \delta\}, \tag{2.8}$$

where $\eta(C) = -U_{CC}C/U_C$ is the elasticity of the marginal social utility of consumption. Throughout much of this paper I assume that η is constant.

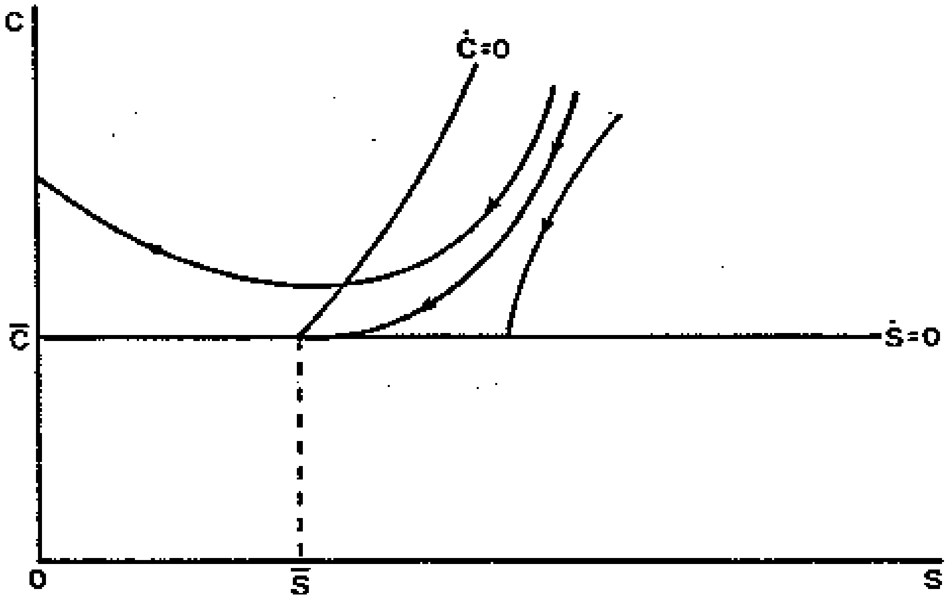
The stationary point $\overline{S}$ is defined by

$$U_S(\overline{S})/\delta = U_C(\overline{C})/a\overline{S}^{-b}\sigma. \tag{2.9}$$

Eq. (2.9) says that deforestation should cease when the marginal consumption benefit of species extinction ($U_C(\overline{C})/a\overline{S}^{-b}\sigma$) just equals the marginal benefit of species conservation ($U_S(\overline{S})/\delta$). Suppose this occurs at date T. Then note that the marginal consumption benefit of species extinction (or, more precisely, the social utility of the consumption obtained from depleting S by one more unit) accrues to generation T only, whereas the marginal benefit of species conservation (the social utility obtained from an additional conserved species) is the integral of the discounted marginal benefits enjoyed by all generations from time T onwards. Eq. (2.9) thus reflects our assumption that the consumption benefits of deforestation are enjoyed only by the generation that fells the forest, whereas preservation benefits are also enjoyed by future generations.

FIGURE 1

Phase Diagram for Model 1



The phase diagram for this problem, shown in Figure 1, characterizes the optimal solution. Before stating the optimal deforestation and biological conservation program formally, consider the following definition.

Definition. *The quantity of wildlife reserves provided by a society is the steady state quantity of wild or undeveloped territory.*

This definition captures the impression that wildlife reserves are not temporary sanctuaries but rather are intended to last forever.

Proposition 1. *If* $\bar{C}$ *and* σ *are positive constants, then the optimal deforestation/conservation program corresponding to problem (2.4) is to choose:* $c_t = 0 \; \forall \; t \geq 0$ *if* $S_0 \leq \bar{S}$, *where* $\bar{S}$ *is defined by (2.9); and* $c_t > 0 \; \forall \; t \in [0,T)$ *and* $c_t = 0 \; \forall \; t \geq T$ *if* $S_0 > \bar{S}$, *where* T *is the (finite) time it takes to reach* $\bar{S}$ *along the optimal path. Furthermore, the optimal approach path to the optimal stationary state is monotonic. If* $S_0 > \bar{S}$ *then* $\dot{C} < 0$ *and* $\dot{c} < 0 \; \forall \; t \in [0,T)$. *The optimal provision of wildlife reserves is* min $(A_0, \bar{A})$, *where* $\bar{A}$ *is calculated as* $\bar{A} = (\bar{S}/\alpha)^{1/\beta}$.

To be clear, these reserves need not be established *at* time T. In fact, there is every reason to set aside the land as soon as possible. For simplicity, I have assumed that all land is identical. But this is clearly not so. Some properties are particularly favorable for wildlife protection. Others can generate huge incomes if developed. Policy makers should identify the best sites for wildlife reserves and protect these before options are foreclosed.

We have thus far dealt with the autonomous case. But our concern is with optimal conservation in an evolving economy. A central question then is this: How will the optimal program change in response to changes in $\overline{C}_t$ and σ_t? The answer will depend not only on the direction of such changes but also on whether the changes are anticipated or unanticipated. Unanticipated changes in $\overline{C}$ and σ are easy to analyze but are of little interest to us here. Our concern in this paper is with *planning*, and so I confine my analysis to anticipated changes. To sharpen our focus, I further restrict our attention to the cases where there is technical progress in the economy. These are clearly the cases of greatest interest.

2.4 *The Case of $\overline{C}_t$ Increasing*

Define $\tilde{C}$ by

$$U_S(S_0)/\delta = U_C(\tilde{C})/aS_0^{-b}\sigma,$$

and suppose that $\overline{C}_t$ rises monotonically. Then the optimal program requires $c_t = 0 \;\forall\, t \geq 0$ if $\overline{C}_0 \geq \tilde{C}$. But if $\overline{C}_0 < \tilde{C}$ things are more complicated. For under these circumstances it becomes clear that planning must be far-sighted. The following lemma will help us solve this more difficult problem.

Lemma. *If $\overline{C}_0 < \tilde{C}$ and if $\overline{C}_t$ rises at a constant rate κ, $\kappa > 0$, then the optimal deforestation/conservation program corresponding to problem (2.4) demands that deforestation cease at a date* T *and species diversity level* S_T *which satisfy*

$$U_S(S_T)/\delta = U_C(\overline{C}_0 e^{\kappa T})/aS_T^{-b}\sigma. \tag{2.10}$$

Proof. See Appendix.

We see at once how (2.10) resembles (2.9). In both the autonomous and nonautonomous cases deforestation should cease at a time when the marginal consumption benefit of species extinction equals the marginal benefit of conservation. The difference is that in the nonautonomous case the equilibrium value for S is not determined uniquely but instead depends on the *date* at which deforestation ceases. This is just as we would expect. For with non-forest-related consumption increasing, if the terminal date T is increased the marginal utility of consumption (with $c_T = 0$) falls. Since the consumption benefit of species extinction is now lower it must be optimal to "consume" fewer species--that is, to conserve more.

Unfortunately, as the problem now stands we have insufficient data to solve (2.4); we require one additional terminal condition. However, we can rewrite problem (2.4) in such a manner that a solution can be obtained. Towards this, let

$$M(S_T,T) = U_C(\overline{C}_0e^{\kappa T})/aS_T^{-b}\sigma - U_S(S_T)/\delta. \tag{2.11}$$

M is the *net* marginal benefit of deforestation at time T.

Our problem becomes

$$\left.\begin{aligned} &\max_{\{c_t\}} \int_0^T U(C_t,S_t)e^{-\delta t}dt,\ \delta > 0 \\ &\text{s.t.}\ \ \mathring{S}_t = -aS_t^{-b}\sigma c_t,\ S_0 > 0 \text{ given} \\ &\qquad C_t = \overline{C}_0e^{\kappa t} + c_t \\ &\qquad M(S_T,T) = 0. \end{aligned}\right\} \tag{2.12}$$

where T and S_T are free. Since we require M = 0, c_t must be chosen nonnegative on [0,T]; therefore, the irreversibility constraint is unnecessary. Our problem then is to choose the deforestation policy that will guide us from the initial state S_0 to the manifold $M(S_T,T) = 0$ in such a manner that social welfare on the interval [0,T] is maximized. Since $M(S_T,T) = 0$ at T the welfare of generations born after T will be maximized by setting $c_t = 0\ \forall\ t > T$. Therefore, if we solve problem (2.12) we have solved problem (2.4) as well.

The Hamiltonian corresponding to problem (2.12) remains (2.5). The necessary conditions for a maximum are (2.7), (2.3), (2.6a) and (2.11). In addition, we have the transversality conditions[12]

$$p_T = \varsigma\partial M/\partial S_T \ = \ \varsigma aS_T^{-b}\sigma[U_S(S_T)b/S_T - U_{SS}(S_T)] \tag{2.13}$$

$$H_T + \varsigma\partial M/\partial T = 0 \ \Rightarrow\ U(\overline{C}_0e^{\kappa T},S_T) = \varsigma\delta\kappa\eta U_C(\overline{C}_0e^{\kappa T}), \tag{2.14}$$

where ς is a number associated with the constraint $M(S_T,T) = 0$. The transversality conditions state that deforestation should cease at a time T when $H_T + p_T(\partial S_T/\partial T) = 0$.

Condition (2.13) replaces the usual transverality condition $p_T = 0$ when S_T is free but T is fixed. Condition (2.14) replaces the condition $H_T = 0$ when S_T is fixed but T is free. In this problem T and S_T are both free but they must satisfy the constraint $M = 0$. M is increasing in S_T and decreasing in T. Thus if we increase T by a small amount we must also increase S_T if the constraint $M = 0$ is to be obeyed. The transversality condition $H_T + p_T(\partial S_T/\partial T) = 0$ thus states that deforestation should cease at a stock S_T and time T when the current flow of utility realized at date T ($U(C_T,S_T)$) less the loss in utility expected to be realized in the future due to the current rate of decrease in species diversity ($p_T\mathring{S}_T$) plus the gain in utility expected to be realized in the future due to the increase in S_T that would be required to make the constraint $M = 0$ hold ($p_T(\partial S_T/\partial T)$) vanishes.

Combining (2.13) and (2.14) and using (2.6a) we obtain

$$U_C(\overline{C}_0e^{\kappa T})/(aS_T{}^{-b}\sigma)^2 =$$

$$U(\overline{C}_0e^{\kappa T},S_T)[U_S(S_T)b/S_T - U_{SS}(S_T)]/[\delta\kappa\eta U_C(\overline{C}_0e^{\kappa T})]. \tag{2.15}$$

Eqs. (2.10) and (2.15) form two equations in two unknowns. Thus the problem can be solved.

What does the optimal approach path look like? When $c_t > 0$, the rate of growth in consumption must obey (2.8). Since it is optimal to set $c_t > 0$ only if $U_C/aS^{-b}\sigma > U_S/\delta$, we know $\mathring{C}/C < 0$. Furthermore, since $\mathring{C} = \kappa\overline{C}_0e^{\kappa t} + \mathring{c}_t$, $\mathring{C} < 0 \Rightarrow \mathring{c} < 0$. Hence, the rate of deforestation must fall monotonically to zero.

The solution is illustrated in Figure 2, where I suppose it is optimal to choose c_0 positive (otherwise the solution is trivial). The optimal solution, denoted by the solid paths, is most easily understood if we compare it to the optimal unconstrained solution, given by the dashed paths in Figure 2. The optimal unconstrained solution is to set $c_t > 0$ on $[0,T'')$ and $c_t < 0$ on $t > T''$. But of course this solution is not feasible. A feasible solution to the constrained problem is to follow the unconstrained path to T', and to then cease deforestation abruptly (T' is calculated by substituting values for S_t on the falling segment of the optimal unconstrained path such that $M = 0$).

The solution (S_T',T') is feasible, but it is not optimal: with c_t discontinuous at T' social welfare could be increased by taking away some consumption from generations born prior to T' and giving that amount to generations born after T'. The optimal constrained solution must therefore follow paths such as the solid paths in Figure 2.

We have therefore proved

Proposition 2. *If η and σ are positive constants and if $\overline{C}_t$ rises at constant rate κ, then the optimal deforestation/conservation policy corresponding to problem (2.4) is to choose:* $c_t = 0$ $\forall\, t \geq 0$ *if* $\overline{C}_0 \geq \tilde{C}$; *and* $c_t > 0\ \forall\, t \in [0,T)$ *and* $c_t = 0\ \forall\, t \geq T$ *if* $\overline{C}_0 < \tilde{C}$, *where* T *and* S_T *must satisfy eqs. (2.10) and (2.15). Furthermore, on* $[0,T)$, $\mathring{C} < 0$ *and* $\mathring{c} < 0$. *The optimal provision of reserves is* min (A_0, A_T), *where* $A_T = (S_T/\alpha)^{1/\beta}$.

Corollary 1. *If deforestation is optimal initially at current values (i.e., if $\overline{C}_0$ is less than $\tilde{C}$) and if κ is positive, then the optimal provision of reserves exceeds the quantity that would be set aside by a planner who ignored growth in the economy's nonforestry sectors.*

2.5 *The Case of σ_t Decreasing*

Now consider the case where $\overline{C}$ is constant but σ_t falls monotonically (i.e., there is technical progress in the forestry sector).

Define $\tilde{\sigma}$ by

$$U_S(S_0)/\delta = U_C(\overline{C})/aS_0^{-b}\tilde{\sigma},$$

and suppose for simplicity that σ_t falls monotonically at a constant rate $\gamma > 0$. Then it is clear that if $\sigma_0 < \tilde{\sigma}$ the economy would wish to begin deforestation immediately but that if $\sigma_0 > \tilde{\sigma}$ it would be optimal to delay deforestation until the marginal consumption benefit of species extinction surpassed the marginal benefit of species conservation. When deforestation becomes optimal, the rate of growth in consumption will be given by

$$\mathring{C}/C = 1/\eta(C)\{\gamma - \delta + U_S aS^{-b}\sigma_0 e^{-\gamma t}/U_C\}, \tag{2.16}$$

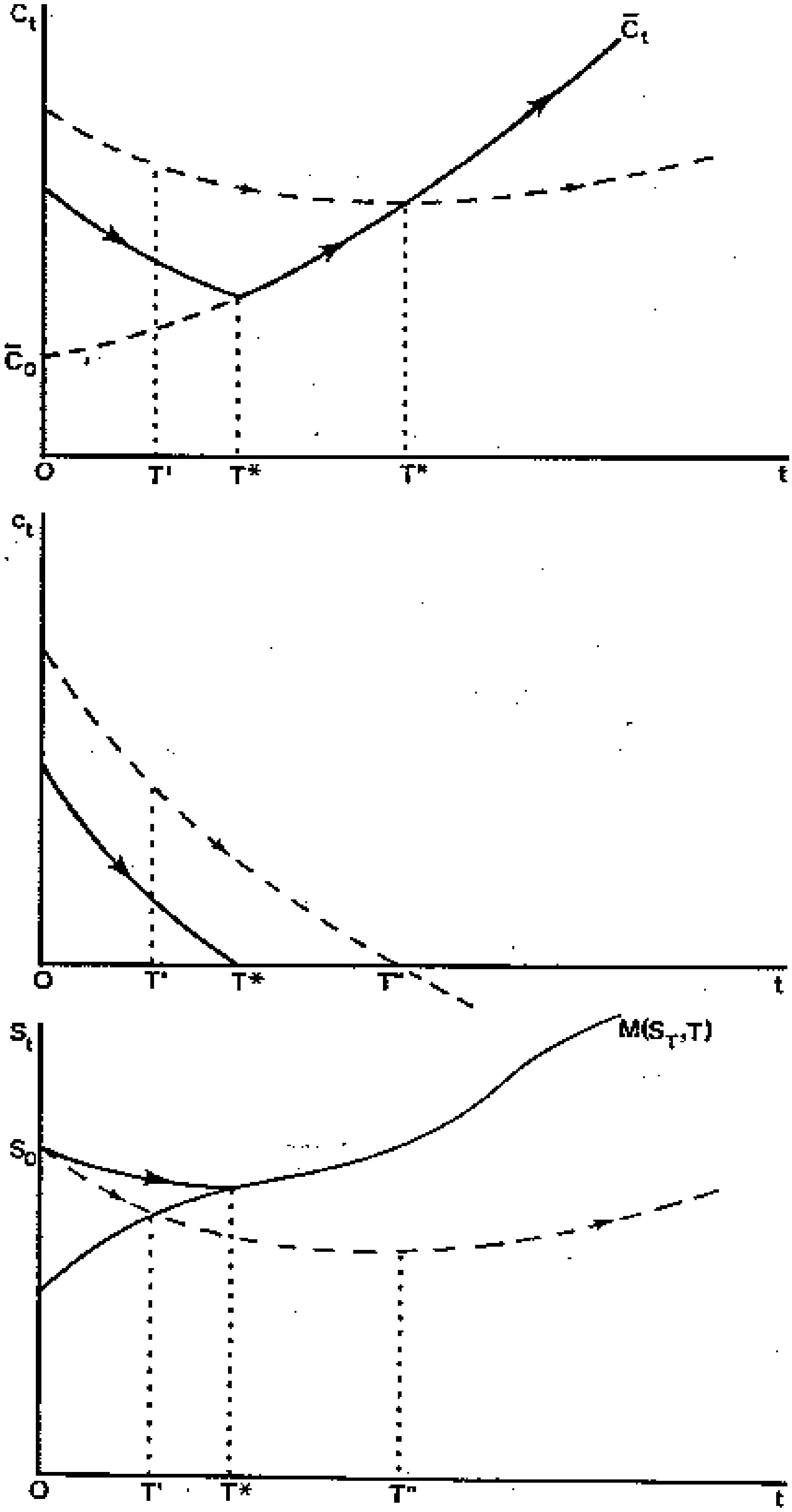
which is positive if $\gamma > \delta$.

We then have

Proposition 3. *If $\overline{C}$ is constant and if σ_t falls at constant rate $\gamma > 0$, then the optimal deforestation/conservation program corresponding to problem (2.4) is to choose:* $c_t = 0\ \forall\, t \in [0,T]$ *and* $c_t > 0\ \forall\, t > T$ *if* $\sigma_0 > \tilde{\sigma}$, *where T is the solution to* $\sigma_0 e^{-\gamma T} = \tilde{\sigma}$; *and* $c_t > 0\ \forall\, t \geq 0$ *if* $\sigma_0 < \tilde{\sigma}$. *In either case it is optimal for the planner to set aside no reserves. Furthermore, if $\gamma > \delta$, then it will be optimal for the economy to set aside no reserves even though consumption is increasing.*

FIGURE 2

Feasible and Optimal Solutions to Problem (2.12)



What does the optimal deforestation policy look like when $\gamma > \delta$? The rate of deforestation, $\sigma_0 e^{-\gamma t} c_t$, is zero on $[0,T]$ and positive $\forall\ t > T$ ($T > 0$ if $\sigma_0 > \bar{\sigma}$, and $T = 0$ if $\sigma_0 < \bar{\sigma}$). Since $\dot{C}/C > 0\ \forall\ t > T$ and $\overline{C}$ is constant, $\dot{c} > 0\ \forall\ t > T$. Proposition 3 tells us that it is optimal to set aside no reserves. But from our assumptions about U we know that it cannot be optimal to deplete the virgin forest in finite time. Hence, the forest must be exhausted asymptotically, even though consumption is increasing--a finding which echoes Krautkraemer's (1985) Proposition 1. Since consumption must be continuous, if $\sigma_0 > \bar{\sigma}$ (that is, if $T > 0$), then when deforestation becomes optimal the rate of deforestation must at first be increasing (hence, at first $\dot{c}/c > \gamma$). But since the forest is finite, the rate of deforestation must eventually fall and asymptote to zero (hence, eventually $\dot{c}/c < \gamma$).

2.6 The Most Likely Case

We have seen that if $\overline{C}_t$ is monotone increasing and σ_t is constant it is optimal to cease deforestation in finite time and to set aside some positive quantity of reserves (Proposition 2). We have also seen that if σ_t is decreasing (at rate γ) and $\overline{C}_t$ is constant it is optimal to set aside no reserves (Proposition 3). Furthermore, if $\gamma > \delta$ then it is not optimal to set aside wildlife reserves even though consumption is increasing. Precisely the same possiblities arise if $\overline{C}_t$ increases and σ_t decreases simultaneously. I will simply state the result.

Proposition 4. *Let* $X = U_S(S_0)/\delta$ *and let* $Y = U_C(\overline{C}_0)/aS_0^{-b}\sigma_0$. *Then if* η (> 0) *is constant;* σ_t *decreases at a constant rate* γ, $\gamma > 0$; *and* $\overline{C}_t$ *increases at a constant rate* κ, $\kappa > 0$, *the optimal deforestation/conservation policy corresponding to problem (2.4) is to choose:* $c_t = 0\ \forall\ t \geq 0$ *if* $X \geq Y$ *and* $\eta\kappa \geq \gamma$; $c_t = 0\ \forall\ t \in [0,\hat{T}]$ *and* $c_t > 0\ \forall\ t > \hat{T}$ *if* $X \geq Y$ *and* $\gamma > \eta\kappa$, *where* $\hat{T}$ *is finite (and determined by* $X = U_C(\overline{C}_0 \exp(\kappa\hat{T}))/aS_0^{-b}\sigma_0 \exp(-\gamma\hat{T})$); $c_t > 0\ \forall\ t \geq 0$ if $X < Y$ and $\eta\kappa < \gamma$; *and* $c_t > 0\ \forall\ t \in [0,T)$ *and* $c_t = 0\ \forall\ t \geq T$ *if* $X < Y$ *and* $\eta\kappa \geq \gamma$, *where* T *and* S_T *in this case must satisfy*

$$U_S(S_T)/\delta = U_C(\overline{C}_0 e^{\kappa T})/aS_T^{-b}\sigma_0 e^{-\gamma T} \tag{2.17}$$

$$U_C(\overline{C}_0 e^{\kappa T})/(aS_T^{-b}\sigma_0 e^{-\gamma T})^2 =$$

$$U(\overline{C}_0 e^{\kappa T}, S_T)[U_S(S_T)b/S_T - U_{SS}S_T]/[\delta U_C(\overline{C}_0 e^{\kappa T})(\eta\kappa - \gamma)]. \tag{2.18}$$

Proof: See Appendix.

We thus see that some positive quantity of wildlife reserves should be set aside if $\eta\kappa \geq \gamma$, irrespective of the initial values of $\overline{C}$ and σ. Notice too that if $X < Y$, $\eta\kappa \geq \gamma$, and $\gamma > \delta$ we know that consumption will be increasing. Furthermore, if deforestation is initially optimal we know that the rate of deforestation (and c_t) must eventually fall (continuously) to zero (at T). However, since $\overset{\circ}{C} = \kappa\overline{C_0}e^{\kappa t} + \dot{c}$ and the rate of change in the rate of deforestation is given by $\dot{c}/c - \gamma$, it is possible that the rate of deforestation may increase before eventually falling.

If $\eta\kappa \geq \gamma > \delta$, then $\overset{\circ}{C}/C > 0$. So here it is optimal to set aside some positive quantity of reserves with consumption increasing and with technical progress in resource extraction. We see, therefore, that Krautkraemer's gloomy conclusion breaks down if non-resource-related consumption is increasing, given η, at a rate sufficiently large to offset the incentive to deforest created by technical progress in resource extraction. To take an example, suppose κ and γ are identical. That is, suppose all sectors of the economy experience the same rate of technical advance. Then as long as η exceeds one, as seems reasonable, it will be optimal to set aside some positive quantity of reserves. Furthermore, provided the rate of technical progress in the economy exceeds δ, as seems plausible, wildlife conservation will not eat all economic growth.

We also have

Corollary 2. *If deforestation is optimal initially at current values and if* $\eta\kappa > \gamma$, *then it is optimal to set aside a quantity of reserves which is greater than the amount that would be set aside by a planner who ignored future changes in* $\overline{C}_t$ *and* σ_t.

3. FARMING THE FOREST (MODEL 2)

Tropical forests are often felled more for cultivatable land than timber. In Model 2 I drop the assumption that deforested land is unproductive and assume instead that deforested land serves as an input in an agricultural production function. In this model I also assume that the timber itself is of no value, that the forest is felled at zero cost, and that $\overline{C} = 0$.

3.1 The Model

Let D_t denote the stock of deforested land at time t. That is,

$$D_t = D_0 + \int_0^t \sigma c_\tau d\tau,$$

where σc_τ denotes the rate of deforestation as defined in (2.2). Let the agricultural sector's production function be given by $F(L_t, D_t)$, where L_t is the agricultural labor force at time t.

If we assume L_t is constant, we can rewrite this production function as $f(D_t)$. Assume $f'(D) > 0$ and $f''(D) < 0$ (this follows naturally from the assumption of a fixed work force).

It will simplify matters if we express f in terms of our original state variable, S. To do this, note that we can write $D_t - D_0 = A_0 - A_t$ if total land area is constant for all t. But A_t can be written as a function of S_t using the species-area relation. Hence, the agricultural production function can be rewritten as $g(S_t) = f[D_t(S_t)]$. It is easy to verify that $g_S = f_D D'(S) < 0$ and $g_{SS} = f_D D''(S) < 0$ for $\beta < 1$.

The forest farming society's problem is the same as (2.4) but with $C_t = g(S_t)$.

3.2. Necessary Conditions

The current value Hamiltonian for this problem remains (2.5). However, the Hamiltonian is now linear in the control, c_t. The necessary conditions include[13]

$$\mathring{p} = \delta p - U_C g_S - U_S - pabS^{-(b+1)}\sigma c \tag{3.1}$$

$$c = 0 \text{ if } p > 0 \tag{3.2a}$$

$$c \geq 0 \text{ if } p = 0. \tag{3.2b}$$

In the stationary state we require $\mathring{S} = 0 \Rightarrow c = 0$; we also require $\mathring{p} = 0$. The stationary state is thus given by

$$\delta\hat{p} - U_C[g(\hat{S})]g_S(\hat{S}) = U_S(\hat{S}). \tag{3.3}$$

The optimal solution requires that S be held fixed at S_0 or, if the solution is interior, that the stationary state be reached as quickly as possible. Since the upper limit placed on c is infinite, this means that if it is optimal to reduce S from its initial level the steady state should be attained *instantly* by means of an impulse control; that is, the solution requires that there be a discontinuous jump in S at the initial moment. There are then two possibilities:

$$c_0 = 0 \text{ if } -U_C[g(S_0)]g_S(S_0) < U_S(S_0) \tag{3.4a}$$

$$c_0 = \infty \text{ if } -U_C[g(S_0)]g_S(S_0) > U_S(S_0). \tag{3.4b}$$

If (3.4a) holds then p must be chosen positive at time zero and $\hat{S} = S_0$. The choice for $\hat{p}$ is determined by

$$\delta\hat{p} - U_C[g(S_0)]g_S(S_0) = U_S(S_0). \tag{3.5}$$

If (3.4b) holds then $\hat{p}$ must equal zero. In this case, S jumps instantly at $t = 0$ to $\hat{S}$, which in this case is determined by

$$- U_C[g(\hat{S})]g_S(\hat{S}) = U_S(\hat{S}). \tag{3.6}$$

Finally, if $-U_C[g(S_0)]g_S(S_0) = U_S(S_0)$ then society is indifferent at the margin between deforesting and leaving the forest in its natural state.

Is the solution is unique? We know that U_C is decreasing in g and that g is decreasing in S; hence, U_C is increasing in S. We also know that g_S is negative and decreasing in S; hence, $-g_S$ is increasing in S. The term $-U_C g_S$ must therefore be increasing in S as well. U_S is of course decreasing in S. Thus under our assumptions the solution is unique.

Proposition 5. *Let* $X = U_S(S_0)$ *and* $Y = -U_C(g(S_0))g_S(S_0)$. *If* $X \geq Y$, *then the optimal deforestation/conservation program corresponding to the forest farming problem is to choose* $c_t = 0 \ \forall \ t$. *If* $X < Y$, *then the optimal program is to choose* $c_0 = \infty$ *and* $c_t = 0 \ \forall \ t > 0$ *such that* S_0 *jumps instantly to* $\hat{S}$.

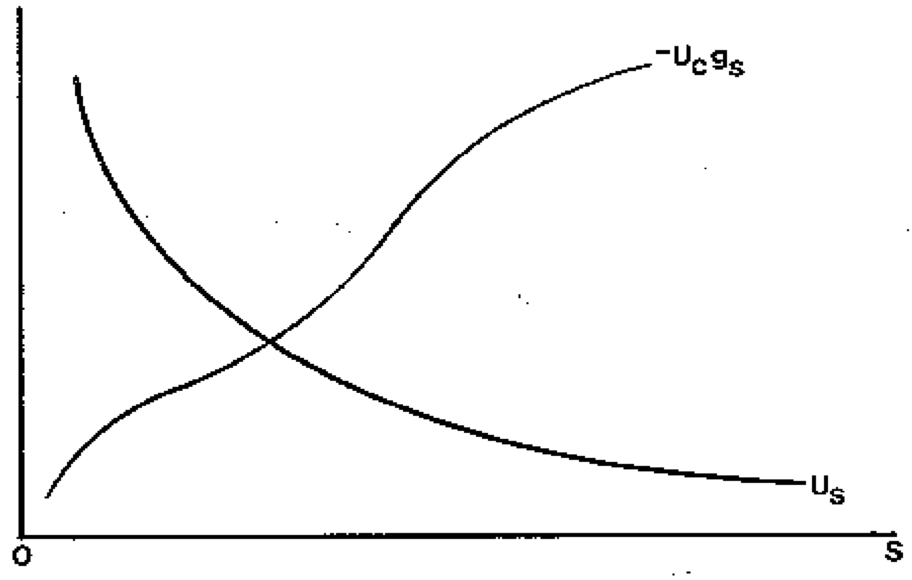
The intuition behind this result is straightforward. $-U_C[g(S_0)]g_S(S_0)$ is the marginal benefit of development at S_0 and $U_S(S_0)$ is the marginal benefit of preservation at S_0. According to (3.4a), if the marginal benefit of preservation exceeds the marginal benefit of development at S_0, then it is optimal to refrain from clearing the forest. Deforestation will decrease S. Since the marginal benefit of preservation decreases in S and the marginal benefit of development increases in S, any deforestation activity will serve only to widen the gap between these marginal benefits. Such a policy cannot be optimal. (See Figure 3.) If, on the other hand, the marginal benefit of preservation at S_0 is less than the marginal benefit of development, then as additional forest land is cleared for farming the gap between these marginal benefits will shrink. The optimal policy is to choose the amount of forest land to clear for farming which shrinks this gap to zero.

In Model 1, consumption of some amount of forest today means that there will be that much less to consume in the future. There is therefore an incentive to spread deforestation over a number of years. In Model 2, the clearing of some amount of forest today means that consumption will be higher not only today but in every future period. There is as a consequence nothing to be gained (and much to lose) by stretching deforestation out over a number of years.

The difference between Models 1 and 2 can also be seen by comparing (2.9) to (3.6). In Model 1, the consumption benefits of deforestation accrue only to the generation that fells the forest, while the preservation benefits accrue to all future generations. This is why eq. (2.9) states that deforestation should cease at a time T when the marginal consumption benefit to generation T of felling the forest equals the integral of the discounted marginal benefits of preservation accruing to all generations born after T. In Model 2 the preservation benefits *and* the consumption benefits of deforestation accrue to all future generations. This is why the social rate of pure time preference does not appear in eq. (3.6).

FIGURE 3

Graphical Solution to Model 2



3.4 Anticipated Technical Progress in Agriculture

If agricultural output is expected to increase monotonically over time because of technical progress, then the optimal policy may still be to undertake deforestation immediately, if at all. To obtain this result, however, we require what is essentially an infinite blocked interval.[14]

Integrating (3.1) gives

$$p_0 = \int_0^\infty (U_C g_S + U_S + pabS^{-(b+1)}\sigma c)e^{-\delta t}dt. \tag{3.7}$$

We know c = 0 on a blocked interval. Using this fact and (3.2) we obtain

$$\hat{S} \leq S_0 \tag{3.8}$$

$$\int_0^\infty \{U_C(g(S_0))g_S(S_0) + U_S(S_0)\}e^{-\delta t}dt \geq 0, \tag{3.9}$$

where (3.8) and (3.9) cannot both hold with strict inequality. If (3.9) holds with strict inequality then $c_0 = 0$ and $\hat{S} = S_0$. Otherwise ($\hat{S} < S_0$) there should be a once-and-for-all jump that brings S instantly to a level that makes (3.9) hold with equality. This result is analogous to that obtained by Fisher, Krutilla and Cicchetti (1972).

What conditions are sufficient to guarantee an infinite blocked interval?

Propostion 6. *Let* $X = U_S(S_0)$ *and let* $Y = -U_C(g(S_0))g_S(S_0)$. *Then, if* η *is constant,* $g(S_t,t) = g(S_t)e^{\omega t}$, *and* $\omega > 0$, *an infinite blocked interval exists if* $X < Y$ *and* $\eta > 1$.

Proof: See Appendix.

We also have

Corollary 3. *If an infinite blocked interval exists, then it is optimal to set aside a quantity of wildlife reserves which is greater than a comparison of current marginal benefits would suggest is optimal.*

Proof: See Appendix.

The myopic planner would select the quantity of habitat to protect by equating $U_S(S_t)$ and $-U_C(g(S_t,t))g_S(S_t,t)$ at every moment. But if $\omega > 0$ and $\eta > 1$, then the marginal consumption benefit of species extinction will fall over time. From the viewpoint of any future date, the decision taken by the myopic planner will be revealed to be suboptimal. The problem is that with deforestation irreversible, it is not feasible to equate the marginal consumption benefit of species extinction and the marginal benefit of species conservation at every instant. The best one can do is to choose the quantity of reserves which equates these marginal benefits on average over the entire planning period. The optimal provision of reserves must be "too large" in the near term and "too small" in the long term when evaluated on the basis of current valuations.

Obviously if $X \geq Y$, deforestation will never be optimal if $\omega > 0$ and $\eta > 1$. But under what conditions will it be optimal to completely exhaust the forest?

Proposition 7. *Let* $X = U_S(S_0)$ *and let* $Y = -U_C(g_0(S_0))g_S(S_0)$. *Then, if* η *is constant,* $g(S_t,t) = g(S_t)e^{\omega t}$, *and* $\omega > 0$, *it will be optimal to set aside no reserves if* $\eta < 1$. *This result holds irrespective of the values taken by* X *and* Y.

Proof: See Appendix.

4. FELLING AND FARMING THE FOREST (MODEL 3)

In this section I assume that the forest is felled for timber as well as cultivatable land. This model thus generalizes the previous two. Model 3 is also more realistic. For logging in remote areas often opens up formerly virgin forests to settlers in search of new agricultural land. As usual I begin by assuming that g is autonomous and σ constant.

4.1 Solution to the Autonomous Case

If the forests are cut down both for timber and cultivatable land, as they are in general, society's problem remains (2.4) but with $C_t = c_t + g(S_t)$. This problem has the same Hamiltonian as (2.5). The only first order condition which changes from Model 1 is (2.7).[15] This now takes the form of (3.1). The dynamic equation for C now becomes

$$\mathring{C}/C = [1/\eta]\{(U_S/U_C)aS^{-b}\sigma - \delta + g_S aS^{-b}\sigma\}, \tag{4.1}$$

which differs from (2.8) by the addition of the (negative) term $g_S aS^{-b}\sigma$.

The phase diagram for this problem is shown in Figure 4. The optimal deforestation policy demands that the rate of deforestation decline over time. This is similar to Model 1. However, as S falls the equilibrium level of consumption rises. This is characteristic of Model 2.

Define $\bar{S}$ by

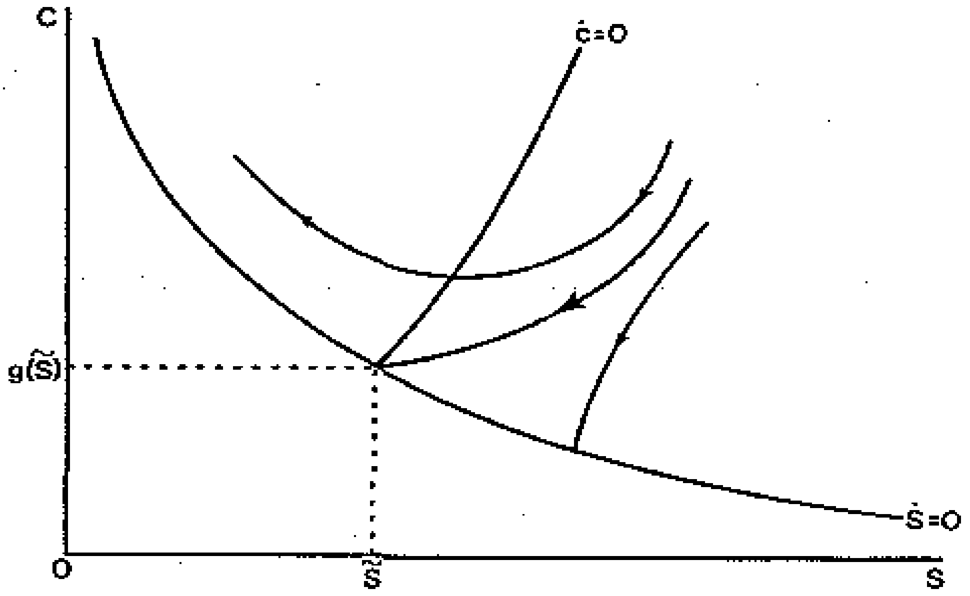
$$U_S(\bar{S})/\delta = U_C(g(\bar{S}))/a\bar{S}^{-b}\sigma - U_C(g(\bar{S}))g_S(\bar{S})/\delta. \tag{4.2}$$

$\bar{S}$ is thus the stationary value for S. Note how (4.2) compares to (2.9) and (3.6). The LHS of eq. (4.2) is the marginal benefit of preservation. The RHS is the marginal consumption benefit of species extinction. This is composed of two terms. The first term on the RHS of (4.2) is the consumption benefit of timber one obtains by felling an area of forest of sufficient size to effect an incremental extinction. The second term is the consumption benefit derived from the agricultural land freed up by the incremental extinction. In Model 1 this second term was zero. In Model 2 the first term on the RHS of (4.2) was zero.

Is $\bar{S}$ unique? The LHS of (4.2) is of course decreasing in S. Some simple calculus shows that the RHS is increasing in S. Hence $\bar{S}$ is unique.

FIGURE 4

Phase Diagram for Model 3



Proposition 8. *If g is autonomous and σ constant, then the optimal deforestation/conservation policy corresponding to Model 3 is to choose:* $c_t = 0\ \forall\ t \geq 0$ *if* $S_0 \leq \tilde{S}$*; and* $c_t > 0\ \forall\ t \in [0,T)$ *and* $c_t = 0\ \forall\ t \geq T$ if $S_0 > \bar{S}$, *where* T *is the (finite) time it takes to reach* $\bar{S}$ *along the optimal path. Furthermore, the approach to the steady-state is monotonic: if* $S_0 > \bar{S}$, *then* $\mathring{C} < 0\ \forall\ t \in [0,T)$. *The optimal provision of wildlife reserves is equal to* min $(A_0,\bar{A})$, *where* $\bar{A} = (\tilde{S}/\alpha)^{1/\beta}$.

4.2 The Full Planning Solution

What policy should be pursued if σ and g are increasing functions of time? Using the *preceding analysis it is easy to prove*

Proposition 9. *Let* $X = U_S(S_0)/\delta$ *and let* $Y = U_C(g(S_0))/aS_0^{-b}\sigma_0 - U_C(g(S_0))g_S(S_0)/\delta$. *Then, if* η *is constant;* $g(S_t,t) = g(S_t)e^{\omega t}$, $\omega > 0$; *and* $\mathring{\sigma}/\sigma = -\gamma$, $\gamma > 0$, *the optimal policy is to choose:* $c_t = 0 \ \forall \ t \geq 0$ *if* $X \geq Y$, $\eta > 1$ *and* $\eta\omega \geq \gamma$; $c_t > 0 \ \forall \ t \in [0,T)$ *and* $c_t = 0 \ \forall \ t \geq T$ *if* $X < Y$, $\eta > 1$ *and* $\eta\omega \geq \gamma$, *where* T *and* S_T *must satisfy*

$$M(S_T,T) = -\ U_S(S_T)/\delta + U_C(g(S_T)e^{\omega T})/(aS_T^{-b}\sigma_0 e^{-\gamma T})$$

$$-\ U_C(g(S_T)e^{\omega T})g_S(S_T)e^{\omega T}/[\omega(\eta - 1) + \delta] = 0$$

and

$$[U_C(g(S_T)e^{\omega T})/(aS_T^{-b}\sigma_0 e^{-\gamma T})]/[U(g(S_T)e^{\omega T},S_T)] = -\ (\partial M/\partial S_T)/(\partial M/\partial T),$$

where

$$\partial M/\partial S_T = (U_{CC}g_S e^{\omega T} + bU_C/S_T)/(aS_T^{-b}\sigma_0 e^{-\gamma T})$$

$$-\ (U_C g_{SS} e^{\omega T} + U_{CC} g_S e^{\omega T} g_S e^{\omega T})/(\omega(\eta - 1) + \delta) - U_{SS}/\delta$$

and

$$\partial M/\partial T = -\ [U_C(\eta\omega - \gamma)/(aS_T^{-b}\sigma_0 e^{-\gamma T}) + [U_C g_S(S_T)e^{\omega T}\omega(\eta - 1)]/[\omega(\eta - 1) + \delta];$$

$c_t > 0 \ \forall \ t \geq 0$ *if* $X < Y$, $\eta < 1$ *and* $\eta\omega < \gamma$; *and* $c_t = 0 \ \forall \ t \in [0,\hat{T}]$ *and* $c_t > 0 \ \forall \ t > \hat{T}$ *if* $X \geq Y$, $\eta < 1$ *and* $\eta\omega < \gamma$, *where* $\hat{T}$ *is finite (and determined uniquely by* $X = U_C(g(S_0)\exp(\omega\hat{T}))/[aS_0^{-b}\sigma_0\exp(-\gamma\hat{T}) - U_C(g(S_0)\exp(\omega\hat{T}))g_S(S_0)\exp(\omega\hat{T})/\delta]$.

A positive quantity of reserves should be set aside if $\eta > 1$ and $\eta\omega \geq \gamma$, irrespective of the initial conditions.

Corollary 4. *Using the definitions in Proposition 9, if* $X < Y$, $\eta > 1$ *and* $\eta\omega > \gamma$, *then it is optimal to set aside a quantity of reserves which is greater than a comparison of the marginal consumption benefit of extinction and the marginal benefit of preservation measured at time T would suggest is optimal. In other words, deforestation should cease at a time when the marginal consumption benefit of deforestation exceeds the marginal benefit of preservation.*

Proof: See Appendix.

In Model 1 a planner who ignored anticipated changes in $\overline{C_t}$ and σ_t would set aside too small a quantity of reserves if $X < Y$ and $\eta\kappa > \gamma$. In Model 2 an infinite blocked interval is guaranteed if $X < Y$ and $\eta > 1$. Here the corresponding requirements are $X < Y$, $\eta\omega > \gamma$ and $\eta > 1$.

If we assume that the condition $\eta > 1$ is met, as seems reasonable,[16] then ω need not exceed γ for Corollary 4 to hold. If $\eta = 5$, for example, then even if ω were one-fourth the size of γ it would be optimal to set aside more reserves than the amount set aside by a planner who ignored anticipated chanes in $\overline{C_t}$ and σ_t. The values taken by γ and ω are therefore of some significance, a matter which I consider in the concluding section.

Note finally that consumption can no longer be guaranteed to increase on $[0,T)$ if $\gamma > \delta$. The reason is roughly as follows. In Model 1 it is optimal for consumption to increase with $\gamma > \delta$ because consumption becomes cheaper over time--less land needs to be deforested to generate a dollar's worth of consumption. In period t-1, consumption per hectare deforested is $1/\sigma_{t-1}$. But if $1/\sigma_t$ grows at a constant rate $\gamma > 0$, then in period t consumption per hectare deforested is $1/\sigma_t = 1/(\sigma_0 e^{-\gamma t}) > 1/\sigma_{t-1}$. On a present value basis, consumption per hectare deforested is higher in period t than in period t-1 if $\gamma > \delta$. When $\overline{C}$ increases this result remains unchanged. But in Model 3 society obtains an additional benefit in deforesting now rather than later: the land can be put into agricultural production. If society postpones deforesting a hectare until next year, this year's agricultural output is lost; and yet output next year is not enhanced by this decision. It is therefore better to deforest earlier rather than later. It will be optimal for consumption to increase on $[0,T)$ only if γ is "large" relative to δ and agricultural productivity at the margin is fairly low.

5. POLICY IMPLICATIONS

One can take two views regarding the policy implications of our results. The traditional view, as expressed for example by Krutilla (1967) and Fisher, Krutilla and Cicchetti (F-K-C, 1972), is that the forces driving our conclusions are exogenous. Under this view our results suggest the following policy recommendation: taking η as given, government policy should be dictated by the values of γ and ω. If one takes this view, the parameters should be estimated empirically, much like F-K-C estimated the rate of technical change in power production when assessing whether the Hells Canyon should be developed as a hydroelectric facility or preserved in its natural state.

However, the parameters γ and ω are unlikely to be straightforward to estimate. This is because the relevant data are often unavailable or at the very least unreliable. Value added data do not distinguish between agriculture and forestry. A significant but unknown amount of agricultural production is not exchanged for money and so is not included in national income statistics. Thirty percent or more of tropical logs are felled illegally and therefore also do not appear in official statistics (FAO, 1982, p. 59). Furthermore, even if the relevant data were available and reliable it is unlikely that they would be suitable. Subsidies are often available for logging, and domestic agricultural prices are often artificially depressed, in developing countries. One can hardly determine an optimal policy based on data that are themselves the product of suboptimal, distortionary policies.

These comments suggest an alternative view, and that is that the values taken by γ and ω are themselves influenced by policy. The regulation of prices and the provision of subsidies affects the immediate returns to permanent agriculture and deforestation, and in the long run alters the incentives to invest in research and development and to adopt new technologies.[17] Policies often influence γ and ω by means other than the price mechanism as well. The World Bank and other aid organizations invest substantial sums in projects designed to increase productivity in agriculture and forestry. In 1986 alone the Bank provided $3.7 billion as loans and credits to agriculture and rural development projects in tropical countries (World Bank, 1986).

At any given time both exogenous and endogenous forces will be shaping γ and ω. To the extent that exogenous forces influence these rates of technical progress, the traditional view of the role for policy will remain valid. But when γ and ω are also influenced by policy, the policy implications of our analysis cut deeper and wider. It is not enough that planning be far-sighted; if wildlife conservation is seen to be a part development, then countries must *actively* invest in projects that will preserve the environment. Put differently, if the results of this paper show that it is not growth *per se* that matters for conservation but the nature of the growth, then policy makers should be seeking to encourage growth of the "right" kind. In the context of deforestation and wildlife conservation, policy should encourage growth in sectors such as permanent agriculture that can choke off the need to deplete the remaining primary rain forests.

The results presented in this chapter suggest that an economy can grow and yet still preserve its environmental resources. This is not to say, however, that wildlife conservation entails no sacrifices. It certainly does. But economic growth and development are not synonomous; if they were it would make no sense to include S in the social utility function. In addition to wildlife conservation, improvements in life expectancy, literacy and health are also development goals. Sri Lanka has a per capita income several orders of magnitude less than that of Mexico, but life expectancy in both countries is about equal. This is because the government of Sri Lanka has actively invested in the fields of health care, food consumption and education. Of course Sri Lanka could have sacrificed life expectancy for the sake of growth, but Sen (1983) has shown that if it had it would have taken somewhere between 58 and 152 years for life expectancy in Sri Lanka to have reached current levels. Sen (1983, p. 753) notes: "If the government of a poor developing country is keen to raise the level of health and the expectation of life, then it would be pretty daft to try to achieve this through raising its income per head, rather than going directly for these objectives through public policy and social change...." This argument bites even harder in the case of wildlife conservation: while a country might be able to afford more conservation in the year 2000 than it can today if it did not set aside reserves, the opportunity to do so at the turn of the century may well have been lost. This is the curse of irreversibility.

APPENDIX

Proof of Lemma. Integrating (2.7) yields

$$p_t e^{-\delta t} = \int_t^{\infty} [U_S + pabS^{-(b+1)}\sigma c] e^{-\delta\tau} d\tau \tag{A.1}$$

since $\lim_{t\to\infty} p_t e^{-\delta t} = 0$.[18]

Using the fundamental theorem of calculus we can write

$$U_C e^{-\delta t}/aS^{-b}\sigma = \int_t^{\infty} \{[U_C(\eta\mathring{C}/C + \delta - b\mathring{S}/S)/aS^{-b}\sigma) e^{-\delta\tau} d\tau. \tag{A.2}$$

Combining (A.1), (A.2) and (2.6) gives

$$\int_t^{\infty} \{[U_S + pabS^{-(b+1)}\sigma c] - [U_C(\eta\mathring{C}/C + \delta - b\,\mathring{S}/S)/aS^{-b}\sigma]\} e^{-\delta\tau} d\tau \geq 0, \tag{A.3}$$

which holds with equality for all $t \geq 0$ if we have an interior solution.

With $\overline{C}_0 < \bar{C}$ and with $\overline{C}_t$ increasing it seems reasonable to suppose that the optimal policy must be to set $c_t > 0$ on an interval $[0,T)$ and $c_t = 0$ on an interval $t \geq T$. (In other words, it must be optimal to cease deforestation in finite time.) On the latter interval (2.6b) holds. With $c = 0$ and $\mathring{S} = 0$, (A.3) becomes

$$\int_t^{\infty} \{U_S - [U_C(\overline{C}_\tau)[\eta\kappa + \delta]/aS^{-b}\sigma]\} e^{-\delta\tau} d\tau \geq 0 \ \forall\ t \geq T \tag{A.4}$$

if we assume $\overline{C}_t$ rises over time at a constant rate κ, $\kappa > 0$. Eq. (A.4) can be taken to mean that the forest should not be felled whenever the discounted stream of preservation benefits brought about by a marginal change in species diversity exceeds the corresponding discounted stream of consumption benefits.

Solving (A.4) we obtain

$$U_S(S_t)/\delta \geq U_C(\overline{C}_0 e^{\kappa t})/aS_t^{-b}\sigma \ \forall\ t \geq T. \tag{A.5}$$

Note in particular that (A.5) holds at date T.

On the interval [0,T) we know $c_t \geq 0$. Hence we must have

$$U_S(S_t)/\sigma \leq U_C(\overline{C}_0 e^{\kappa t})/aS_t^{-b}\sigma \;\forall\; t < T. \tag{A.6}$$

The RHS of inequality (A.6) decreases with t while the LHS increases with t. By assumption S is continuous. Hence, we can rewrite (A.6) as

$$U_S(S_T)/\delta \leq U_C(\overline{C}_0 e^{\kappa T})/aS_T^{-b}\sigma. \tag{A.7}$$

Combining (A.5) and (A.7) we obtain eq. (2.10).

Proof of Proposition 4. If $X \geq Y$, then it is not optimal to deforest at $t = 0$. Deforestation is then never optimal provided $U_S(S_t)/\delta \geq U_C(\overline{C}_t)/aS_t^{-b}\sigma_t \;\forall\; t \geq 0$. With $\overline{C}$ increasing at rate κ and σ decreasing at rate γ, the marginal consumption benefit of species extinction will not rise when $c_t = 0$ provided $\eta\kappa \geq \gamma$. Since the marginal benefit of species conservation is constant when $c_t = 0$ this means that deforestation is never optimal if $X \geq Y$ and $\eta\kappa \geq \gamma$. If $\eta\kappa < \gamma$ then the marginal consumption benefit of species extinction will rise and deforestation will be optimal at some time $\hat{T}$.

If $X < Y$ then deforestation is optimal at $t = 0$. If the marginal consumption benefit of species extinction rises even when $c_t = 0$, as it will if $\eta\kappa < \gamma$, then deforestation will always be optimal. If this marginal benefit does not rise when $c_t = 0$, then it will be optimal to cease deforestation in finite time. The marginal consumption benefit of species extinction will not rise with $c_t = 0$ if $\eta\kappa \geq \gamma$. Eqs. (2.17) and (2.18) correspond to eqs. (2.10) and (2.15). | |

Proof of Proposition 6. An infinite blocked interval will exist if the marginal benefit of preservation can be shown to increase over time relative to the marginal consumption benefit of deforestation. The marginal benefit of preservation is fixed in time. However, the marginal consumption benefit of deforestation is not. If $\omega > 0$, then $-g_S$ rises at rate ω. An infinite blocked interval can exist only if the marginal benefit of development falls over time. Therefore, U_C must fall at a rate greater than ω. Since g rises at rate ω, this means that we require $\eta > 1$. | |

Proof of Corollary 3. If an infinite blocked interval exists, then deforestation should be completed instantaneously at $t = 0$ such that (3.9) holds with equality. Denote the solution S^*. We then have

$$U_S(S^*)/\delta = -U_C(g(S^*))g_S(S^*)/[\omega(\eta - 1) + \delta].$$

By Proposition 6, an infinite blocked interval exists if $\omega > 0$, $X < Y$ and $\eta > 1$. But under these conditions we have $U_S(S^*) < -U_C(g(S^*))g_S(S^*)$ at $t = 0$. | |

Proof of Proposition 7. Again we need only prove that the marginal benefits of preservation are falling over time relative to the marginal consumption benefits of deforestation. Since $-g_S$ rises at rate ω we require that U_C fall at a rate less than ω. Since g rises at rate ω, this means that η must be less than one. | |

Proof of Corollary 4. If the above conditions hold, then the optimal conservation of biological diversity S_T must satisfy

$$U_S(S_T)/\delta = U_C(g(S_T)e^{\omega T})/(aS_T^{-b}\sigma_0 e^{-\gamma T}) - [U_C(g(S_T)e^{\omega T})g_S(S_T)e^{\omega T}]/[\omega(\eta - 1) + \delta].$$

But then

$$U_S(S_T)/\delta < U_C(g(S_T)e^{\omega T})/(aS_T^{-b}\sigma_0 e^{-\gamma T}) - [U_C(g(S_T)e^{\omega T})g(S_T)e^{\omega T}/\delta].$$ | |

NOTES

1. While the literature has focused almost exclusively on problems of overexploitation, habitat destruction has caused almost all of the 500 extinctions known to have occurred in the U.S. since European settlers first arrived. Two-thirds of these extinctions occurred in tropical Hawaii. See Harrington and Fisher (1982, p. 124).

2. Myers (1986, p. 408). Myers does not state how he arrived at this figure. However, the figure can be obtained from the species-area relation described in the next section. If $\beta = 0.3$ then the preservation of ten percent of habitat will conserve 50 percent of species.

3. I assume that the society ignores any benefits of biological conservation accruing to the citizens of other nations. These benefits are probably very large (Harrington and Fisher, 1982). But the moment we admit these benefits our problem becomes a game and not simply an exercise in planning. One way in which the interests of external parties can be reflected in domestic wildlife conservation is through the mechanism of "debt-for-nature" swaps (see Hansen, 1988). Another mechanism is the World Heritage Convention, which can offer poorer countries financial assistance for protecting "outstanding" wildlife habitats.

4. Following Frankel and Soulé (1981, p. 4), "conservation" is taken here to mean providing not only for the maintenance of species but also for their continuing evolution. By this definition zoos and germplasm storage facilities *preserve* species; only wildlife reserves *conserve* species.

5. This is the simplest notion of species diversity. There are others. For example, species diversity can be defined in terms of the distribution of the number of species according to their relative abundances. Note here also that species diversity appears to be the most important single criterion used in choosing sites for wildlife reserves. In a sample of 17 wildlife conservation evaluation studies published betweeen 1971 and 1981, 16 used diversity as a criterion. See Usher (1986).

6. Dasgupta (1982, Chapter 10) and Fisher and Krutilla (1985) have also demonstrated this for the example of deforestation and species extinction.

7. I refer in this paper only to Krautkraemer's first model.

8. In an analysis of 100 species-area relations, Connor and McCoy (1979) found only three with a $\beta < 0$ and two with a $\beta > 1$; the average was about 0.31.

9. See Boecklen and Gotelli (1984) for cautionary remarks on the use of the species-area relation in directing conservation policies.

10. See, e.g., Diamond (1973). Two points should be noted. First, if small reserves are set aside, relaxation time will be much faster. Most reserves are in fact relatively small. Second, species extinction probably follows a logistic path, increasing rapidly at first and then at an ever diminishing pace until equilibrium is finally attained (see, e.g., Terborgh, 1976). Thus the majority of extinctions will occur fairly quickly.

11. Since $H_{CC} < 0$ and $H_{SS} < 0$, the transversality conditions,

$$\lim_{t\to\infty} e^{-\delta t}p_tS_t = 0, \ \lim_{t\to\infty} e^{-\delta t}p_t \geq 0$$

are sufficient for a maximum.

12. I am naturally assuming that the constraint $T \in (0,\infty)$ is satisfied. For a more general treatment of the transversality conditions corresponding to this type of problem, see Seierstad and Sydsæter, 1987, p. 180).

13. Observe that $H_{SS} = U_Cg_{SS} + U_{SS} - pab(b+1)S^{-(b+2)}\sigma c < 0$ for $\beta < 1$, and so the transversality conditions corresponding to problem (2.4) will be sufficient for an optimum here if we assume $\beta < 1$. As noted in Section 1, virtually all empirical studies of the species-area relation obtain an estimate for β that is less than one.

14. That is, we require that (3.4a) hold for all t positive. See Arrow (1968).

15. Since $H_{SS} < 0$ for $\beta < 1$, the transversality conditions for Model 1 will be sufficient for a maximum if we continue to assume $\beta < 1$.

16. See Stern (1977) for a survey of estimates of the elasticity of the marginal utility of income.

17. Hayami and Ruttan (1985) argue that agricultural development in developing countries has been poor mainly because government policies have impeded rather than induced appropriate technical and institutional innovations.

18. Our assumptions regarding instantaneous social utility imply that it will never be optimal to fully deplete S (as long as $\overline{C} > 0$). By the transversality conditions, therefore, $\lim_{t \to \infty} p_t e^{-\delta t} = 0$.

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