

Appendix A: Theoretical Model

Definitions

Output of the agricultural sector (q) is given by the production function:

$$q = q(n_1, k_1, Z_1, T_1, \theta W_1) \quad (\text{A.1})$$

where:

n_1 : agricultural labor,
 k_1 : agricultural capital,
 Z_1 : environmental input,
 T_1 : “effective” stock of land used in agricultural production,
 θ : ground-water extraction rate, and
 W_1 : stock of ground-water.

Output of the non-agricultural sector (x) is given by the production function:

$$x = x(n_2, k_2, Y, L_2) \quad (\text{A.2})$$

where:

x : non-agricultural good,
 n_2 : non-agricultural labor,
 k_2 : non-agricultural capital,
 Y : water quality effect on non-agricultural production ($\partial x / \partial Y > 0$), and
 L_2 : land used in non-agricultural production.

Household or non-market production (h) is given by:

$$h = h(n_h, x_h, k_h) \quad (\text{A.3})$$

where:

n_h : household labor,
 x_h : intermediate inputs used in household production,
 k_h : household capital.

The household production function includes non-marketed activities beyond those related to the environment.

The equation of motion for the effective productivity of farmland is

$$\dot{T}_1 = \gamma \left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1} \right) L_1 - dL_1 \quad (\text{A.4})$$

where land can be managed (improved) by adding labor, intermediate inputs (fertilizer), and capital

according to a management function

$$\gamma = \gamma\left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1}\right) \quad (\text{A.5})$$

where:

- γ : is a rate of appreciation,
- n_3 : labor used in managing land,
- x_3 : intermediate inputs used in managing land,
- k_3 : capital used in managing land, and
- d : soil erosion rate.

The management function $\gamma(\cdot)$ is assumed linearly homogeneous in its arguments $(n_3/L_1, x_3/L_1, k_3/L_1)$ and in $n_3, X_3,$ and k_3 .

The equation of motion for water quality is

$$\dot{Y} = [a - D(Z_1) + \eta(n_4, x_4, k_4)]Y \quad (\text{A.6})$$

where the impact of agricultural production on water quality is represented by:

$$D = D(Z_1) \quad (\text{A.7})$$

Water quality can be managed (improved) by adding labor, intermediate inputs, and capital:

$$\eta = \eta(n_4, x_4, k_4) \quad (\text{A.8})$$

where:

- n_4 : labor used in managing water quality,
- x_4 : intermediate inputs used in water quality,
- k_4 : capital used in managing water quality, and
- a : natural repair of water quality.

The damage function $D(Z_1)$ and the repair function $\eta(\cdot)$ are also assumed linearly homogeneous in their respective arguments.

Our equation of motion for the stock of ground-water is

$$\dot{W}_1 = [\psi - \theta(n_5, x_5, k_5)]W_1 \quad (\text{A.9})$$

where the extraction of ground-water for use in agriculture is represented by:

$$\theta = \theta(n_5, x_5, k_5) \quad (\text{A.10})$$

where:

- n_5 : labor used in extracting ground-water,
- x_5 : intermediate inputs used in extracting ground-water, and
- k_5 : capital used in extracting ground-water, and
- ψ : the rate ground-water is **replenished**.¹⁴

As discussed in the text, each natural capital asset is regenerative or renewable but could be exhausted from over-use. The net rate of regeneration, as captured by the equations of motion is a function of the intensity of use, the effectiveness of management to offset the intensity of use of an asset, the level of the stock of the resource itself, and the natural rate of regeneration.

The Model

Social welfare (U) is defined as a function of final goods and services (q, x_2), household production (h), an index of water quality (Y), land in its natural state (L_0), land used in agriculture (L_1), and leisure (n_7). The social planner's goal is to maximize:

$$\text{Max} \int_0^{\infty} e^{-rt} U(q, x_2, h, Y, L_0, L_1, n_7) dt \quad (\text{A.11})$$

where:

- q : agricultural output (final good),
- x_2 : non-agricultural (final) goods and services,
- h : household production,
- Y : index of water quality, ($\partial U / \partial Y > 0$)¹⁵
- L_0 : unused land (natural state),
- L_1 : land used in agriculture,
- n_7 : leisure, and
- r : social discount rate

subject to the equations of motion for the stock of effective land, surface-water quality, and the

¹⁴ This is a simplified representation. The ground-water replenishment rate ψ is a function of precipitation, inflows and outflows, and the return flow of water extracted for agricultural uses.

¹⁵ Corner solutions are problematic. For perfect water quality human efforts at improvement have no impact. With no water quality agriculture creates no added damages. We assume these situations are unique so that our results are not affected.

stock of ground-water:

$$\dot{L}_1 = \gamma \left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1} \right) L_1 - dL_1 \quad (\text{A.12})$$

$$\dot{Y} = [a - D(Z_1) + \eta(n_4, x_4, k_4)] Y \quad (\text{A.13})$$

$$\dot{W}_1 = [\psi - \theta(n_5, x_5, k_5)] W_1 \quad (\text{A.14})$$

In addition to natural capital, there are equations of motion for each of our six types of reproducible capital:

$$\dot{k}_l = I_l - \delta_l k_l \quad \text{for } l = 1, \dots, 6 \quad (\text{A.15})$$

where: I_l represents gross investment in the l th type of reproducible capital and δ_l represents the depreciation rate for each type of reproducible capital.

A materials balance equation and constraints for labor and land complete the model:

$$x(n_2, k_2, Y, L_2) = x_2 + x_3 + x_4 + x_5 + x_6 + I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \quad (\text{A.16})$$

$$N = \sum_{i=1}^7 n_i \quad (\text{A.17})$$

$$L = \sum_{i=0}^2 L_i \quad (\text{A.18})$$

The materials balance equation accounts for the output of the non-agricultural sector, x , in the economy. For example, some non-agricultural output goes to final non-agricultural consumption goods and services x_2 . Non-agricultural output is also used as investment goods I_i ; inputs that go into managing the stock of effective farmland x_3 , water quality x_4 , and the stock of ground-water x_5 ; and as inputs in the household production function x_6 .

The current value Hamiltonian in flow of output terms is:

$$\begin{aligned}
 H = & U [q(n_1, k_1, Z_1, T_1, \theta W_1), \\
 & x(n_2, k_2, Y, L_2) - x_3 - x_4 - x_5 - x_6 - l_1 - l_2 - l_3 - l_4 - l_5 - l_6, \\
 & h(n_8, x_8, k_8), Y, L_0, L_1, n_7] \\
 & + \rho_3 [\gamma (\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1}) L_1 - dL_1] \\
 & + \rho_4 [a - D(Z_1) + \eta(n_4, x_4, k_4)] Y \\
 & + \rho_5 [\Psi - \theta(n_5, x_5, k_5)] W_1 \\
 & + \sum_{i=1}^6 \mu_i [I_i - \delta K_i] \\
 & - \omega [\sum_{i=1}^7 n_i - M] \\
 & - \Omega [\sum_{i=0}^2 L_i - L]
 \end{aligned} \tag{A.19}$$

where ρ_i , μ_i , ω_i , and Ω , are co-state variables.

The Measurement of Net Welfare

The Hamiltonian along the optimal trajectory is the national welfare measure in utility terms (Mäler, 1991; Hung, 1993). The linear approximation of the Hamiltonian along the optimal path is the exact correspondence to the net national welfare measure. It measures the current utility of consumption (of goods and services and environmental services) and the present value of the future utility stream from current stock changes. This follows because stock prices measure the present value of the future contribution to welfare from a marginal increase in the stocks.

Net welfare is measured as

$$\begin{aligned}
NWM = & \frac{\partial U}{\partial q} \left[\frac{\partial q}{\partial n_1} n_1 + \frac{\partial q}{\partial k_1} k_1 + \frac{\partial q}{\partial Z_1} Z_1 + \frac{\partial q}{\partial T_1} T_1 + \frac{\partial q}{\partial W_1} W_1 \right] \\
& + \frac{\partial U}{\partial x_2} \left[\frac{\partial x}{\partial n_2} n_2 + \frac{\partial x}{\partial k_2} k_2 + \frac{\partial x}{\partial Y} Y + \frac{\partial x}{\partial L_2} L_2 \right] \\
& - \frac{\partial U}{\partial x_2} [x_3 + x_4 + x_5 + x_6 + l_1 + l_2 + l_3 + l_4 + l_5 + l_6] \\
& + \frac{\partial U}{\partial h} \left[\frac{\partial h}{\partial n_6} n_6 + \frac{\partial h}{\partial x_6} x_6 + \frac{\partial h}{\partial k_6} k_6 \right] + \frac{\partial U}{\partial L_0} L_0 + \frac{\partial U}{\partial L_1} L_1 + \frac{\partial U}{\partial Y} Y + \frac{\partial U}{\partial n_7} n_7 \\
& + \sum_{i=1}^6 \mu_i [l_i - \delta k_i] \\
& + \rho_3 \left[\gamma \left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1} \right) L_1 - dL_1 \right] \\
& + \rho_4 [s - D(Z_1) + \eta(n_4, x_4, k_4)] Y \\
& + \rho_5 [\psi - \theta(n_5, x_5, k_5)] W_1
\end{aligned} \tag{A.20}$$

Recognizing the relationship between net welfare and net product, equation (A.20) can be viewed as the flow of output or expenditure approach to income accounting. That is, GDP = consumption + gross investment and NNP = GDP - capital depreciation = consumption + net investment. The first line in equation (A.20) represents final expenditures on the agricultural good. We assume all output of the agricultural sector (food) is a final consumption good, thus abstracting from the food processing sector. The second line captures total expenditures on the non-agricultural good x . Some x is, however, used as intermediate goods or inputs into the production of other goods. The expenditures on x that do not represent final consumption are subtracted in the third line of equation (A.20). The second and third line, therefore, capture expenditures on the

final consumption of the non-agricultural good.

The fourth line of equation (A.20) captures implied expenditures on the household product, natural-state land, aesthetic farm landscape, water quality, and leisure. The fourth line that contains most of the extensions to the traditional GDP accounts. However, some of these expenditures may already be included in the GDP accounts. For example, government expenditures to improve water quality and explicit expenditures by environmental groups to save natural-state land such as old growth forests already show up in the accounts. The fifth line of equation (A.20) captures net investment in each of the six types of physical capital, while the last three lines report net investment in the three types of natural capital. The gross investment components of these last three lines are also extensions of the GDP accounts.

The first three lines of equation (A.20) and the gross investment components of line 5 sum to the traditional measure of GDP. Adding line 4 and the gross investment components of lines 6, 7, and 8 gives the extended GDP measure. Lines 1, 2, 3, and 5 sum to the traditional NNP measure. The entire expression given by equation (A.20) represents the extended NNP measure.

Two final observations stemming from equation (A.20) are worth noting. First, concern for sustainability and properly valuing natural resource depletion leads to extending the accounts by including lines 6, 7, and 8 of equation (A.20). Second, concern with including “non-market” goods (e.g. housework, land in its natural state, rural landscape, water quality, and leisure) in the accounts leads to expanding the accounts by including line 4.

Appendix B: The Optimality Conditions

The optimality conditions are obtained by partially differentiating the Hamiltonian (equation A.19) with respect to the control and state variables. The control variables are the seven uses of labor, the uses of the manufactured output x , gross investment in the six type of reproducible capital, the three uses of land, and the level of water pollution, Z_1 . For labor, the optimality conditions are:

$$\frac{\partial H}{\partial n_1} = \frac{\partial U}{\partial q} \frac{\partial q}{\partial n_1} - \omega = 0 \quad (\text{B.1})$$

$$\frac{\partial H}{\partial n_2} = \frac{\partial U}{\partial x_2} \frac{\partial x}{\partial n_2} - \omega = 0 \quad (\text{B.2})$$

$$\frac{\partial H}{\partial n_3} = \rho_3 \frac{\partial \gamma}{\partial n_3} - \omega = 0 \quad (\text{B.3})$$

$$\frac{\partial H}{\partial n_4} = \rho_4 \frac{\partial \eta}{\partial n_4} \gamma - \omega = 0 \quad (\text{B.4})$$

$$\frac{\partial H}{\partial n_5} = \frac{\partial U}{\partial q} \frac{\partial q}{\partial \theta} \frac{\partial \theta}{\partial n_5} W_1 - \rho_5 \frac{\partial \theta}{\partial n_5} W_1 - \omega = 0 \quad (\text{B.5})$$

$$\frac{\partial H}{\partial n_6} = \frac{\partial U}{\partial h} \frac{\partial h}{\partial n_6} - \omega = 0 \quad (\text{B.6})$$

$$\frac{\partial H}{\partial n_7} = \frac{\partial U}{\partial n_7} - \omega = 0 \quad (\text{B.7})$$

Equations (B.1), (B.2), and (B.6) indicate the value of the marginal product of labor is equalized across the three production sectors. This value ω , the shadow wage rate, is also the marginal value of leisure, equation (B.7), and the marginal value of labor in enhancing land, equation (B.3), repairing water quality, equation (B.4), and depleting ground-water stocks, equation (B.5).

The manufactured good x can be directly consumed (x_2), used as intermediate input or for

investment. The optimality conditions for x as an intermediate input for improving land, water quality, and depleting ground-water stocks are:

$$\frac{\partial H}{\partial x_3} = -\frac{\partial U}{\partial x_2} + \rho_3 \frac{\partial \gamma}{\partial x_3} = 0 \quad (\text{B.8})$$

$$\frac{\partial H}{\partial x_4} = -\frac{\partial U}{\partial x_2} + \rho_4 \frac{\partial \eta}{\partial x_4} \gamma = 0 \quad (\text{B.9})$$

$$\frac{\partial H}{\partial x_5} = \frac{\partial U}{\partial q} \frac{\partial q}{\partial \theta} \frac{\partial \theta}{\partial x_5} W_1 - \frac{\partial U}{\partial x_2} - \rho_5 \frac{\partial \theta}{\partial x_5} W_1 = 0 \quad (\text{B.10})$$

These conditions show that the value of the marginal product of the manufactured good in each of its intermediate uses must equal $\partial U/\partial x_2$, the opportunity cost of direct consumption.

The optimality conditions for x as investment in reproducible capital are:

$$\frac{\partial H}{\partial I_l} = -\frac{\partial U}{\partial x_2} + \mu_l = 0 \quad (l = 1, \dots, 6). \quad (\text{B.11})$$

As with intermediate goods, the marginal value of investment in each type of capital (μ_l) must equal the marginal value of the consumption good x_2 ($\partial U/\partial x_2$).

Partially differentiating with respect to each land type determines the distribution of land across sectors:

$$\frac{\partial H}{\partial L_0} = \frac{\partial U}{\partial L_0} - \Omega = 0 \quad (\text{B.12})$$

$$\frac{\partial H}{\partial L_1} = \frac{\partial U}{\partial L_1} + \rho_3 [\gamma(\cdot) - \frac{\partial \gamma}{\partial A} \frac{n_3}{L_1} - \frac{\partial \gamma}{\partial B} \frac{x_3}{L_1} - \frac{\partial \gamma}{\partial C} \frac{k_3}{L_1}] - \rho_3 d - \Omega = 0 \quad (\text{B.13})$$

where $A = n_3/L_1$, $B = x_3/L_1$, and $C = k_3/L_1$. Because γ is assumed homogeneous of degree 1 in A , B , and C , equation (B. 13) reduces to:

$$\frac{\partial H}{\partial L_1} = \frac{\partial U}{\partial L_1} - \rho_3 d - \Omega = 0 \quad (\text{B.14})$$

The remaining use of land, L_2 , is chosen so that

$$\frac{\partial H}{\partial L_2} = \frac{\partial U}{\partial x_2} \frac{\partial x}{\partial L_2} - \Omega = 0 \quad (\text{B.15})$$

Recall the unique character of each type of land. Land in its natural state, L_0 , has only a direct welfare effect and no productivity effect. Land used in non-agricultural production, L_2 , affects welfare indirectly as an input in production. Farmland, L_1 , however, has both a productivity effect in agriculture and a direct welfare effect in utility in terms of providing rural landscape.

The shadow value Ω gives the price of land in its natural state. This price exceeds the direct marginal contribution of farmland to welfare because some farmland erodes, while pristine land and non-agricultural land are assumed not to erode. This price Ω also equals the value of the marginal product of land in the non-agricultural sector.

An additional control variable to consider is Z_1 , the environmental input to agricultural production. The optimality condition for this variable is:

$$\frac{\partial H}{\partial Z_1} = \frac{\partial U}{\partial q} \frac{\partial q}{\partial Z_1} - p_4 \frac{\partial D}{\partial Z_1} Y = 0 \quad (\text{B.16})$$

Here the choice of Z_1 can be interpreted as the optimal use of an environmental input, water quality. Equation (B.16) indicates that the value of the marginal product of water pollution in agricultural production is equal to the marginal change in welfare from increasing water quality.

The optimality conditions associated with the state variables describe the choice of stock levels for the six types of physical capital and the three types of natural capital. For the physical capital variables, the optimality conditions are

$$\frac{\partial U}{\partial q} \frac{\partial q}{\partial k_1} = (r + \delta_1)\mu_1 - \dot{\mu}_1 \quad (\text{B.17})$$

$$\frac{\partial U}{\partial x_2} \frac{\partial x}{\partial k_2} = (r + \delta_2)\mu_2 - \dot{\mu}_2 \quad (\text{B.18})$$

$$\rho_3 \frac{\partial Y}{\partial k_3} = (r + \delta_3)\mu_3 - \dot{\mu}_3 \quad (\text{B.19})$$

$$\rho_4 \frac{\partial \eta}{\partial k_4} Y = (r + \delta_4)\mu_4 - \dot{\mu}_4 \quad (\text{B.20})$$

$$\frac{\partial U}{\partial q} \frac{\partial q}{\partial \theta} \frac{\partial \theta}{\partial k_5} W_1 - \rho_5 \frac{\partial \theta}{\partial k_5} W_1 = (r + \delta_5)\mu_5 - \dot{\mu}_5 \quad (\text{B.21})$$

$$\frac{\partial U}{\partial h} \frac{\partial h}{\partial k_6} = (r + \delta_6)\mu_6 - \dot{\mu}_6 \quad (\text{B.22})$$

These conditions demonstrate that the value of the marginal product of reproducible capital in each activity (including land enhancement, water quality repair, and diminishing ground-water stocks) is equal to a rental price of capital. Because the investment good is treated as the undifferentiated intermediate good, $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6$. However, the rental prices may differ because of different economic depreciation rates.

The final optimality conditions involve our natural capital stocks: effective farmland, water quality, and ground-water stocks. These conditions are:

$$\frac{\partial U}{\partial q} \frac{\partial q}{\partial T_1} = r\rho_3 - \dot{\rho}_3 \quad (\text{B.23})$$

$$\frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2} \frac{\partial x}{\partial Y} = (r\rho_4 - \dot{\rho}_4) - \rho_4[a - D(Z_1) + \eta(n_4, k_4, x_4)] \quad (\text{B.24})$$

$$\frac{\partial U}{\partial q} \frac{\partial q}{\partial W_1} \theta = (r\rho_5 - \dot{\rho}_5) - \rho_5[\Psi - \theta(n_5, k_5, x_5)] \quad (\text{B.25})$$

Equation (B.23) has a straight forward interpretation as rental price of effective farmland.

Unlike the conditions for physical capital stocks, equation (B.23) does not have a depreciation rate. Soil erosion, which is similar to a physical depreciation rate, is already captured in equation (B.23). The optimality condition for the stock of water quality is also a rental rate similar to those for physical capital. However, given the form of equation (B.24), this rental rate is adjusted for water quality appreciation rather than depreciation.

Finally, it is interesting to compare the shadow values for reproducible capital to natural capital. For example, a unit of reproducible capital that is used to in the agricultural sector has a value:

$$\mu_1 = \frac{\frac{\partial U}{\partial q} \frac{\partial q}{\partial k_1}}{(r + \delta_1)} + \frac{\dot{\mu}_1}{(r + \delta_1)} \quad (\text{B.26})$$

or

$$\mu_1(t) = \int_t^{\infty} e^{-(r + \delta_1)(s-t)} \frac{\partial U}{\partial q} \frac{\partial q}{\partial k_1}(s) ds \quad (\text{B.27})$$

In other words, the value of a unit of reproducible capital in time t is equal to the discounted value of the future services it will provide in terms of agricultural output. An increase in the discount rate (r) or the rate of depreciation (δ_1) will reduce the value of capital.

Our shadow value of natural capital has similar characteristics. For example, a unit of water quality has a shadow value:

$$p_4 = \frac{\frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2} \frac{\partial x}{\partial Y}}{[a - D(Z_1) + \eta(n_4, k_4, x_4)]} + \frac{\dot{p}_4}{[a - D(Z_1) + \eta(n_4, k_4, x_4)]} \quad (\text{B.28})$$

or

$$p_4(t) = \int_t^{\infty} e^{-(r + a + \alpha Z_1) - \eta(n_4, k_4, x_4)(s-t)} \left(\frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2} \frac{\partial x}{\partial Y}(s) \right) ds \quad (\text{B.29})$$

For natural capital, an increase in the natural rate of regeneration or an increase in human attempt to improve the quality of water reduces the discount rate and increases the shadow value associated with water quality. In addition, unlike reproducible capital, the shadow value captures the discounted value of water quality to both consumers $(\partial U/\partial Y)$ and producers of the manufactured good $[(\partial U/\partial x_2)(\partial x/\partial Y)]$.

Some Issues Related to Ecological and Economic Modeling of Ecosystem
“Landscapes”

Nancy Bockstael and Jackie Geoghegan

Discussion paper for 1994 AERE Workshop Participants

In this discussion paper are outlined some of the issues and problems we are encountering in a multidisciplinary (ecological and economics) research endeavor sponsored by EPA. The “vignettes” that follow correspond to sections of our presentation and are supplied here in hopes of stimulating discussion and some good ideas. After a brief description of the project, we address each of the following topics in turn:

- the general structure of an ecological-economic model
- the treatment of spatial data in economic analysis
- modeling landscape reconfiguration.

Overview of Project

This work is sponsored by EPA’s OPPE (Mary Jo Kealy and Michael Brody, project officers.) The researchers include ecologists from the Center for Estuarine and Environmental Studies, U. of Maryland (R. Costanza, W. Boynton L. Wainger) and economists from the Department of Agricultural and Resource Economics (N. Bockstael, I. Strand, J. Geoghegan K. Bell).

The immediate goal of the project is to model the spatial configuration and dynamic evolution of an ecological landscape by capturing ecological fictions, human behavior, and their interaction. This will provide a means of describing the evolving landscape under different policy scenarios on land use controls, non-point source pollution regulations, etc. Also, the effort may ultimately provide some insights into the valuation of ecosystems - and even the much debated issue of sustainability, although neither of these topics will be given much attention here.

The watershed chosen for the case study is the Patuxent watershed in southern Maryland, one of the nine river basins of the Chesapeake Watershed and covering about 1,000 square miles. This includes parts of seven counties, ranging from the Washington DC suburbs and the state capital to predominantly rural counties at varying stages of development. Significant portions of land within the area are dedicated to each of the major land uses - commercial, high/medium/low density residential, agriculture (mainly cropland and pasture, with few orchards), forests (both deciduous and coniferous), and wetlands. There are a few industrial centers and some military establishments. It is worth noting that agriculture comprises 32% of the watershed’s land and forests comprise 46%.

We begin with a very cursory description of a generic ecological landscape model developed by Costanza and Maxwell (1991), because it serves as the starting point for the research effort. The term “landscape” model which we use throughout has come to mean a spatially-articulated dynamic model of an area of land. Traditional ecological studies, similar to traditional economic studies, assumed that systems and actors were spatially homogeneous. Landscape ecology is an outgrowth which analyzes and interprets landscape heterogeneity and spatially explicit ecological processes (see Turner and Gardner, 1991). In our subsequent discussions we will be focusing on the economic issues, but it is the landscape nature of the ecological model that has led us in the particular direction we are taking. In fact, we propose a development parallel to that from conventional to landscape ecology for economic modeling.

Serendipitously, the approach taken in the landscape ecology model of Costanza and associates’ is particularly close in spirit to one which seems appropriate for economic land use problems. Analogous to the generic ecosystem model that predicts expected changes in habitat conditions, with inter-cell flows of hydrological information linked with physical and chemical parameters, we are interested in predicting expected changes in land use, with inter-cell flows of economic information of spatial and aspatial variables.

A compelling feature of this model is that it is designed to simulate a variety of ecosystem types with a fixed model structure. While the structure is general, however, different sets of ecosystem functions are activated for any site in the landscape, depending on its location and ecosystem type. Additionally, parameters of these functions are specific to the ecosystem type and site and are derived from field data. The underlying model structure is more complex than any particular application is likely to need, but allows for selection among functions and aggregation over levels of detail where applicable. The generic approach is appealing because it is an efficient way to construct models of this sort. Recalibration for a particular ecosystem is time consuming, but not so costly as reinventing the entire model. Additionally a sort of comparability and uniformity across applications becomes possible. Differences in results can be attributed to differing ecological conditions rather than modeling idiosyncrasies.

An important feature of the generic model is its spatial disaggregation. In broad terms, the model operates by dividing the landscape into cells and modeling the ecological functions within each cell and the vertical fluxes of mass above and below sediment. The horizontal mass fluxes of water, soil and nutrients between cells are then simulated over time using a spatial dynamic simulation program. The model is driven largely by hydrological algorithms (varying depending on the ecosystem type) and focuses predominantly on the responses of macro- and microphytes to nutrient availability, light, temperature, water availability, etc. Approximately 14 sectors (including a number of state variables) are incorporated, such as the inorganic sediments sector, dissolved phosphorus sector, hydrologic sector, macrophyte sector, etc. (see Table 2). The Patuxent application of the model focuses on nutrient and sediment loading in the watershed and predicts such things as changes in water quantity and quality, vegetation and amount and quality of wildlife habitat, all at a spatially disaggregated level.

The ecosystem functions and the parameters of those functions that are simulated for any given cell in the landscape are dictated by the cell's "land use" or "habitat" designation at the beginning of any simulation round. Then conditioned on that land use and the stocks of the state variables at that point in time in the cell, the processes and fluxes are calculated. Conceptually, there are two "levels" at which human behavior could be expected to affect this simulation. One is in the land use designation of a cell; the other is in the nature of ecological processes that occur within a cell conditioned on its land use.

Understandably, the ecosystem model without economic input, imposes rather than models this human behavior. Consider the land use designation. The ecological model calculates land use designation through a "habitat switching" model which determines when through natural succession or weather-driven ecological catastrophe (e.g. flood, forest fire), the habitat shifts from one type to another. Human instigated land use changes must be imposed exogenously and hypothetically. Perhaps the most important contribution of the economists will be to model this human land use conversion and how it is related to both the ecological and economic features of the landscape.

Human interactions with the environment conditioned on land use, are similarly imposed in the current ecological model, which uses something akin to a fixed coefficient technology to capture these. For example, if a cell is designated as being in cropland, then a given set of processes and parameters are assumed to operate, conditioned on ecological features such as slope/soil type. Variation across individuals or responses to external stimulae, like changing prices, are ignored. In order to assess the effects of some non-point source policy, the model must impose an assumed change in these processes and parameters, ignoring human response to the change in the regulatory environment. The second type of contribution that the economists can make is in modeling these conditional human interactions. Our first endeavor of this sort involves modeling farmer's behavior, both in crop choice and best management practices adoption, as functions of ecological and economic forces. We anticipate that a transportation sector or a residential sector might follow.

The General Structure of the Integrated Model

The shortcomings of an ecological model with no "moving economic parts" are obvious to economists. The shortcomings of our own treatment of ecosystem-related problems should be equally obvious. While we are not primarily interested in valuation here, how economists have treated ecosystem valuation is relevant to the discussion. With the exception of a few who have written largely in conceptual terms, most economists have been forced to consider only those services of ecosystems that are well-defined, are easily measurable using conventional market or non-market valuation methods, and have immediate consequences for humans. Piecemeal valuation of this sort ignores the more subtle, long range contributions of the ecosystem to human welfare; and it ignores the

importance of the configuration of the ecosystem landscape in determining its value, Where things are matters. Analysis that ignores spatial location and spatial arrangement misses important dimensions of the problem. One way of thinking about ecosystem valuation might be: how do we value the reconfiguration of the landscape in its various states as it evolves over time?

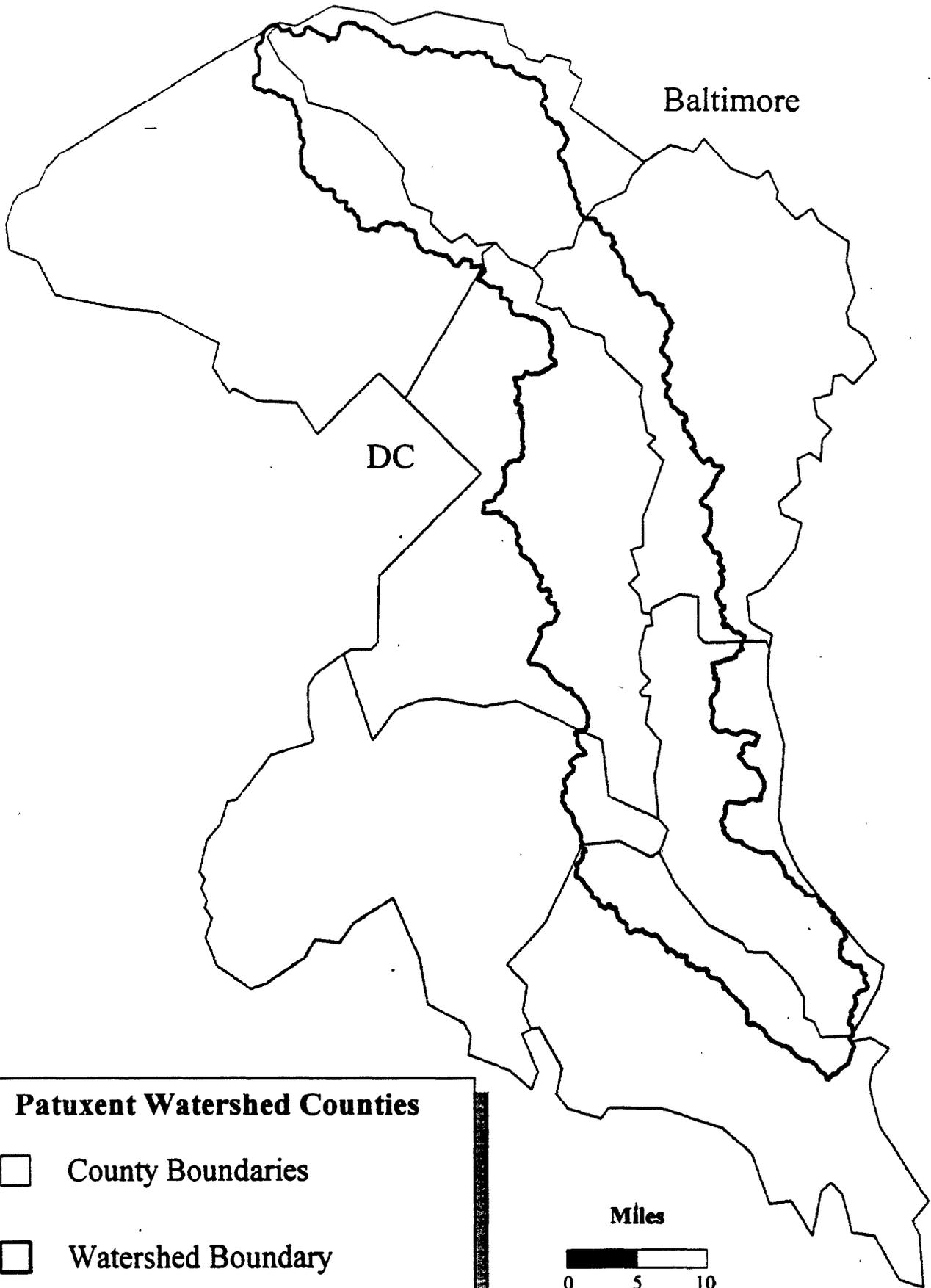
The appeal of a joint modeling effort that looks at the interaction of ecological processes and economic behavior in a spatially disaggregate framework as it plays out over time seems self-evident. The pressing question is how to structure such a modeling effort. Simply put the purpose of having an integrated model is to capture how the distribution of human activities (farming, electric power generation, commercial and residential development, recreation wastewater treatment highway construction fishing) affect the ecosystem as well as to capture the effect of the ecosystem landscape on the quality and value of goods and services (e.g., recreation, wildlife enjoyment water quantity and quality, housing environmental aesthetics, etc.) and, therefore on human decisions. The model needs also to capture how human activity and its impact on the ecosystem may differ under different regulatory regimes.

But an integrated model need not be a “black box”. At this point we do not intend to meld both ecological and economic models into one “super-model.” Instead, we plan for the two types of models to exist in parallel but to exchange information on ecological and economic elements generated by the other. This approach preserves the integrity and intuition of both models. It also allows the appropriate choice of time step, geographical scale, and level of aggregation which might differ between the ecological and economic models. The inconsistencies that are likely to arise in these dimensions are worth discussing because they pose problems in information exchange, no matter how the integration is structured.

Boundaries

By design the ecological model establishes physical boundaries. From the start the ecologists wanted agreement on these physical boundaries since these determine how many cells and of what types must be covered in their model. For them, the area of interest ranges from the tops of the trees to the depths of the groundwater and extends up to the limits of the drainage basin. The economists had no particular problems with the vertical boundaries (except to the extent that air quality issues of certain types maybe omitted from consideration). However, there is no reason to expect that the drainage basin of the Patuxent is a meaningful economic boundary. The question from our perspective has to do with the extent of relevant markets, and the relevant markets will be labor and land markets and possibly markets for products of the area-principally agricultural, forest and recreational products.

Market boundaries are largely undefinable and sometimes are not related to space at all. However the markets we are interested in - land, labor, recreation and products that have high transportation costs or are perishable-are likely to peter out or dissipate with distance. Regional economic modeling deals with these artificial boundaries of markets, and generally does so using political boundaries. The attached map shows the difference between the county boundaries and the watershed boundaries, but both are clearly arbitrary delineations



Patuxent Watershed Counties

□ County Boundaries

□ Watershed Boundary

Miles



from an economist's perspective. The boundary definition affects what explanatory variables are considered endogenous to the system (and thus must be predicted internally by the model for any scenario simulation) and what variables are considered exogenous to the system (and thus must be predicted by some model of the regional economy). The problem is more complicated than our usual economic intuition would suggest because we are not dealing with aggregates within and outside our region, but with spatially disaggregated decisions that are probably serially correlated over space (more about this in the next section.) Decisions made at point x in the landscape may be affected by characteristics of the landscape within y miles of the spot. Thus if we are interested in simulating activity in the watershed we may need to know about activity that extends some y miles beyond the watershed boundaries -or up to some natural geographic barrier such as an ocean major river, etc. Because our GIS data is available by county, we currently have information that extends up to the political boundaries in the attached map. This poses no problem for information exchange between the two models, since the ecological model will use only that part of our information which it needs. But the "sliding" boundary problem remains an issue for the internal workings of the economics model.

Organizational Complexity

The ecological model is structured around a desired level of ecological complexity and resolution. It simulates the activities of thirteen sectors and tracks twenty-five state variables all of which are listed in Table 2. Modeling with greater levels of disaggregation is possible, but costly, and requires a significant amount of additional data collection and programming. However, many of the state variables of importance for tracking ecological processes are not of direct interest to the modeling of human behavior (or for assessing the value of the landscape configuration).

Unfortunately, the ecological model cannot afford much detail in the state variables that are most visible and important to humans. The animal kingdom is represented by one state variable "consumers" and the macro-plant kingdom by the state variable, macrophytes levels of aggregation decidedly unacceptable to the economists. A proposed solution is to introduce the details exogenously by determining in side calculations the subgroups of macrophytes and consumers that are likely to be found in a given cell depending on its habitat/land use type, surrounding land uses and distances to critical ecological features (streams, etc.) and human disruptions (highways, etc.) The model will include markers and detailed rules for species loss, treating habitat evaluation as a side calculation. A function will be developed that will indicate the likelihood of game species and other forms of wildlife in particular habitat types. This approach allows for the provision of additional complementary information without increasing the level of disaggregation of the generic ecosystem model.

Time Scale

The ecosystem model operates on a time scale of a day or less. Yet, given available data the economic models will be estimated on an annual basis. This means that the timing of the exchange of information and the time-dependent nature of that information must be carefully thought out. The economic decisions can be modeled on an annual basis but then distributed over the year according to rules or separate side calculations. For example, intra-year timing of the agricultural decisions will be easy to predict, since these are governed

by growing seasons. The timing of those decisions that are prompted by weather can be driven by the ecological simulation that incorporates weather pattern simulations as well.

Land conversion decisions cause more trouble. Their timing is important because construction can have different immediate ecosystem impacts depending on the season. One solution is to use independent data on building starts and construction durations to forecast the seasonal impacts of construction. We may also add another habitat/land use type- land in transition, since this state can cause more sediment loss than almost any other.

Geographical Scale

The geographical scale of resolution between the two models will also differ. The ecosystem model divides the study area into cells each covering approximately ~~0.364 km²~~ or 90 acres. But for land use conversion decisions in states like Maryland, 90 acres is far too large relative to the decision unit. We have a choice (described in a later section) of using actual ownership parcels or of dividing the landscape into calls but the cells would likely be smaller than 90 acres and more closely matched the size of areas that are observed to convert in a given year.

In any event, the economic model will need to use observational units smaller than the cells in the ecological model and this poses one of the more serious modeling conflicts for the project. The economic model of land use conversion will generate predictions at a higher level of spatial resolution than the ecological model will need. However, since the former is likely to take the form of a discrete choice model it will produce predicted probabilities that can be interpreted as proportions. The ecological model can accommodate heterogeneity in the form of shares) within a cell if it is not necessary to preserve information on the specific locations of the heterogeneous factors within the cell. Devising weights to monitor what is happening in cells, thresholds can be set so that cells could go from homogeneous to heterogeneous units and vice versa. This additional detail will also allow the model to make inferences on a wider variety of land use restrictions (i.e., agricultural policies, zoning policies, and environmental protection policies).

Disaggregating the output from the ecological model for use in the economics model may be more difficult. The exact locations of some features of the landscape that are important to economic decisions will be known independently and will be unchanging (e.g. location of streams) but information about others (e.g. quantity and quality of stream flow) will be available only as output from the ecological model. We do not yet know how serious a problem this will turn out to be.

Time Horizons

Some ecosystem effects of human actions take a long time to play out, and as a consequence the ecologists are interested in scenarios of at least 20 years. A time horizon of this length makes economists nervous - so much that affects human behavior (technology, changing preferences, . . .) is impossible to predict very far in advance. Nonetheless, we have agreed to 20 year scenarios, but there will be an array of these subject to a host of different assumptions.

Spatial Data/Issues in Economics

The emphasis in the discussion so far has been on “space” and “time”. If “ecological-economic” modeling has any meaning at all, it must have something to do with the interactions between humans and natural systems over space and time. Economists have excelled at modeling time dynamics, but spatial issues have received much less attention. Perhaps this is because the markets for most goods are not spatially driven. Land, while not the only exception, is certainly the most obvious one.

What happens to land, not just aggregate land but the spatial arrangement of land, is a topic of increasing interest to multiple disciplines. Land use is inextricably tied to public infrastructure demands that are more or less costly depending on their spatial distribution. Land use is almost synonymous with locational externalities - visual, noise, etc. And land use has environmental consequences that differ markedly depending on the pattern of remaining habitat and the size and proximity of disturbances to ecologically sensitive areas. The configuration of land is one of the major contributors to the quality of life.

Yet, traditional fields of economics have reduced the complexity of spatial relationships, almost to the point of making spatial issues non-issues. Either aggregate relationships have been specified or the spatial components in a model have been reduced to uni-dimensional variables, e.g. the distance between economic activities in a location model, the wage differential in a migration model, cost of access in a transportation mode choice model. The concept of a landscape *mosaic* of natural and human-managed patches is foreign to economists.

Data drives analyses. In the absence of spatially articulated data, there has been no impetus to develop broadly adopted methods for analyzing two dimensional space. But now that GIS data is becoming more readily available, economists are reconsidering their analytical tools. Along with others at a similar stage of thinking, we are looking for away to take full advantage of this new type of data. Is there some way of explicitly thinking about spatial interactions and their impacts on decision making beyond including location specific amenities and distances to features of importance? Can we model these spatial issues using higher dimensions in order to increase the predictive power of our model? If not a totally new approach, can we use these new data to better describe the aspects of space that matter?

While most economists know that GIS is a technology that can store, analyze, and display spatial and descriptive data, not so many economists have had the opportunity to work with such data. A GIS technology takes information from existing maps or aerial photographs and digitizes it, keying points, lines or polygons in one way or another to map coordinates. GIS software is used to manage the database system to store and retrieve data to analyze data and to report analyses and display maps.

Our GIS data includes mappings of land uses at four points in time for the counties of interest. We also have, or will soon have, access to digitized maps of ecological features, such as slopes, soil types, elevations, and hydrology (streams, rivers, etc.), as well as the output of the ecological model simulations that will provide values for state variables in a GIS format. We expect to obtain GIS data on zoning and land use controls in our counties, as well as likely scenarios for future land use management. Additionally, our data base includes transportation networks, business districts, street addresses, etc. The latter allows us to match information from other sources (including a tax assessment data base and a survey of farmers) to map coordinates. GIS software provides a means of obtaining a variety of measures, including calculating distances, registering contiguous attributes, and measuring percentages of areas of various shapes and sizes made up of different attributes.

While we are still searching for the most valuable way to use these data there are some spatial attributes that are clearly of importance to the value of land in different uses. For example, the value of a parcel in residential use will be affected by access to employment centers (given by transportation networks and proximity to business districts) and private and public infrastructure (shopping, schools, recreational facilities), etc. But it will also be affected by the spatial arrangement of ecological features and man-made structures making different parcels equi-distant from employment centers of differing value because of these spatially oriented amenities/disamenities. Additionally, the ability to convert land to a developed use will be circumscribed by regulatory mechanisms and incentives: zoning, land use controls, taxation patterns, best management practice incentives, etc. The value to society of land in an undeveloped state will also depend on attributes of the land and its spatial arrangement. For example, the suitability of a patch for wildlife habitat will depend on its water and vegetative features, its size, shape and habitat edges and its proximity to human disturbances and human access.

Spatial Measures in Modeling

The disciplines of landscape ecology and geography, as well as a sub-field of econometrics called “spatial econometrics” (see, for example, Anselin, 1988) offer interesting alternatives to conventional measurements of space. Here we discuss two types of measures of spatial pattern that have emerged in some of this literature: measures which capture in a two-dimensional way relationships among cells in the landscape and measures that capture the complexity of spatial pattern. We consider their application to economic models that attempt to describe what goes on at any given location in the landscape.

The original motivation for the following measures were driven by regional economic development issues. Therefore, all the following measures were derived in order to use spatial aggregate data, on large spatial units such as counties or census bureau tracts. However, our model will use disaggregate data on much smaller spatial

units, such as land parcels, so the following measures will have to be modified to use on disaggregate data. Given this caveat, we now describe some of these measures.

Spatial contiguity matrices describe spatial relationships between all pairs of spatial units in the landscape. The simplest is based on binary contiguity between spatial units, where each cell is represented by a row and a column in a matrix. For any i,j combination of cells a 1 appears as the i,j element of the matrix if the cells are contiguous and a 0 otherwise. This requires dividing the landscape into units, and for regular structures mathematical properties are well defined. It is also possible to define higher order measures of contiguity.

Spatial weight matrixes are extensions of spatial contiguity matrices that add weights to the contiguity measure. Matrixes with terms such as the following are commonly employed:

$$w_{ij} = b_{ij} a_i B_{ij}$$

or

$$w_{ij} = [d_{ij}]^{-\alpha} [B_{ij}]^{\beta}$$

or

$$w_{ij} = \alpha \exp(-d_{ij} / \beta)$$

where

b_{ij} = binary contiguity factor

a_i = the share of area i in the entire spatial system

B_{ij} = the proportion of the interior boundary of unit i in contact with unit j

d_{ij} = distance between unit i and unit j

and α, β = parameters.

In the first two expressions above, the matrix contains non-zero information only for contiguous cells, although as the third example suggests, weight matrices can easily be defined that allowed relationships with more distant cells. In our disaggregate model, which has much smaller spatial units, these measures can be modified in a number of ways. For example, the first two measures, which are based on binary contiguity, can be extended to allow for higher levels of contiguity. In this way, land use parcels can be affected by other spatial attributes that are not directly contiguous, but yet are of interest for their potential impact on the land area in question. Measures in the spirit of the third example above already permit impacts from noncontiguous units, so can easily be used to create matrices that incorporate influences from a further distant.

An obvious way to use these matrices in econometric modeling is to add structure to the pattern of correlation among errors. Spatial data introduces the likelihood of spatial autocorrelation. One can also imagine using these weights to discount location-specific explanatory variables with distance. In this context, one might think of these weights as spatial lag operators.

Landscape ecologists have also developed indices of complexity of spatial pattern, derived from information theory and fractal geometry. These indices have been used principally to compare spatial heterogeneity across landscapes of considerable size, but seem adaptable to our type of problem (O'Neill et al 1988). A well-known and commonly used measure of diversity (or conversely dominance) from information theory is applicable here: Within any given sized sub-area of landscape, diversity of land uses could be measured by:

$$H = -\sum_{k=1}^m P_k \ln P_k$$

where P_k is the percent of the sub-area in land use k and m is the total number of land uses. H ranges from 0 when all land in the sub-area is of the same land use to $\ln m$, the value of H when all land uses are represented equally. Consequently, a measure of dominance is given by:

$$D = \ln m - H$$

and ranges from 0 to $\ln m$, at maximum dominance.

A second and less well-known information theory measure is a measure of "contagion". This index is concerned with edges and contiguity, and reflects the extent to which land uses are clumped.

$$C = 2n \ln n + \sum_{i=1}^n \sum_{j=1}^n Q_{ij} \ln Q_{ij}$$

where Q_{ij} is the proportion of cells of type i adjacent to cells of type j and n is the total number of cells in the sub-area. Note that $2n \ln n$ is the maximum value of the second term. At high values of C , land uses are highly concentrated; at low values the landscape is heavily dissected.

Finally a measure adopted from fractal geometry is frequently used to capture the complexity of the sub-area. The fractal dimension is twice the slope of the regression line found by regressing the log of one-quarter of the perimeter on the log of the area. The fractal dimension ranges from 1.0 if all patches are simple square shapes to 2.0, which represents a patch with the same area, but with a very complex shape.

In the next section, we explore how we might actually do some economic modeling in space and how we might use some of the above concepts to add richness to our modeling effort.

Modeling Land Conversion

Recognizing that the ecological effects of human activity are driven by the specific uses man chooses to make of the stock of natural capital, one of the major contributions we can make to the ecologists' landscape model is an understanding of how the land use decisions are made by individuals. This is critical for the integrated modeling effort, since the simulation of each geographically designated cell's ecological functions are driven by land use designation.

More specifically, the purpose of this phase of the project is to develop the ability to predict future land use of a parcel or unit of land, given information on its history, relevant zoning and other land use restrictions, the general level of regional economic activity, and the variety of often spatially related economic and ecological variables that affect the value of the parcel in different uses. Given this information, we intend to predict the probabilities that a parcel of land with certain characteristics will stay in its present land use or convert to alternative uses.

There have been numerous attempts by economists to model land use conversion (see, for example, models of urban fringe development by Dunford, Marti, and Mittlehammer, 1985; Alig and Healy, 1987; Barnard and Butcher, 1989; McMillan, 1989) but they have been hampered by limited data. The data we have available, while not perfect, offer the potential for a richer and more spatially disaggregate model than has previously been possible. But as the previous section explains, we are still uncertain as to how to take full advantage of this spatial data.

We have two interesting data sources that contain information on land use conversion. The first consists of snapshots, at four points in time, of land uses in the seven Patuxent watershed counties prepared by the Maryland State Office of Planning. These are GIS data, and in this format different land uses are recorded as polygons on a digitized map. A polygon of a minimum of 10 acres will appear on the map with a separate land use designation. This GIS database allows us to see three periods of land use changes - from 1973 to 1981, from 1981 to 1985, and from 1985 to 1990. The land use designation categories are reported in Table 1, but can be summarized as types of agricultural land, types of forests, types of residential, industrial, institutional or commercial development, barren land, wetlands, etc.

Tax assessment files comprise the second data source of interest and were acquired from Maryland's Department of Assessments and Taxation. These files include observations on each individually or publicly owned parcel of land in the seven relevant counties as of 1993. The database includes fields for a wide range of interesting characteristics of the land parcel and the owner. Not all fields are filled in for all observations or all counties, but there remains considerable information on each parcel. Variables include size, location, zoning, land use designation property factors (e.g. sewer, water, historic, etc.), structure description, market value, tax assessment, building value, land value, etc. Of particular interest to us are the variables that report property transfer

information, and year built, if a structure exists on the property. Because the data base includes addresses, we can, at least in theory, map the locations of these parcels onto our GIS database using Census Bureau TIGER files that supply GIS coordinates for street and road addresses. This process is underway and we are currently attempting to resolve the matching problems that invariably occur with such data sets.

These two data sources together provide important information and can be merged in the GIS database, but they are different in a number of important dimensions. The State Office of Planning land use maps give us a good picture of land use change over time. Land use changes are recorded in terms of polygons switching from one land use designation to another, rather than individual parcel owners' decisions. This maybe a useful format if we choose to employ a grid or cell type approach in defining our units of observation. In that case we could model the proportion of each cell in a given land use at a point in time. However, from these maps changes can be observed only in approximately 5 year intervals. This obscures observation of the sequencing of changes and lengthens the time unit of measurement even further relative to the ecological model.

In contrast, the tax assessment database is extremely detailed and includes data by parcel of ownership, should we choose to use that as the unit of observation. However, because it records information as of the current period, it must be used creatively to extract information about past changes. These changes must be deduced from information on time and conditions of property transfer, date at which property was converted from one tax category to another, and year structure was built. Additionally, if we have difficulty mapping all parcels, we may encounter selection biases in our sample of observations.

Despite the shortcomings in both data sets, merging them will provide far better information than has been available to analyze land use conversion in the past. At this point we expect that our observational units will be cells rather than parcels, in part because even in the tax assessment data base the observations are based on parcel ownership only in the current time period not at the time the decision was made. Thus, from these data it will be impossible to determine whether several new housing units came from one or more conversion decisions. Economists are more comfortable using observations on decision makers than on units of the commodity, but somewhat related problems arise in some types of surveys. For example, on site surveys in recreation yield samples of trips rather than samples of recreationists.

Also included in the GIS data base is information on transportation networks and central business districts, hydrology (streams, rivers, etc.), land slopes, soil types and elevations. (We are currently attempting to acquire historical transportation information.) This is all in addition to the GIS level data supplied by the ecological model. These data allow us to calculate, for any arbitrarily small cell in the landscape, such things as distances from roads and highways, towns and employment centers, and natural ecological features of interest - like shoreline or recreational facilities. It also provides a means of calculating

variables that reflect what is going on around a particular point on the landscape and what may be happening to the quality of the environment.

Two other external sources of information are worth mentioning at this point. The state of the regional economy is likely to be an important factor in determining land use conversion in the Patuxent watershed. In order to simulate future scenarios of land conversion, we need a forecasting model of the economic activity in the region. The most likely candidate for this is a well recognized regional model of Maryland developed and marketed by Mahlon Strazheim of the Economics Department of the University of Maryland.

Another source of externally supplied information will come from the Patuxent Demonstration Project. This is an inter-governmental research group that has assembled the current zoning and land use restrictions for the Patuxent watershed counties in a detailed GIS format. They have also developed a set of potential land use management scenarios that could conceivably evolve over the next two decades in this area. These include zoning based on comprehensive plans and sewer/water service plans; forest conservation and agricultural best management practices programs; and clustering requirements together with urban best management practice programs.

While we have a host of data related problems to overcome, including some potentially serious sample selection problems, our ultimate data set is likely to consist of discrete panel data: time series observations on land use of individual parcels or of equi-sized cells in the landscape. We plan to use models of discrete panel data (see Heckman, 1983) either to predict the probability of any parcel of land, or the proportion of any equi-sized geographic cell, being in a given land use at time t .

Heckman's treatment of panel data incorporates intertemporal connections among decisions and the resulting increased complexity in error structures. Adapting Heckman's general model, we consider that the continuous latent random variable (i our problem reflecting utility or returns from putting parcel i in land use m at time t) can be given by a systematic function of exogenous variables and variables capturing the dynamic nature of the decision (i.e. functions of past decisions and values of past latent variables) as well as an error term.

Heckman frames his problem in a dichotomous choice context, but we will have either polychotomous choices or nested dichotomous choices. In a general model, we would be interested in predicting the probability that a parcel, conditioned on current land use, will end up in any of m land uses in the next period, where m might be as many as 5 or more land uses depending on aggregation over categories in Table 1. For our particular study area, however, most conversions take place from some relatively undeveloped use (e.g. forest or agriculture) to a developed use (some type of residential or, far less often, commercial). Rather than having a majority of zero cells in a conversion matrix, we might alternatively consider a series of nested dichotomous choices:

1. develop or not

2. if develop residential or commercial
3. if residential: low or high density

Both polychotomous choice and nested dichotomous choice problems are most easily framed in the context of multinomial logit. However, the complicated error structures that are suggested below are not possible in a logit framework unless they can be captured by fixed effect terms.

Dynamic Issues

There are a variety of types of dynamic relationships possible in discrete panel data. First and foremost, the parcel's state in the previous period will be expected to have an effect on the decision. This type of term would appear in a simple Markov chain model. In our problem it is clear that the land use in time $t-1$ will have an important effect on land use choice in time t , because of inertia and varying costs of transition (none of which are likely to be fully captured with explanatory variables). It is not obvious that choices in time periods $t-j$, $j > 1$ can be expected to have a separate effect. The Markov effects may not be stationary, however. They may be changing overtime because of (otherwise unmeasurable) changes in land use policies, for example.

Additionally the cumulative history of the parcel might matter. For example, the valuation of a parcel in a particular use may be affected by how long the parcel has been in its current state. Accumulation and depreciation of natural, human, and structural capital, as well as other forms of time dependency, can be reflected this way. "Renewal" terms of this sort may have interesting interpretations in land conversion models related to soil depletion, timber cycles, or depreciation of man-made capital, but whether our data will support such subtleties remains a question.

We might also expect a lagged adjustment to past valuations of alternative states. Given the near irreversibility of some land use conversion decisions, responses to a persistent economic signal are more likely than sudden responses to a one-time change in economic conditions. Additionally, given the time it takes to plan, obtain permits, etc. there will likely be a lag between conversion decision and observable action.

Exogenous Variables and Spatial Issues

The model needs to capture those factors that dictate the value of a parcel of land in different uses. These may be ecological features of the landscape, such as soil type, slopes, water availability, scenic amenities. They will also include man-made features of the landscape, such as access to employment centers (given by transportation networks and proximity to business districts), and access to both private and public infrastructure (shopping, schools, recreational facilities), etc. The ability to convert land and its ultimate value in alternative uses will be circumscribed by regulatory mechanisms and incentives: zoning, land use controls, taxation patterns, best management practice incentives, etc. But even this relatively straightforward consideration has locational spill-over effects, since the zoning of the land next door has an effect on the value of a particular parcel. Finally, the value of a parcel in a given land use is very much affected by the land uses of surrounding land, not just specific features with point locations.

There are a few ways we could imagine incorporating the spatial measures mentioned earlier into the systematic part of our land use conversion model. A weighting scheme based on distance and contiguity might be used as a spatial lag operator on exogenous variables. For example, instead of using as an explanatory variable equal to the distance to the nearest employment center, we might include all relevant employment centers measured by their size and weight them by the spatial weights (i.e. discount them by distance and/or contiguity.)

We could also apply spatial lag operators to variables that reflected land use, the dependent variable, for surrounding cells. The probability that a particular undeveloped parcel will be developed during time period t will be affected by the land use configuration surrounding the parcel at the beginning of t . We might measure the proportion of land within any concentric circle, for example, in a particular land use, and then weight these measures by the distance of the concentric circle from the parcel and/or by contiguity factors.

These measures are promising but might not fully capture the aesthetic, congestion, access, etc. aspects of land configuration that make location so important in land values. Models of land value or land conversion may make particularly good use of the measures of spatial heterogeneity and complexity that have, up till now, been used principally for description. By choosing an appropriate size for a sub-area, we can calculate measures of diversity, contagion, etc. for circles or squares centered on each cell. By doing so, we encounter the “sliding” neighborhood phenomenon making knowledge of areas within an ever expanding boundary necessary for simulation. This argues all the more strongly for modeling an area bounded by geographical “walls” such as bays, rivers, etc. rather than the boundaries of the watershed.

Error Structure

The error structure in our problem poses particular problems. In his general model, Heckman assumes that the errors are distributed with mean vector zero and covariance, Σ , which is a $T \times T$ positive definite matrix. This specification allows non-stationary and serially correlated errors. Although more general than previous models, Heckman’s specification assumes that $\epsilon(i)$ is independent of $\epsilon(j)$, $j \neq i$, because he is concerned with panel data in which the cross section observations are taken over randomly selected individuals.

In our case, the observations will be overland parcels and the spatial relationship among parcels is likely to dictate a pattern in the error structure in the cross-section dimension as well as the time series dimension. Perhaps the most obvious use of the spatial contiguity or spatial weight matrices described in the last section is to provide structure for the covariance matrix of the errors. Clearly our model will not capture all relevant factors and the omitted ones will certainly be correlated over space because of the immense importance of locational spill-over effects. The types of weight matrices

discussed above can provide structure - dependent on distance and contiguity factors - for the covariance matrix of the errors.

The complexity of the error structure, together with the polychotomous or nested nature of the choice problem, poses estimation difficulties. If we assume a generalized extreme value distribution for the ϵ_i 's, thus generating a multinomial logit specification then only a fixed effect model is practicable. However, if we wish to represent the likely error structure, we would need to assume a normal distribution (as does Heckman). We have not yet resolved this modeling problem and any ideas will be gratefully received.

Table 1

— The Habitat or Land Use Designation Types

Developed/Urban Land Uses:

- Low density residential
- Medium density residential
- High density residential
- Commercial
- Industrial
- Institutional
- Extractive
- Open urban land

Agriculture:

- Cropland
- Pasture
- Orchards/horticulture
- Row/garden crops

Forest:

- Deciduous forest
- Evergreen forest
- Mixed forest
- Brush

Other:

- Water
- Wetlands (by State Land Use definition; not Section 404 definition)
- Bare ground

Table 2

— State Variables in the Generic Ecosystem Model

Hydrology Sector:

Surface water
Unsaturated water
Saturated water

Hydrodynamic Sector:

Horizontal Flows (rivers, waves)
Vertical Flows (snow, rain)

Inorganic Sediments Sector:

Deposited inorganic sediments
Suspended inorganic sediments
Pore space

Salt (NaCl) Sector (Conductivity):

Salt crystals
Salt in surface water
Salt in sediment water

Dissolved Phosphorus Sector:

Phosphate in surface water
Phosphate in sediment water

Dissolved Nitrogen Sector:

Dissolved inorganic nitrogen in surface water
Dissolved inorganic nitrogen in sediment water

Dissolved Oxygen Sector:

Dissolved oxygen in surface water

Non-Macrophyte Sector:

Algae (phytoplankton and/or periphytons)

Macrophyte Sector:

Macrophyte photosynthetic biomass
Macrophyte non-photosynthetic biomass

Above Sediment Organic Matter and Detritus Sector:

Suspended organic matter
Standing detritus

Organic Sediments/Soil Sector:

Deposited organic matter

Consumer Sector:

Consumer biomass (all fauna except microscopic decomposes)

Fire Sector:

Fire Igniters
Fire Propagates

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ABSTRACT

Landscapes, Ecosystem Value, and Sustainability

by

Robert Gottfried, David Wear and Robert Lee

This paper offers an ecologically-based view of land and land value, building upon the concepts of ecosystems as multiproduct assets and of landscape ecology.* Having briefly reviewed landscape ecology, the paper questions the ability of markets to create optimal landscapes, even when traditional methods of internalizing externalities are applied. The paper concludes that attempting a complete valuation of ecosystems appears to be a rather quixotic enterprise. Managing natural systems to optimize production of certain valued outputs, perhaps subject to certain sustainability provisions, may represent a more practical goal. Achieving sustainable landscapes, however, requires both sufficient ecological knowledge and institutions capable of bringing about this result inasmuch as the unaided market cannot do so. The paper argues that landscape modeling may help provide needed information, and examines forms of public and private ownership to assess how well particular institutional conditions might facilitate ecological adaptation. Flexibility and creativity will be needed in designing institutions that can deal effectively with landscape-scale management.

* This paper is the outgrowth of a series of discussions by the authors as part of the US Man & the Biosphere Temperate Zone Directorate Project "Land Use Patterns in the Olympic and Southern Appalachian Biosphere Reserves: Implications for Long Term Sustainable Development and Environmental Vitality."

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People and Parks: Economic Management of Khao Yai National Park, Thailand

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October 1994

Abstract

Following the policy literature on people-park conflicts, this paper provides an economic analysis of the efficiency of park management decisions and their impact on rural incomes in developing countries. Using Khao Yai National Park (KYNP) in Thailand as a case study, analysis of an economic model reveals the importance of spatial and intertemporal characteristics of land use in and around a park area for establishing management schemes that meet both preservation and rural development goals. Sensitivity analysis of the model reveals the role of discount rates, the importance of habitat size and spatial externalities, and the impact of the perspective of the manager-local, national, international-on optimal land use. The spatial analysis suggests that current management of KYNP fails to consider the impact of the park on economic development in surrounding and, in so doing, allocates too much land to a pure preservation use. A buffer zone policy paired with rights for extractive good collection within the park would increase the social benefits created by KYNP.

Resented at the Association of Environmental and Resource Economists Workshop, "Integrating the Environment and the Economy: Sustainable Development and Economic/Ecological Modeling." Boulder, Colorado, May 5-6, 1994.

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**VALUING BIODIVERSITY FOR USE IN
PHARMACEUTICAL RESEARCH**

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1994 AERE Workshop
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6 June 1994**

VALUING BIODIVERSITY FOR USE IN PHARMACEUTICAL RESEARCH

Abstract

There has been considerable recent interest in "genetic prospecting" among wild plants and animals for novel chemical compounds. Such prospecting might uncover new pharmaceutical products and provide a mechanism for saving endangered ecosystems. It is unclear what values may arise from such activities, however. Evidence from observed transactions is incomplete. Existing theoretical investigations are flawed in their treatment of the probability of discovery of novel chemical compounds. In this paper we develop a simple model in which the "marginal species" maybe redundant with respect to its potential as a source of new chemical leads. By optimizing the value of the marginal species with respect to the probability with which it yields a commercially successful product we are able to place an upper bound on its value. This upper bound may itself be relatively modest. Slight modifications in assumptions lead to drastic reductions relative to this upper bound. We also extend our findings from the value of the marginal species to that of the marginal hectare of habitat by combining our results with a common model of the species-area relationship. We find that the incentives for habitat conservation generated by pharmaceutical research are also, at best, very modest, and are more likely to be negligible.

Introduction

There has been considerable recent interest in “genetic prospecting.” Genetic prospecting is the search for chemicals produced by wild organisms. In nature, these compounds are employed to escape predators, capture prey, increase reproduction, and fight infection. These chemical compounds might be of considerable commercial value if adapted to industrial, agricultural, and, particularly, pharmaceutical applications.

Genetic prospecting has also been touted as a tool for the conservation of biodiversity. It has been argued that incentives for the preservation of areas in which genetic diversity is greatest, particularly tropical rain forests, might be increased if landholders could be compensated for the values generated by endangered organisms used in new product research (this argument has been made, with varying degrees of enthusiasm, by, among others, Farnsworth and Soejarto, 1985; Principe 1989; Wilson, 1992; Reid *et al*, 1993; and Rubin and Fish, 1994).

In order to determine the strength of such conservation incentives, we would need to know the value of the “marginal **species**”¹ in genetic prospecting. A number of studies, including those of Farnsworth and Soejarto [1985], Principe [1989] McAllister [1991], Harvard Business School [1992], Pearce and Puroshothamon [1992], and Aylward [1993]² have adopted, with differing degrees of sophistication, a straightforward approach to valuing biodiversity for pharmaceutical search. In each of these contributions, the authors have multiplied an estimate of the probability of discovering a commercially valuable substance by the value of such a discovery. There is considerable disagreement among the studies as to the magnitude of estimation of the latter quantity, although the sober estimates offered by the more recent studies seem the

¹ We will argue in Section VI that the “marginal species” is in fact a meaningful concept. To anticipate that discussion many biologists--and even many describing apocalyptic scenarios--model the loss of species as a continuous function of the conversion of habitat rather than as a catastrophic discontinuity.

² An excellent summary of all these studies may be found in Aylward, 1993.

more probable. The results of these exercises vary widely, ranging from as little as \$44 per untested species *in situ* [Aylward, 1993] to as much as \$23.7 million (Principe, 1989).³

The studies in which the value of indigenous genetic resources in pharmaceutical research have been more thoughtfully derived are useful in that they incorporate detailed treatments of the nature of the benefits to be derived from new Product discovery. We believe the method underlying all these studies to be flawed, however. It is curious that this existing work on economic valuation of genetic resources takes little account of scarcity. Redundant resources are not scarce, and hence are not of great value on the margin. By multiplying the probability with which an organism sampled at random contains *some* chemical compound of commercial value--whether unique to that organism or not--by the expected value of a successful commercial product earlier researchers have failed to recognize the *possibility* of redundancy among natural **compounds**.⁴ Thus potential values may be overstated in even the more carefully conducted work.

Our approach is more closely related to that of Brown and Goldstein [1984]: we value the marginal species on the basis of its incremental contribution to the probability of making a commercial discovery. Our work is also related to that of Polasky and Solow [1993], Solow, Polasky, and Broadus [1993], and Weitzman [1992, 1993]. In these papers the authors measure biological diversity in terms of the genetic "distances"⁵ between related species; in fact, Polasky and Solow [1993], and Weitzman [1992] show how their proposed measures of diversity can be related to the incremental probability of discovering

³ There is also some confusion in many of these studies between the average and the margin value of biodiversity. The total value maybe truly astronomical, and hence the average value substantial. We show that the value of the marginal species is likely to be negligible, however.

⁴ Note that we emphasize the possibility of redundancy, rather than assert its existence Our findings do not rest on the existence of redundant compounds, but rather on the fact that if the marginal material from which sampling may occur is so rare as not to be redundant the probability of its discovery is small. This point is made more formally below, but should be borne in mind through the entire discussion .

⁵ See Weitzman [1992] for an explanation of how distance may be measured by matching DNA.

commercially valuable compounds. In each of these papers, however, the authors are attempting to describe a *measure* of biodiversity; that is, a ranking by which one collection of organisms may be said to be more or less diverse than **another**.⁶ In our work, we accept current **taxonomic**⁷ practice as the appropriate measure; we suppose that all species within a particular taxon are “equally different.” We then ask by how much is *value* augmented by increasing the number of species that maybe tested in new drug research.

Valuation methods based on the work of these other authors will prove more valuable as greater information concerning the genetic constitutions of species-and even individuals-becomes available. Our simpler approach is closer to practical application, however. Biologists estimate there to be between ten and one hundred million living species. Of these, only about 1.4 million have been described [Wilson, 1992] and a far smaller number have been subjected to chemical or genetic analysis [Farnsworth, 1988]. The types of measures suggested by Weitzman and Polasky, Solow, and Broadus simply cannot be performed on a broad scale with existing data and computational limitations. In our work we will treat each new species to be evaluated as an independent Bernoulli trial with an equal probability of yielding the commercial product for which it is being tested. Since much of the literature on biodiversity preservation emphasizes the importance of saving as yet unknown species as genetic insurance against as yet unidentified diseases, our approach seems appropriate.

The reader may find it curious that the roundabout methods we describe for determining values are necessary. One might suppose that our questions could be

⁶ A more recent paper by Polasky and Solow [1994] does deal explicitly, and in a relatively sophisticated manner, with valuation issues. The Polasky and Solow paper does not address values on the margin, however, and it does not incorporate any costs of prospecting--hence, there is no “stopping rule” to determine when additional search is justified. Finally, it would appear that the recent Polasky and Solow paper we written in part to address omissions in an earlier version of this paper.

⁷ We will use “taxonomy,” “taxon” and its plural, “taxa” often in this paper. A taxon is a collection of species, or a collection of collections of species, etc.; e. g., a genus, class or order. Taxonomy is the science of categorizing species according to the successfully narrower taxa to which they belong.

answered merely by observing market transactions. We discuss the reasons for which this is not feasible in the next section. Following that, we provide a very brief overview of the natural products pharmaceutical research process. We then turn to a discussion of possible sources of redundancy in genetic prospecting. Our main results are presented in the fourth through sixth sections of the paper. We present a simple model in which discoveries may prove redundant. We are able to derive an upper bound on the value of the marginal species--and, by extension, on the marginal unit of habitat on which it exists. We demonstrate that this upper bound will be substantial only under very optimistic assumptions, and that the value of the marginal species falls off very rapidly if the probability of discovery differs from that which maximizes the marginal value.

Any model that purports to measure something as speculative as the value of a species for its pharmaceutical research potential must be built on a number of simplifying assumptions. We discuss these assumptions and their implications in a seventh section, but we can summarize hereby saying that we do not believe that a more realistic treatment would change our results much.

We state our conclusions in a final section but we should emphasize one point now. This paper is concerned solely with pharmaceutical researchers' willingness to pay for indigenous genetic resources as inputs into commercial products. Biodiversity may have important values over and above those as inputs into pharmaceutical research. Our point is not that biodiversity has little value at the margin; it may give rise to a great number of other ecological, moral, and esthetic values that are not captured in market transactions. To the extent that the incipient markets for genetic resources will not generate revenues adequate to support the preservation of endangered habitats, it is all the more important that alternative means for financing conservation be developed.

I. The Value of Genetic Resources in Observed Transactions

One reason for which there is little evidence concerning the prices at which genetic resources have traded is that they are non-rival goods and property rights in them have typically not been well established [see Sedjo, 1992; see also Chichilinsky, 1993; and Vogel, 1993]. The seminal contributions of Coase [1960] and Demsetz [1976; see also Barzel, 1988] suggest that property rights will come to be established either *de facto* in the form of contracts between parties or *de jure* when the benefits of their definition exceed the costs of their enforcement. The legal and institutional treatment of indigenous genetic resources is, in fact, changing. The Biodiversity Convention [UNEP, 1992] prepared for the 1992 UNCED meetings in Rio de Janeiro and recently signed by the United States guarantees states sovereignty over their genetic resources and forbids their appropriation without prior informed consent. Organizations in many countries are now entering into commercial agreements with foreign pharmaceutical researchers. The most noted of these is probably that signed between Merck and Company, a large U.S. pharmaceutical firm, and Costa Rica's *Instituto Nacional de Biodiversidad* (INBio). This agreement calls for a fixed payment of some one million dollars and premises of substantial royalties in the event of new product discovery [Sittenfeld, 1993].

While institutional developments are indicative of a new enthusiasm and optimism concerning the value of indigenous genetic resources, they provide little evidence concerning the value of unimproved genetic resources *in situ*. "Markets" for transactions in indigenous genetic resources are just beginning to emerge. While payments of between \$50 and \$200 per kilogram for samples have been reported [Laird, 1993], the interpretation of fixed payments for samples as a measure of the value of resources *in situ* is suspect for at least two reasons. The first is suggested by our discussion above: it is not entirely clear that the collector has (or should have) legal title to the samples she sells. For this reason, observed "prices" might be misleadingly low. The second reason is that sample collection is typically a much more difficult process than it may appear at first. Payments

made for samples may reflect compensation for collection and processing labor and taxonomic expertise rather than rents for the materials **themselves**.⁸

Compensation for access to samples is often not made in the form of simple cash transactions, however. Many agreements specify royalty provisions rather than up-front payments. Inasmuch as the terms of these provisions are generally secret, and the parties' estimation of both the probability of discovery and the payoff in the event that a valuable discovery is made are unknown, little can be inferred about the value of resources in situ from public information concerning these contracts. For these reasons, most existing attempts to estimate the value of indigenous genetic resources for pharmaceutical research have been based on inferences from indicators other than observed transactions.

II. The Use of Indigenous Genetic Resources in Pharmaceutical Research

Indigenous genetic resources are the genetic codes containing the "recipes" for chemical compounds of potential value in pharmaceutical products. These recipes can be exploited for commercial purposes by acquiring a breeding stock of the organism that produces the desired compound transplanting genes, or using the naturally occurring compound as a model for the synthesis of the same or related compounds. Pharmaceutical research on natural products is more often intended to develop "leads" than to identify natural products that can be used in an essentially unmodified form. Leads are promising molecules: blueprints of compounds that may show promise in their naturally occurring form, but must be modified to increase efficacy or reduce side-effects.

Part of the reason for the increased recent interest in natural products research is a renewed appreciation of the importance of natural leads. While considerable efforts at "rational design" of drugs from inorganic materials continue, researchers have also come

⁸ The Merck-INBio agreement illustrates this point. Of the million-dollar up-front payment, less than ten percent was designated for conservation activities. The remainder went for equipment purchases and to defray INBio's expenses [Sittenfeld and Gamez 1993].

to recognize that nature has perfected chemicals that synthetic chemists might never dream up [Reid et al., 1993]. Wild plants and animals have evolved elaborate chemical means to enhance reproductive success, deter predators, and resist infection. These chemicals may have great promise in pharmaceutical applications.

The development of new drugs from indigenous genetic resources proceeds in many steps and may take ten or more years from the time a promising lead is discovered to the first commercial sales of derived compounds. The process begins with field collection. It is important that collection be undertaken by trained taxonomists; appearance and location must be carefully recorded so that finds will be replicable. Samples are next dried and ground. While these processes may sound straightforward, they must also be performed to tight tolerances. The next step is typically to extract active compounds with a chemical solvent. Extracts are then tested to determine activity for certain purposes. These tests, or assays, are today typically performed *in vitro* in a matter of minutes, and are intended to determine if a certain chemical reaction occurs.

Once products with promising properties are identified, their active compounds must be isolated. These isolated active compounds may then be “optimized” that is, chemically modified to increase efficacy or reduce side-effects. Experimental drugs are subjected to several rounds of clinical trials, which may, of course, be terminated at any point if it is determined that the research is unlikely to be successful. Production planning, patent application, and pursuit of regulatory approval maybe conducted concurrently with other activities. Finally, if tests have beta successful and regulatory hurdles cleared, commercial sales may begin.

III. Value and Redundancy in Indigenous Genetic Resources

In this paper we seek to determine the value of indigenous genetic resources in situ for pharmaceutical research, and, by extension, the incentives that might be created by

pharmaceutical research for the preservation of undisturbed habitat; we derive a demand curve for indigenous genetic resources and their habitat. We then determine from this demand curve the willingness to pay for the “marginal **species.**”⁹

In deriving this demand curve we must consider not only the likelihood that useful products will be found in one sample, but that they will be duplicated by other finds. The marginal value of genetic information for medicinal purposes is measured by its contribution to the improvement of available health care. For example, the value of a new cancer treatment is determined by its capacity to improve remission rates, reduce side effects, lower costs, and so forth. A new drug that maybe effective but is identical or inferior to an existing treatment is of little value. While the discovery of a novel compound may not often prove completely superfluous it is often the case that one product will largely duplicate another, or that discovery of one effective compound will reduce the urgency, or even eliminate the need to continue research on others. ¹⁰

The essence of the argument we will make more formally below is that *regardless* of the probability with which the discovery of a commercially useful compound may be made, if the set of organisms that may be sampled is large, the value of the marginal species may be very small. At any given time, researchers will be searching for compounds effective in particular application. If the probability that a species chosen at random will yield an effective compound is high, the probability that two or more species

⁹ We will, for want of a better index, treat "species" as the basic units of genetic differentiation. It would be inaccurate to suppose that the all species are seperated by the same degree of genetic variation. It is common, however, to consider the species both as the basic unit of biological diversity [Wilson, 1992] and of economic value.

¹⁰ This point is illustrated by taxol, a drug derived from the bark of the pacific yew tree that is used to combat ovarian cancer. Though perhaps the most important anti-cancer find in recent years, the drug provides only an incremental improvement in our ability to treat the disease. Comparing it to the most effective alternative treatment, while taxol has in some tests shrunken tumors in a higher proportion of women for a few more months, is has more severe side effects, costs three times as much, and has not conclusively extended lives. “The Aura of Miracle Fades from a Cancer Drug,” Gina Kolata, *New York Times*, November 7, 1993.

will be found to do so is also high. To the extent that additional species from which to sample are likely to be redundant, their marginal value will be low. Conversely, if potentially valuable compounds are so rare as to make their discovery in two or more species highly unlikely, the probability of their discovery in any species will be unlikely.

We will treat these issues more formally below; we note in passing, however, that there are several reasons for which redundancy of genetic resources may be relatively common. First, individuals of the same species may be redundant. The same species may be found over a wide range. If all representatives of a species produce a particular compound, individuals in excess of the number needed to maintain a viable population are redundant. Second, there are numerous instances in which identical drugs, or drugs with similar clinical properties, have been isolated from different species [Farnsworth, 1988].¹¹ To give a recent example, the discovery of the anti-cancer drug taxol in the Pacific Yew of Western North America has set pharmaceutical researchers looking for similar compounds in its old-world **relatives**.¹² Given the numerous examples of parallel morphological development in the evolution literature, it should not be surprising to find that different organisms that have evolved in similar ecological niches have developed similar chemicals.

Finally, there is a dimension of what we might label clinical or medicinal, redundancy. Very different compounds, perhaps even drugs working through different mechanisms, may be effective in treating the same set of symptoms. Moreover, while the inventiveness of nature in developing useful compounds is much extolled as a factor in the increased demand for natural products for pharmacological research [Findeison and Laird, 1991], it is possible that synthesis from non-organic sources would yield substitutes for natural product leads.

¹¹ It may also be the case that there are a host of other sources of common compounds that remain undiscovered because current sources are adequate.

¹² See, e. g., "A New Cancer Drug May Extend Lives - at Cost of Rare Trees," Marilyn Chase, *Wall Street Journal*, April 9, 1991.

IV. A Simple Model

In this section we derive a simplified demand function for indigenous genetic resources in pharmaceutical prospecting, determine the maximum willingness to pay for the “marginal species,” and consider the sensitivity of the value of the marginal species to the probability of discovery and assumptions concerning overall profitability. We begin with a very simple model. Suppose that medical researchers have identified a need for a new product. A new product, if successfully developed, will earn net revenues of R . R is assumed to be net of production, advertising, and marketing costs, but gross of any costs of product research and development (i. e., costs of determining whether or not a natural material will in fact lead to a commercially successful product). These costs of research and development will be denoted by c .

Suppose that there are n species of organisms that may be sampled in the search for the new product. Suppose further that p is the probability with which any species sampled at random yields a successful commercial product. We treat each new sampling as an independent Bernoulli trial with equal probability of success. Testing for a particular application ends with the first success: once a successful product is found, further discoveries would be redundant. Thus, the value of the entire collection of n samples is

$$\begin{aligned} V(n) &= pR - c + (1-p)[pR - c] + (1-p)^2[pR - c] + \dots + (1-p)^{n-1}[pR - c] \\ &= \frac{pR - c}{p} [1 - (1-p)^n]. \end{aligned} \tag{1}$$

That is, with probability p , the first organism tested yields a commercially successful product and the search ends. With probability $1-p$, the first organism tested does not yield a successful product and the second organism is tested, and so on. If none of the n organisms tested yields a commercially successful product, search ceases.

What is the value of the “marginal species?” In other words, how much does total expected value increase with the addition--or decrease with the loss--of a species that

could be tested? The increase in total value to be realized by the preservation of an additional species is

$$\begin{aligned} V(n+1) - V(n) &= \frac{pR - c}{p} [1 - (1-p)^{n+1}] - \frac{pR - c}{p} [1 - (1-p)^n] \\ &= (pR - c)(1-p)^n \end{aligned} \quad (2)$$

we will abbreviate this expression for the value of marginal species as $v(n)$ in what follows.

Note the straightforward intuition underlying expression (2): the value of the marginal species is the expected payoff in the event it is sampled $pR - c$, times the probability with which search is unsuccessful in the set of n other species, $(1-p)^n$.

Obviously, the buyer must believe that $pR - c > 0$ if any sampling is deemed worthwhile; on the other hand, as p becomes larger the magnitude of $(1-p)^n$ declines more quickly than than of $pR - c$ increases. In what follows, we describe how the value of the marginal species varies with the probability of success in any given trial. We derive two main results in this section. First, one must make optimistic assumptions in order to believe that the value of the marginal species is very large even if the probability of success in each trial were that which maximizes the value of the marginal species. Second, the function relating the value of the marginal species to the probability of success in any given trial is sharply peaked. With large numbers of organisms from which to sample, not only is the maximum value of the marginal species low, but the value also falls off steeply if the probability of success differs even slightly from the maximizing probability.

Differentiate (2) with respect to p to find that

$$\begin{aligned} \frac{\partial v}{\partial p} &= -n(pR - c)(1-p)^{n-1} + R(1-p)^n \\ &= [R - c - (n+1)(pR - c)](1-p)^{n-1} = 0 \end{aligned} \quad (3)$$

when p is chosen to maximize $v(n)$.

The second-order condition for a maximum requires that

$$\frac{\partial^2 v}{\partial p^2} = -(n-1)[R - c - (n+1)(pR - c)](1-p)^{n-2} - (n+1)R(1-p)^{n-1} \leq 0.$$

As the satisfaction of the first-order condition requires that the expression in square brackets is zero at the maximum the second-order condition is satisfied. It is also easy to see that there is only one extreme point on the interval [0, 1], so the probability that maximizes the value of the marginal species is unique.

The first-order condition may now be expressed as

$$p^*R - c = \frac{R - c}{n+1},$$

or

$$p^* = \frac{R + nc}{(n+1)R} = \frac{1}{n+1} + \frac{n}{n+1} \frac{c}{R} \quad (4)$$

The restrictions that $p^*R - c > 0$ and $p^* < 1$ are both satisfied if $R > c$.¹³

Using (4), we can derive the maximum possible value of v , which we will call v^* :

$$v^* = v(n) \Big|_{p^*} = \frac{R-c}{n+1} \left(\frac{R-c}{R} \frac{n}{n+1} \right)^n. \quad (5)$$

The approximation $\left(\frac{n}{n+1} \right)^n \approx \frac{1}{e}$ (where e is the base of the natural logarithm,

approximately 2.718) is very accurate for values of n on the order of those we are

considering for wild species. Incorporating this approximation, we have

$$v^* \approx \frac{R-c}{(n+1)e} \left(\frac{R-c}{R} \right)^n. \quad (6)$$

Expression (6) still involves a number of variables concerning whose magnitudes and relative magnitudes we have not yet said anything. At this point we can see, however, that it is entirely possible that the *maximum* possible value of the marginal species could be insubstantial. As n grows large, v^* will be small for even relatively small values of c . This is true for two reasons. The first is the $n + 1$ in the denominator of (6). The second

¹³ Of course, we would expect $R \gg c$; the value of a proves discovery substantially exceeds the cost of evaluation.

is that $\frac{R-c}{R}$ is raised to the nth power in (6); for large values of n, this expression will

become quite small for even moderate values of c relative to R.

It is also revealing to express (6) in another way. From (1), we can define the expected revenues of a program searching for a particular product as $\Pi = R[1 - (1-p)^n]$, and the total expected costs as $K = \frac{c}{p}[1 - (1-p)^n]$. We can

then rewrite

$$\frac{R-c}{R} = 1 - \frac{pK}{\Pi}.$$

Using (4) to evaluate this expression at p^* , we find

$$\left(\frac{R-c}{R}\right)^n = \left(\frac{(n+1)(\Pi - K)}{(n+1)\Pi - nK}\right)^n$$

For large n, we have approximately

$$\left(\frac{R-c}{R}\right)^n \approx e^{\frac{-K}{\Pi-K}}$$

and the maximum value of the marginal species is approximately

$$v^*(n) = \frac{R-c}{(n+1)} e^{\frac{-\Pi}{\Pi-K}} \quad (7)$$

As K approaches Π , $v^*(n)$ again approaches zero. In short, the value of the marginal species can only be high if the expected aggregate profitability of the research venture is high. In Figure 1 we illustrate this **relationship**.¹⁴

It also bears mentioning both that the marginal species takes on its maximum value at a probability relatively close to that at which prospecting "breaks even" and that the value of the marginal species declines relatively rapidly with respect to probability after having reached a maximum. Recall that prospecting is only profitable in expectation if

¹⁴ The curve in Figure 1 quickly approaches a linear relationship; recall from (7) that

$$v^*(n) = \frac{R-c}{(n+1)} e^{\frac{-\Pi}{\Pi-K}}.$$

For $R \gg K$, the exponential term is almost constant, so the linear term in $R - c$ dominates.

$pR - c > 0$, i. e., $p > R/c$. Our statements about relative closeness maybe made more

concise if we define a basic unit

$$\mu = p^* - \frac{R}{c} = \frac{1}{n+1} \frac{R-c}{R}. \quad (8)$$

Note that μ is necessarily less than $\frac{1}{n+1}$.

If we now consider v , the value of the marginal species, as a function of p , the probability of success in any given trial (fixing n), it follows that $v(p^* - \mu) = 0$. More generally,

$$v(p^* + m\mu) = (m+1) \frac{R-c}{n+1} \left(\frac{n-m}{n+1} \frac{R-c}{R} \right)^n.$$

For large n , the approximation

$$v(p^* + m\mu) \approx \frac{R-c}{n+1} \frac{m+1}{e^{m+1}} \left(\frac{R-c}{R} \right)^n$$

is very accurate. Thus, to a very close approximation

$$v(p^* + m\mu) \approx \frac{m+1}{e^m} v(p^*). \quad (9)$$

The shape of this function is illustrated in Figure 2; it is, of course, the same as the graph of $(pR-c)(1-p)^n$. Note the extreme concentration at the function's peak. Recall that

$< \frac{1}{n+1}$; thus, on an interval of length less than $\frac{10}{n+1}$, $v(n)$ varies from 0 to its

maximum value to $10e^{-9} = 0.0012$ times its maximum value. p^* itself is greater than $\frac{1}{n+1}$. If, as seems likely, a researcher cannot predict the probability with which she

anticipates success in any given sample evaluation within an order of magnitude *ex ante*, her expectation of the value of the marginal species is likely to be very low.

V. Some Specific Examples

It is impossible to estimate the value of marginal species with any precision. Even deriving an estimate for its maximum possible value is a highly speculative exercise. We can, however, get some idea as to the magnitudes involved by using some data from the

pharmaceutical industry. While our estimates are little more than back-of-the-envelope calculations, a more careful treatment might well yield still lower numbers.

In order to relate our model to real-world data, we must aggregate over all possible discoveries. Some of what we believe to be the excessive enthusiasm for the potential of genetic prospecting as a conservation strategy stems from an unrealistic view of the number of products” to be generated from prospecting activities. ¹⁵ One rarely finds things for which one does not look. Genetic prospectors subject samples to a limited series of tests at any given time. While the history of science records many serendipitous discoveries, they are the exceptions. It would be difficult to come up with a figure for the number of applications for which species are tested, ¹⁶ whatever that number, however, we do have statistics on the numbers of new products developed. We should require as a reality check that the probability of discovery times the number of applications for which tests are performed not vastly exceed current numbers of new products developed. ¹⁷

We will suppose that there exist a series of “potential products” that might be derived from genetic resources. Potential products might be regarded as cures for diseases. The demand for them may arise as new infectious diseases become **widespread**,¹⁸ as demographic characteristics change and the health needs of certain groups become more **important**,¹⁹ or as new technologies are developed.²⁰ We label these

¹⁵ We do not treat agricultural and industrial applications here. Casual empiricism and conversations with researchers suggest that the value of the marginal species for these purposes may be much lower still, as a still greater number of substitute research opportunities may be available (in agricultural research, for example, pest-resistant strains can often be developed from the large number of very close--often of the same species--relatives of cultivated varieties).

¹⁶ Conversations with researchers suggest that on the order of one hundred tests or less are done on species for their pharmaceutical potential.

¹⁷ If more thorough genetic prospecting activities did in fact yield a deluge of new products we would have to wonder again if the marginal new product were of any appreciable value.

¹⁸ For example, the AIDS virus was not identified until the 1980s.

¹⁹ The aging of the population and the increased need for geriatric care are good examples here.

as potential products, as there is no assurance that solutions to newly identified needs can actually be found. It is not unreasonable to suppose that new potential products are generated by a Poisson process with **parameter λ** . Then, in expectation, **λ** potential new products will be identified every year. We will suppose that **λ** remains constant overtime: potential new products are identified at a more-or-less constant rate.

We might suppose that each new potential product j identified at time t would have a stream of revenues net of research and development costs denoted by R_{jt} . Similarly, we could say that the cost of evaluating the potential of the i th species for its use in deriving the j th potential product at time t is a random variable C_{ijt} . It is not unreasonable to assume, at this level of detail, that all the R 's and c 's are statistically independent and denote the expectation of each as R and c , respectively. If future returns

are discounted at a constant rate r , the expected value of the marginal species is simply

$$\sum_{n=0}^{\infty} \lambda(1+r)^n (pR - c)(1-p)^n = \frac{\lambda}{r} (pR - c)(1-p)^n. \quad (10)$$

As was noted above, if we are considering extremely large numbers of species, the value of any one species must be negligible. While biologists are unable to specify the number of living species to within even an order of magnitude, a reasonable lower bound would be ten million specks. *The "base case" estimate we report below would have been reduced by forty-one orders magnitudes if we had assumed that all of ten million species were equally likely to yield a successful product.*

Let us, therefore, narrow the range of species over which we consider searching. Some have argued that phytochemicals-compounds produced by higher plants--have exceptional pharmaceutical potential [see, e. g., Joffe and Thomas 1989]. These compounds may be unlikely to be produced by other types of organisms, and may have substantial pharmaceutical value. Aspirin, quinine, and the anti-cancer drugs vincristine,

²⁰ For example, the demand for immunosuppressant drugs has increased greatly as a result of the progress that has been made in organ transplant surgery.

vinblastine, and taxol are all derived from higher plants. There are estimated to be at least 250,000 living species of higher plants [Myers, 1988; Wilson, 1992] .²¹

We will consider the value of the marginal species of higher plant assuming that p is chosen so as to maximize that value. Regrettably, there are no reliable estimates of the parameters λ , R , or c each might be inferred indirectly from knowledge of aggregate industry success rates, revenues, and costs, however. We will ask what the values of the parameters we seek would be if observed data were generated by the probability of success that maximizes the value of the marginal species.

Between 1981 and 1993 the U. S. Food and Drug Administration approved an average of 23.8 new drugs per year [PMA, 1982-1994]. This rate was relatively stable (see Table 1), varying between 14 in 1983 and 30 in 1985 and 1991. There is no discernible trend in the data. As new drug applications include both compounds first approved in the U.S. and subsequently sold to the rest of the world, as well as drugs already sold elsewhere but just being approved in the U. S., we take these figures to be representative of world discovery rates.

About one third of all prescription drugs are derived from higher plants [Chichilnisky, 1993]; we will assume that ten new drugs per year are expected to be discovered from investigating higher plants. The expected number of new products developed per year is the expected number of new potential products identified, λ , times the probability with which a successful commercial product is developed, $1 - (1-p)^n$.

Di Masi, et al. [1991] estimate pharmaceutical research and development expenditures per successfully derived product to be \$231 million. A recent report suggests that “a reasonable upper bound” on the figure is \$359 million [OTA 1993]. We

²¹ Farmsworth [1988] places the number at between 250,000 and 750,000, so our estimates of the value of the marginal species should again be biased upward.

will assume a value of \$300 million for our calculations. In our notation the R&D cost per successful product developed would be expressed as $\frac{c}{p} = \frac{K}{1 - (1-p)^n}$.

We summarize some data relating net revenues to R&D costs for major pharmaceutical companies in Table 2. We assume that marketing and administrative costs vary in proportion to the number of products marketed, so we define net revenues as sales less production costs and marketing and administrative costs.

This data cannot be applied directly, however. In our model we have assumed that samples are evaluated, costs are incurred, and revenues received instantaneously. In the real world of course, these things occur overtime. Let us consider, then, a pharmaceutical company that earns a stream of revenues from products of various vintages. For simplicity, suppose that products differ only by their dates of discovery; each product of the same age earns the same net revenues (in expectation) regardless of when it reaches that age. $\lambda[1 - (1-p)^n]$ is the number of products expected to be developed in any given period and let ϕ_t be the expected net revenue received by a product of age t . Then the total expected net revenues of a firm of age T will be

$$\Phi = \lambda[1 - (1-p)^n] \sum_{t=0}^T \phi_t.$$

If we assume that net revenues of older products eventually decay and the firm is sufficiently old, the firm's total expected net revenues should be constant over time under our assumptions.

The expected present value of the net revenues of products developed in period T will be less than the value of its current receipts, however, as these revenues will not be received immediately. That is,

$$\lambda[1 - (1-p)^n]R = \lambda[1 - (1-p)^n] \sum_{t=0}^T \frac{\phi_t}{(1+r)^t}.$$

A reasonable specification of the ϕ_t 's might be to suppose a stylized model of patent protection. Suppose that new products are the exclusive property of their inventors for T

periods, during which constant expected net revenues of ϕ are received. After the expiration of the patent we will suppose that all profits are competed away. Under these assumptions we would find that

$$R = \frac{1 - (1-r)^T}{rT} \phi.$$

It is clear that $\frac{1 - (1-r)^T}{rT}$ is less than one. To give some idea of general magnitudes, if

$r = 0.10$ and $T = 17$ --values that might be assumed in consideration of pharmaceutical company discount rates and patent law in the U.S.-- $\frac{1 - (1-r)^T}{rT}$ would be about 0.49.

We might also do a similar correction for the timing of research expenditures; even in a steady state, a firm's current R&D expenditures overstate the expected present value of its expenditures on products under development, as the latter will be incurred in the future, and hence, discounted. The most favorable assumption that we could make on costs would be that they are all incurred at the last possible moment, however. All R&D costs are, by definition, incurred before a product is marketed, so revenues are not received until all costs are incurred. Thus, if we discounted from the time at which research begins until costs are incurred, we would also want to discount from the time at which research begins until revenues begin to be received. These would be offsetting corrections, however (we care about the ratio of total expected costs to total expected revenues).

Combining all these considerations it seems generous to suppose that an investment in pharmaceutical R&D pays a fifty percent return. If the cost per successful product developed is \$300 million, then, we will suppose that the net revenue is $R = \$450$ million. Finally, we will suppose that pharmaceutical firms discount future returns at ten percent per year.

The results of an exercise based on expression (6) and these assumptions are summarized in Table 3. Our assumptions imply that the probability of hitting on any given species for any given potential product that maximizes the value of the marginal species

would be about twelve in a million. Over an entire collection of 250,000 species from which to sample the probability of making a hit is slightly over ninety-five percent. The expected cost of evaluating a sample is around \$3,600. The maximum possible value of the marginal species is slightly less than \$10,000.

We must emphasize that these estimates are extremely sensitive to changes in assumptions, however. Recall that we have evaluated the marginal species at that probability of success that maximizes its value. The results reported in Table 3 indicate that $p^* = 0.000012$. If we continue to assume that $c = \$3600$ and $R = \$450,000,000$, but allow p to vary, we may get very different results. We must have $p \geq 0.000008$ in order to have the expected value of conducting any test be positive. From that level, however, the value of the marginal species quickly increases to the peak at \$9,431. If p were to increase further, to 0.000040, the value of the marginal species declines to only about \$67. If p were an order of magnitude greater than p^* --but still only on the order of 10^{-4} --the value of the marginal species would plummet to less than \$0.0000005!

The second assumption that can make a great deal of difference in our results concerns the relative magnitude of net revenues and costs. In our base case scenario we assumed that expected net revenues exceed expected research costs per successful new product derived by fifty percent. If we assumed instead that expected net revenues exceed expected costs per successful product by twenty-five percent, the value of the marginal species would be only \$1,017.53; if expected net revenues exceed expected costs per successful product by ten percent the value of the marginal species would be **\$2.20**.²²

We will see in the next section that even numbers on the magnitude of \$10,000 may translate into very limited incentives for the preservation of threatened habitats. It is

²² Of course, if we assumed that net revenues exceed expected costs per product developed by a wider margin, we would obtain greater values for the marginal species. At a certain point however, these results become implausible for other reasons; we should not expect the overall profitability of the industry to reach unlikely levels.

worth emphasizing again, however, that we have generated values of that magnitude only under what we regard as generous assumptions. We do not claim to have proved that the marginal species is necessarily of negligible value; extremely fortuitous circumstances may combine to create greater values. Our results do suggest, however, that only very optimistic researchers might demonstrate a substantial willingness to pay.

VI. Incentives for the Conservation of Endangered Habitat

We have concentrated to this point on efforts to evaluate the worth of the “marginal species.” We are, perhaps, past due in Mining this concept and justifying its importance. Economists should be familiar with the notion of valuing resources on the margin but maybe uncomfortable with applying marginal analysis man ecological context. How can one identify the marginal element of a large and complex ecosystem? We will elaborate on our assumptions in this context in a moment; it suffices to say for now that we will assume that the number of species in an ecosystem declines as a continuous function of habitat loss.

It is important to note, however, that we are addressing explicitly only questions concerning the value of the marginal hectare of land on which the marginal species grows. That is, we are concerned only with matters of land conversion. Other human impacts may be more widely felt. The introduction of exotic species, the release of pervasive pollutant, or the effects of global climate change may have devastating impacts on biological diversity. A marginal analysis maybe inappropriate for the consideration of such phenomena. In the event of apocalyptic ecosystem collapse, however, the lost potential for pharmaceutical research might well be the least important of our worries.

Much of the current concern with respect to the extinction of species arises from the destruction of habitat. There is an extensive literature on the relationship between habitat area and the richness of species. We will employ a widely used model in the ecological literature, advanced by Preston [1960; 1962] and incorporated by McArthur

and Wilson [1967] in their influential theory of island biogeography. While this model has been widely criticized by ecologists [See for example, Simberloff and Abele, 1982; Boeklen and Gotelli, 1984; and Zimmerman and Bierregaard, 1986] for its inability to predict the viability of individual populations and its resultant lack of utility in refuge design, its predictions are likely to bias the estimate of the value of the marginal hectare **upward**,²³ and for this reason we will employ it. We might also note in passing that it is generally species-areas relationships that are employed to generate even the more apocalyptic estimates of impending biodiversity losses.

The theory of island biogeography predicts that the number of species, n_i , in a particular taxon found in an area of size A_i is given by

$$n_i = \alpha_i A_i^Z, \quad (11)$$

where α_i is a constant that measures the species richness potential of an area and Z a constant whose value is approximately 0.25 [see e.g., McArthur and Wilson, 1967; Preston, 1962; Wilson, 1988].

To infer the maximum possible value for the marginal hectare of land for genetic prospecting, then, we can differentiate $V[n(A)]$ with respect to A to find that

$$\frac{\partial V}{\partial A} = \frac{\partial V}{\partial n} \frac{\partial n}{\partial A}.$$

$\partial n_i / \partial A_i$ can be found by differentiating (11) with respect to A:

$$\frac{\partial n}{\partial A} = Z \alpha_i A_i^{Z-1} = Z \frac{\alpha_i A_i^Z}{A_i} = Z D_i, \quad (12)$$

where D_i is the species density, i.e., the number of species per unit area.

²³ Island biogeography, as the name suggests, is based on the distribution of species in physically isolated habitats--islands in mid-ocean, labs in large land masses, isolated mountaintops, and the like. The degree to which habitat conversion by, for example, felling forests for agriculture, actually isolates populations is much disputed [see, for example, Lugo, Parrotta and Brown, 1993].

We can combine expression (12) with our earlier results presented in Table 3 to estimate the conservation incentives that would arise in particular threatened habitats. If we accept the figure of \$9,431 for the value of the marginal species of higher plant, we can translate this number into a figure for a pharmaceutical company's maximum willingness to pay to conserve a marginal hectare. In Table 4 we have entered data on Norman Myers's [1988; 1990] eighteen biodiversity "hot spots." We find that the greatest willingness to pay might be on the order of \$20 per hectare in Western Ecuador. In other areas with less genetic diversity the willingness to pay would be considerably lower, on the order of a dollar per hectare or less. Again, it should be emphasized that even these very low estimates arise under optimistic assumptions concerning the probability of discovery and expectations of profitability. Equally plausible conjectures concerning these parameters would yield radically lower values.

VII. Caveats and Extensions

The simple model we have developed above and on which we based the numerical exercises we have reported is unrealistic in several respects. In this section we consider two ways in which it might be improved and how our findings might differ if a more realistic-if less tractable-model had been specified. We then discuss how other sources of uncertainty might affect our results. We conclude this section with some reasons for which we believe the model presented in Section III nevertheless provides useful insights.

Sequential Testing

In the simple model specified above we treat the cost of testing each individual species as a random variable drawn independently from the same distribution. In the real world, of course, testing is a complicated and extensive process. The first test may be very simple (e.g., the "test" may consist of determining whether or not a given species

belongs to a taxon considered likely to contain the desired compound), the next test somewhat more complicated and expensive, and so forth.

Consider a simple example. Suppose that two tests are required to determine if a sample contains the desired product. Suppose that the (expected) cost of the first test is c_1 and that of the second c_2 . Denote by p_1 the probability that a sample chosen at random “passes” the first test and by p_2 the probability that it “passes” the second. As before, let R be the (expected) net revenues earned by a successful product--i.e., one that passes both tests. Then the value of the marginal sample is the expected value of evaluating a sample at random, net of expected testing coats, times the probability with which no successful product is identified among the first n species sampled. That is,

$$v(n) = [p_1 p_2 R - (c_1 + p_1 c_2)] [1 - (1 - p_1 p_2)^n].$$

Differentiating with respect to both p_1 and p_2 yields two first-order conditions:

$$[p_1 p_2 R - (c_1 + p_1 c_2)] n p_2 (1 - p_1 p_2)^{n-1} + (p_2 R - c_2) [1 - (1 - p_1 p_2)^n] = 0$$

and

$$[p_1 p_2 R - (c_1 + p_1 c_2)] n p_1 (1 - p_1 p_2)^{n-1} + p_1 R [1 - (1 - p_1 p_2)^n] = 0$$

Suppose that both of these conditions hold. Multiply the first by p_2 and the second by p_1 .

As both expressions are equal to zero, we must then have

$$(p_1 p_2 R - p_1 c_2) [1 - (1 - p_1 p_2)^n] = p_1 p_2 R [1 - (1 - p_1 p_2)^n], \text{ or}$$

$$p_1 c_2 = 0.$$

Obviously, p_1 cannot be zero if the species is to have any value. If c_2 were zero we would have the problem we have already solved above, with p replaced by $p_1 p_2$ and no meaningful basis for regarding the probability as being separate. Thus, for $c_2 > 0$ we conclude that the value of the marginal species is maximized **if** $p_1 = 1$; that is, the assumption that the first-order conditions are simultaneously satisfied is contradicted. It is easy to demonstrate that this result generalizes to any finite number of required sequential tests. We conclude, then that the assumption that all sequential tests are compressed into

a single number denoting the expected cost of all testing does not bias our estimate of the value of the marginal species downward.

Continued Search

Another way in which our simple model has not been realistic is in its treatment of search following initial sampling successes. We have assumed that search stops after the first success. As we have noted above, however, practice differs from this abstraction. The identification of compounds of potential value in one species may lead to a continued search for similar but more effective compounds in others. Let us consider how this consideration might be incorporated in a more realistic model, what might be gained in detail, and what might be lost in tractability.

A more realistic treatment might specify the payoff to a particular sample taken at random as a random variable θ . Assume again that the cost of evaluating a sample--of determining the realization of θ --is c . We can generalize the model we have presented above by noting that, under reasonable distributional assumptions, once a realization of θ in excess of some certain value, call it θ^* , is encountered search will cease. That is, let $f(\theta)$ be the distribution of θ and $(0, \bar{\theta})$ its support (it is convenient--and realistic--to set the lower bound of the support of θ equal to zero: the pharmaceutical researcher cannot be obliged to develop products of negative value). Suppose also that the θ 's are independently and identically distributed across species.

The expected gain to be realized from evaluating an additional sample given that one of value x has already been identified is

$$\int_x^{\bar{\theta}} (\theta - x) f(\theta) d\theta - c. \quad (13)$$

Denote **by θ^*** that value of x for which (13) is exactly **zero**.²⁴

²⁴ Obviously, such a θ^* will **exist if $\bar{\theta}$ is finite**. More generally, we must require that there not be too much mass in the right tail of the distribution of θ . It seems entirely reasonable to suppose that such a θ^* exists in our context.

Suppose that $\tilde{\theta}(n)$ is the greatest value of θ encountered in a collection of size n (i. e., $\tilde{\theta}(n)$ is the greatest order statistic in a collection of size n). Now we can denote the expected value of a collection of n species with respect to a particular potential product as

$$V(n) = ([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c) + F(\theta^*)([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c) + F(\theta^*)^2([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c) + \dots + F(\theta^*)^{n-1}([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c) + F(\theta^*)^n E(\tilde{\theta}(n)|\tilde{\theta}(n) < \theta^*). \quad (14)$$

This expression is relatively straightforward--and similar to (1). Its m th ($m \leq n$) term consists of the probability with which the m th species yields a product so successful as to obviate the need for further search, times the expected value of the product given that it is sufficiently valuable that search is suspended less the cost of sample evaluation, all times the probability that a product so successful as to motivate the suspension of search is not discovered in the previous $m - 1$ species sampled. The final term is the product of the probability that no species sampled yields a product sufficiently valuable as to motivate the end of search and the expected value of the most valuable product found in searching over all n species, conditional on none yielding a value greater than θ^* .

Note that

$$F(\theta^*)^n E(\tilde{\theta}(n)|\tilde{\theta}(n) < \theta^*) = \int_0^{\theta^*} \theta n f(\theta) F(\theta)^{n-1} d\theta,$$

as $n f(\theta) F(\theta)^{n-1}$ is the probability density of the greatest order statistic in a sample of size n .

It is now straightforward to show that

$$v(n) = V(n+1) - V(n) = ([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c)F(\theta^*)^n + \int_0^{\theta^*} \theta f(\theta) F(\theta)^{n-1} [(n+1)F(\theta) - n] d\theta. \quad (15)$$

The term on the first line to the right of the equal sign is familiar from (2); it is (2), with p replaced by $1 - F(\theta^*)$ and R replaced with $E(\theta|\theta \geq \theta^*)$. It is obvious that (2) and (15) coincide when the distribution of θ is sharply bimodal: if all "failures" are without commercial value and the value of all "successes" are tightly clustered.

The question is, then, whether the value of successes are clustered. We believe that they are likely to be. Continued search for pharmaceutically active compounds for a particular purpose after one “successful” compound has been discovered is likely to be geared toward finding other species in which the same or similar compounds are produced more plentifully. In other words, continued search may be undertaken in order to lower costs of production. Production costs are a relatively unimportant component of pharmaceutical industry profits. Thus, large increments in value may be unlikely to result from subsequent discoveries.

Moreover, it must be remembered that we are asking what the expected value of an untested species is at the margin and *ex ante*. Some additional testing may be done because *conditional* expectations of value are high enough to justify it. While variations in chemical properties among related species may motivate continued search, the lion's share of the value may be realized by finding an organism that serves to identify the taxon to be the subject of further search. All organisms in the taxon may be fairly close substitutes for this purpose. All organisms not in the identified taxon have a conditional value of zero.

Two Additional Sources of Uncertainty

While we have mentioned that R and c may be regarded as the expectations of random variables, we have not dealt explicitly with* underlying stochastic expressions. If we replace each by the corresponding random variable, it can be shown that the maximum value of the marginal species in our simple model--expression (6)--is convex in both. If we sum overall anticipated future potential products and evaluate the resulting expression at the expectations of R and c , our estimate of the maximum possible marginal value will be biased downward. This consideration does not greatly concern us, however. As shown in figure 1, and explained in footnote 14, expression (6) is nearly linear when profit margins are appreciable. The function is sharply curved only when marginal values are negligible anyway.

Another source of unmodeled uncertainty may be more problematic. The extinction of a species is the example *par excellence* of an irreversible **(dis-)investment**.²⁵ It is well known [see, e. g., Pindyck 1991] that such investments should be made only when their expected benefits exceed their costs by a positive differential. The size of this differential is determined by the parameters of the stochastic process by which benefits (and, in a fuller treatment, costs) are assumed to be generated. In particular, greater uncertainty in the process induces a greater differential. This “option value” argument is also often emphasized in the ecological and environmental literature on the value of endangered resources for pharmaceutical research.

We do not propose to suggest a figure by which our earlier numerical examples might be inflated in order to correct for this uncertainty. We will suggest, however, that overall uncertainty may not be great. It is true that spectacular new medical needs are identified from time to time. The sum of marginal values with respect to the various potential products for which testing may take place might evolve considerably more smoothly, however.

Other Extensions

We have just noted two ways in which our treatment of uncertainty may result in estimates of the maximum possible value of the marginal species that are too low. It is also likely that the sharply peaked shape of the value of the marginal species that are too low. It is of the probability with which any species sampled at random yields a “hit” is an artifact of our assumption that all “hits” are equivalent--although, inasmuch as we think this assumption is approximately true, we regard our results as being highly suggestive as well.

²⁵ There are some technological optimists who maintain that the premise of *Jurassic Park* is not far from being realizable, but more sober estimates suggest that retreating extinct species will remain the stuff of science fiction for the foreseeable future.

Other omissions and simplifications in our model have likely led us to overestimate the value of the marginal species, however.

One of these omissions concerns timing and discounting. We have assumed that different species are sampled sequentially, but that each is evaluated instantaneously. To have inserted discounting in our simple model would not have complicated matters much; it could be accommodated by multiplying our expression for the value of the marginal species by a discount factor. If, as seems likely, it could take years before the marginal--or "last"--species would even be evaluated, values would be considerably lower.

Of course, research does not proceed by evaluating all samples sequentially. In practice, firms also decide in how much capacity they ought to invest. Firms with greater research capacity can evaluate different species simultaneously. To evaluate a large number of species simultaneously is to increase the probability with which redundant expenses are incurred however.

Redundant expenses are one of the reasons for which a more realistic treatment of market structure might also result in lower estimates of the willingness to pay for the marginal species. Over and above the fear of being beaten to a promising lead by a competitor, rivals may also dissipate values by overinvesting in research and development. There are a number of models in the industrial economics literature [see, e. g., Loury, 1979; Brander and Spencer, 1984] in which firms innovate too fast--incurring too great an expense--in an effort to finish first.

More importantly, our numerical example does not recognize the abundance of potential sources of new pharmaceutical products. In constructing our numerical example we have supposed that all the world's species--and more generally all possible research opportunities--can be separated into those that might possibly yield a product and those that definitely do not. We suspect that restricting our attention to higher plants is very unrealistic. Major pharmaceutical products have been developed from a microorganism first found in the soil of a Japanese golf course and from a spore that happened to float

through the window of a laboratory in New Jersey and contaminated an ongoing experiment. Synthetic chemistry and other inorganic sources provide other alternatives. The number of available substitutes maybe much higher than we have supposed.

Finally, we have not included Bayesian updating in our analysis. We have supposed that researchers' beliefs concerning the probability that *any* organic source could contain the product sought do not decline regardless of lack of success. To suppose that downward revisions in expectations would not occur after an unbroken string of failures would imply either a very optimistic investigator or one with a very pessimistic prior; if the latter, one would have to wonder if search would have been undertaken in the first place.

VIII. Conclusions

We have developed a simple model of the demand for indigenous genetic resources for use in pharmaceutical research. We have demonstrated that the upper bound on the value of the marginal species--and by extension of the "marginal hectare" of threatened habitat--may be fairly small under even relatively favorable assumptions. Moreover, the value of the marginal species may be a very sharply peaked function of the probability with which any species chosen at random yields a commercially valuable discovery. Finally, we have argued that our model, even though it is very simple, may yet offer some important insights into the real values that biodiversity prospecting might generate for conservation.

Even if the reader rejects all of our other assertions, we would argue that the development of a model of the demand for genetic resources is an important contribution in and of itself. The valuation of genetic resources for pharmaceutical prospecting is an important issue in conservation policy. Despite numerous contributions from ecologists, environmental advocates, and, recently, economists, there has not yet been any adequate treatment of this subject. Whatever else the drawbacks of our study maybe, we have modeled values with an eye to the importance of scarcity. In addition, several recent

papers have advanced economic theories of the measurement of diversity. In none of these instances were these concepts reduced to monetary values, however.

We would also argue that our numerical examples merit serious consideration. It is true that, by making very generous estimates of the profitability of the industry and supposing very fortuitous realizations of the probability of discovery, one might generate moderate estimates for the conservation incentives provided by genetic prospecting. One would have to take a very rosy view to suppose that the probabilities of discovery happen to be precisely those that generate the maximum possible value for the marginal species. If one takes the more reasonable perspective that researchers have some subjective probability distribution over the probability with which individual species sampled will yield commercial products, it seems quite likely that the perceived value of the marginal species will be miniscule. This view seems to be consistent with information concerning observed transactions. This subject should be studied further, and the extensions we have discussed above pursued, but we would not expect a reversal of the conclusion of our analysis, however the value of the marginal species for use in pharmaceutical research, and, by extension, the incentive to conserve the marginal hectare of threatened habitat, is negligible.

We should emphasize again in closing that none of our conclusions imply that we should not be concerned with the problems of declining **biodiversity**.²⁶ Our point is, rather, that if the international community values biological diversity, it should be actively seeking other alternatives for financing its conservation.

²⁶ We should note in passing that the *social* value of the marginal species for pharmaceutical research may be higher than the private, as a successful researcher cannot appropriate the entire surplus for new drug discovery. This does not detract from our conclusion that private incentive to conserve endangered habitats for Pharmaceutical research will not be great. We doubt, however, that even the social incentives for this purpose would be large.

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Figure 1

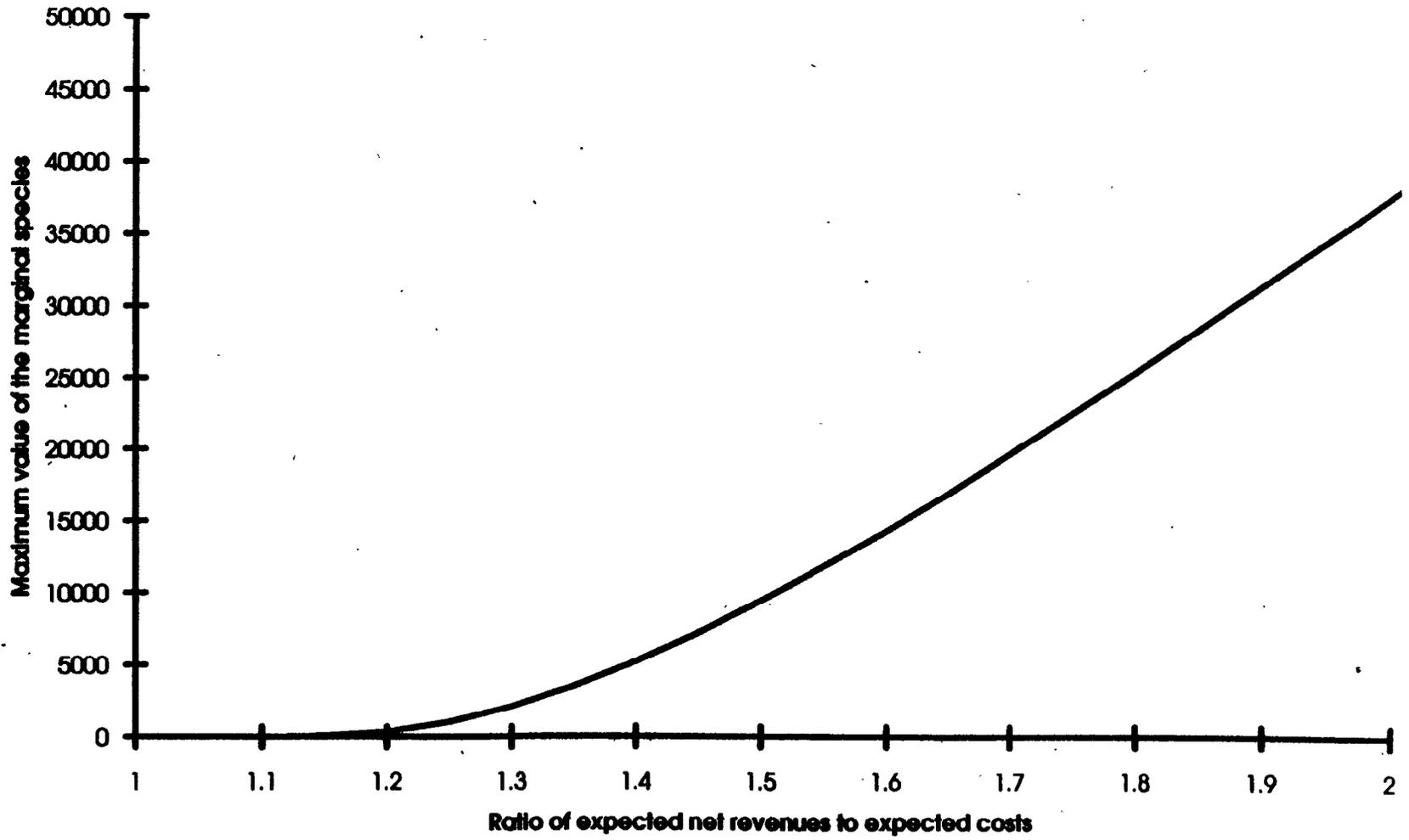


Figure 2

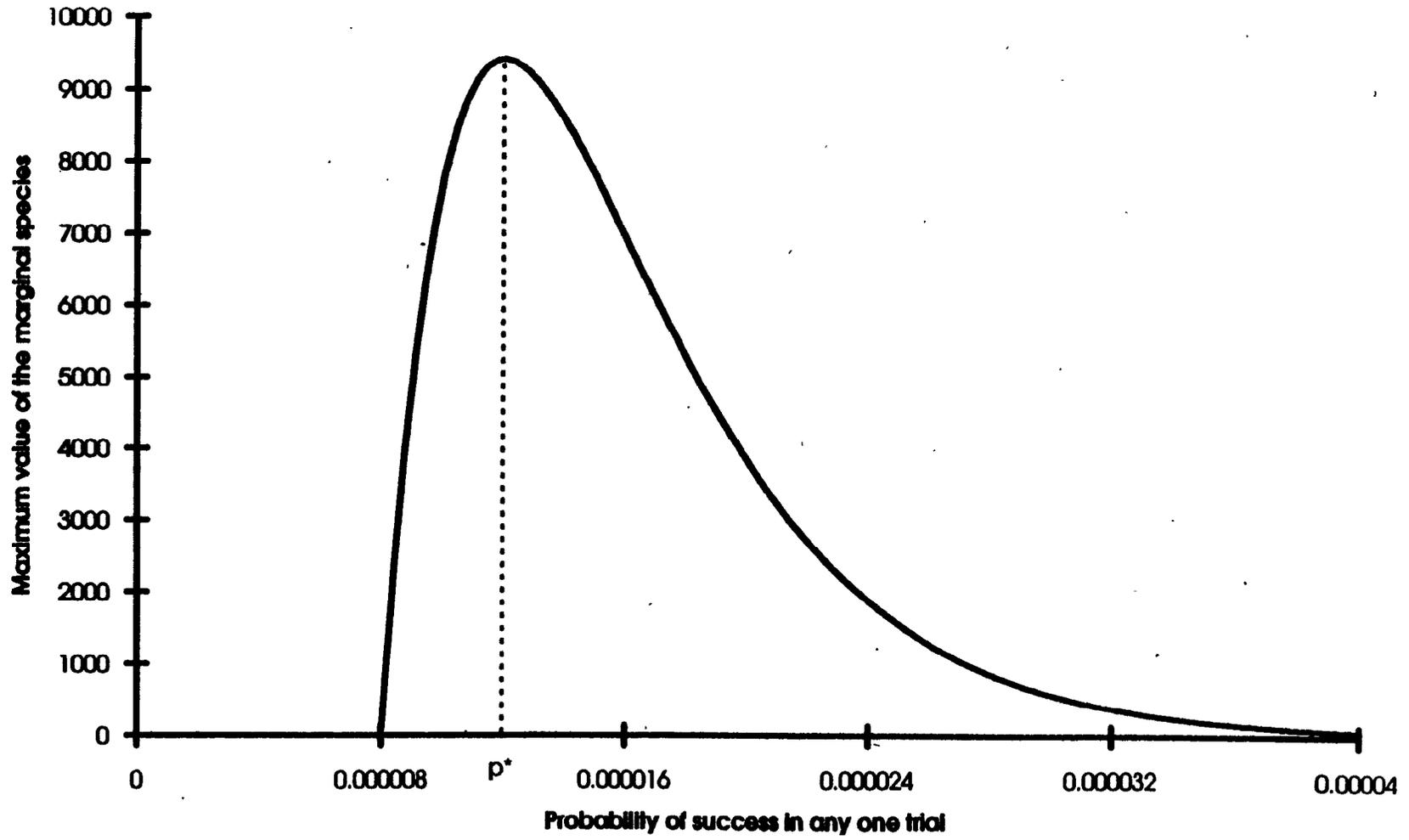


Table 1

New Drug Approvals	
1981	27
1982	28
1983	14
1984	22
1985	30
1986	20
1987	21
1988	20
1989	23
1990	23
1991	30
1992	26
1993	25

Source: U.S. Food and
Drug Administration

Table 2

Net revenues and R&D expenses of three major pharmaceutical companies										
	1992	1991	1990	1989	1988	1987	1986	1985	1984	1983
Merck										
Sales	9,622.5	8,602.7	7,671.5	6,550.5	5,939.5	5,061.3	4,128.9	3,547.5	3,559.7	3,246.1
Materials & production costs	2,096.1	1,934.1	1,778.1	1,550.3	1,526.1	1,444.3	1,338.0	1,272.4	1,424.5	1,263.4
Marketing & administrative expenses	2,963.3	2,570.3	2,388.0	2,013.4	1,877.8	1,682.1	1,269.9	1,009.0	945.5	905.1
Research & development expenses	1,111.6	987.8	854.0	750.5	668.8	565.7	479.8	426.3	393.1	356.0
Upjohn										
Sales	3,668.9	3,426.3	3,032.7	2,732.1	2,530.5	2,292.4	2,063.9	1,800.7	1,695.6	1,557.9
Materials & production costs	981.6	874.6	823.2	763.9	697.6	655.4	639.2	585.4	566.7	518.1
Marketing & administrative expenses	1,432.4	1,342.4	1,158.0	1,030.6	932.6	842.3	736.2	633.9	591.5	546.8
Research & development expenses	548.5	491.1	427.2	407.1	379.7	354.8	313.0	283.2	246.0	217.3
Bristol-Myers Squibb										
Sales	11,156	10,571	9,741	8,578	7,986	7,044	6,163	5,393	5,029	4,721
Materials & production costs	2,857	2,717	2,665	2,418	2,255	2,096	1,905	1,769	1,699	1,678
Marketing & administrative expenses	4,366	4,209	3,906	3,534	3,365	3,002	2,576	2,254	2,110	1,965
Research & development expenses	1,083	983	873	781	680	556	476	405	337	294

Source: 1992 annual reports of companies

Table 3

Base Case Scenario	
Number of species	250,000
Expected number of new products	10
Cost of developing a new product	\$300,000,000
Net revenue-to-cost ratio	1.5
Net revenue	\$450,000,000
Discount rate	0.1
c	\$3,599.96
p^*	0.000012
Probability of a hit	0.9502
λ	10.52
Value of the marginal species	\$9,431.16

Table 4

Maximum willingness to pay to preserve a hectare of land in 18 biodiversity "hot spots"					
Hot-Spots	Present Forest Area (1000 HA)	Number of Plant Species	Proportion of Plant Species Endemic to Region	Endemic Plant Species per Hectare	Maximum Willingness To Pay
Western Ecuador	250	8,750	0.25	0.00875	\$20.63
Southwestern Sri Lanka	70	1,000	0.50	0.00714	\$16.84
New Caledonia	150	888	0.89	0.00527	\$12.43
Madagascar	1,000	3,550	0.82	0.00291	\$6.86
Western Ghats of India	800	4,050	0.40	0.00203	\$4.77
Philippines	800	3,595	0.44	0.00198	\$4.66
Atlantic Coast Brazil	2,000	7,500	0.50	0.00188	\$4.42
Uplands of Western Amazonia	3,500	15,383	0.25	0.00110	\$2.59
Tanzania	600	1,600	0.33	0.00088	\$2.07
Cape Floristic Province of South Africa	8,900	8,600	0.73	0.00071	\$1.66
Peninsular Malaysia	2,600	5,799	0.28	0.00062	\$1.47
Southwestern Australia	5,470	3,630	0.78	0.00052	\$1.22
Ivory Coast	400	2,770	0.07	0.00048	\$1.14
Northern Borneo	6,400	6,856	0.39	0.00042	\$0.99
Eastern Himalayas	5,300	5,655	0.39	0.00042	\$0.98
Colombian Choco	7,200	9,212	0.25	0.00032	\$0.75
Central Chile	4,600	2,900	0.50	0.00032	\$0.74
California Floristic Province	24,600	4,450	0.48	0.00009	\$0.20

Source: Myers (1988; 1990) and authors' calculations.