The Social Value of Using Biodiversity in New Pharmaceutical Product Research

R. David Simpson
Amy B. Craft

Discussion Paper 96-33

September 1996

Resources for the Future
1616 P Street, NW
Washington, DC 20036
Telephone 202-328-5000
Fax 202-939-3460

The Social Value of Using Biodiversity in New Pharmaceutical Product Research

R. David Simpson and Amy B. Craft

Abstract

Biologists and conservation advocates have expressed grave concern over perceived threats to biological diversity. "Biodiversity prospecting" -- the search among naturally occurring organisms for new products of agricultural, industrial, and, particularly, pharmaceutical value -- has been advanced as both a mechanism and a motive for conserving biological diversity. Economists and others have attempted to estimate the value of biodiversity for use in new pharmaceutical project research. Most of these existing approaches are incomplete, however, as they have not considered full social welfare, i.e., both consumer surplus and profit. This paper addresses social welfare by calibrating a model of competition between differentiated products with data from the pharmaceutical industry. We find that the magnitude of losses from even catastrophic declines in biodiversity are negligible in comparison to the value of world production. While social values of biodiversity prospecting might motivate habitat conservation in some areas, these values are likely to be small relative to land value in other uses in even some of the more biologically rich regions of the world.

Key Words: biodiversity prospecting; differentiated products; pharmaceutical research and development; biogeographic models; global warming; habitat conversion

JEL Classification No(s).: D43; L13; Q29

Table of Contents

List of Tables and Figures

The Social Value of Using Biodiversity in New Pharmaceutical Product Research

R. David Simpson and Amy B. Craft[1]

INTRODUCTION

A number of biologists believe that human activities are causing species extinctions at alarming rates. The only precedents, they claim, are to be found in the mass extinctions associated with a handful of apocalyptic volcanic eruptions and/or meteorite strikes distributed over geological time scales (Wilson, 1992). Slowing the rates of greenhouse gas emissions, natural habitat destruction, and other factors that are believed to be inducing modern extinctions could be very expensive, however. It is natural to ask, then, what is the value of preserving biodiversity.

One (although admittedly, among many) argument frequently made is that biodiversity is a source of new industrial, agricultural, and, particularly, pharmaceutical products. Natural organisms, it is argued, are great repositories of genetic information. Wild species, in their struggle to capture prey, escape predators, resist infection, and enhance reproductive success have evolved chemical mechanisms more elaborate and inventive than those synthetic chemists can now create. If these chemical mechanisms could be adapted and refined for human use, they could be of great value. There has, therefore, been considerable interest among natural scientists and conservation advocates in "biodiversity prospecting" -- the search for new commercial products among naturally occurring organisms -- as both a mechanism and an argument for preserving biodiversity (see, e.g., Wilson, 1992; Reid, *et al*., 1993; Rubin and Fish, 1994).

In recent years economists and others have attempted to estimate the value of biodiversity for use in new product development (Principe, 1989; Pearce and Puroshothamon, 1992; Aylward, 1993; Artuso, 1994; Mendelsohn and Balick, 1995; Polasky and Solow, 1995;

---

[1] R. David Simpson, Energy and Natural Resources Division, Resources for the Future; Amy B. Craft, Stanford University.

Simpson, Sedjo and Reid, 1996). These studies vary considerably in their data, methods, and estimates. With the exception of the Principe (1989) paper,[2] however, previous efforts at valuation have not attempted to derive the social, as opposed to private, values of biodiversity for new product research. We turn to that issue in this paper.

This paper also reconciles a difference between the method adopted in Principe (1989), Pearce and Puroshothamon (1992), Aylward (1993), Artuso (1994), and Mendelsohn and Balick (1995) on one hand, and that adopted by Polasky and Solow (1995) and Simpson, Sedjo, and Reid (1996) on the other.[3] In the former set of papers the researchers calculate the value of a species by multiplying the probability with which a species will yield *some* commercial product by the average value of a commercial product. In the latter set of papers, the researchers calculate the value of a species by deriving its incremental contribution to the probability that a particular product of commercial value will be discovered.[4] The former method is unsatisfactory, as it fails to allow for potential competition between different products derived from different sources. The latter method is also unsatisfactory, however, in that it supposes that different products derived from different species must either be perfect substitutes or wholly unrelated.

In this paper we suppose that different products derived from different species can be imperfect substitutes for each other. We begin with a variant of Salop's (1979) model of differentiated products, in which different products are located at different places around a

---

[2] Principe's treatment is problematic for several reasons. First, he measures social welfare from the value of a statistical life saved. It is difficult to ascribe lives saved to particular therapies. Second, he does not consider substitution or marginal valuation, but rather total and average values. Finally, proxies for consumer surplus by pharmaceutical costs, on the basis of an apparently *ad hoc* assumption that they are of comparable magnitudes.

[3] See also Brown and Goldstein (1984) for another paper in which valuation, in this case of agricultural improvement leads, is conducted on the margin. Also, work on the definition of meaningful measures of diversity (see: Weitzman, 1992; 1993; Polasky, Solow, and Broadus, 1993; and Solow and Polasky, 1994) is related, as incremental diversity only increases the measure of a set to the extent that it does not duplicate existing elements.

[4] Multiple discoveries are possible in the Simpson, Sedjo, and Reid paper, however, as each species may be tested for many possible uses.

circle representing the space of all consumers' preferences. In contrast to Salop's approach, we do not assume that products are symmetrically distributed around the circle. Rather, we suppose that each species represents a different research opportunity, and that each is equally likely to yield some commercial product which will be randomly located on the circle. Deriving analytical expressions for expected profits and welfare is difficult in this model, and equilibrium behavior is problematic under some configurations of products. Using numerical calculations and under what we will argue are reasonable assumptions, however, we are able to come to policy relevant conclusions.

Our general finding is that incremental losses of biological diversity will not cause great social losses with respect to the needs of new pharmaceutical product development. There are a number of considerations that motivate this conclusion, but they can all be summed up in the statement that there is a sort of diamonds-and-water paradox at work. Biological diversity is sufficiently abundant that incremental losses are unlikely to have much effect on social welfare.

Our results are relevant to two policy issues. The first concerns the overall consequences of biodiversity loss. Even if substantial biodiversity loss may occur as a result of global changes in climate, our results suggest that the lost value of biodiversity for use in new pharmaceutical research is negligible compared to measures of world product. Thus climate and atmospheric stabilization measures that would demand substantial sacrifices in world product cannot be justified by this consideration alone. We hasten to point out, however, that there are any number of other esthetic, ethical, ecological, and even spiritual reasons for which biodiversity may be important, and all should be investigated before final conclusions concerning the wisdom of climate and atmospheric stabilization policies is judged.

The second policy issue to which our analysis might be addressed concerns land use. Biodiversity is also, and arguably is most, threatened by the clearing of natural habitat for agriculture and other uses. Our results are more ambiguous here. On one hand, the incentives to maintain land in natural habitat are not large, and we can argue that we have been generous in our assumptions. On the other hand, however, since the values generated by converting

marginal lands to agriculture in much of the developing world are not great, modest incentives might be sufficient to motivate conservation of some areas.

The remainder of the paper is laid out in six sections. We introduce the model of differentiated products in the following section. In the second section, we model uncertainty concerning the number of products developed. The model is calibrated to world pharmaceutical industry data in the third section, and policy implications derived in the fourth. The model's shortcomings are discussed, and the relevance of the results defended despite these shortcomings, in the fifth section, and a final section briefly concludes. Some technical details arising in problematic cases are relegated to an appendix.

I. THE MODEL

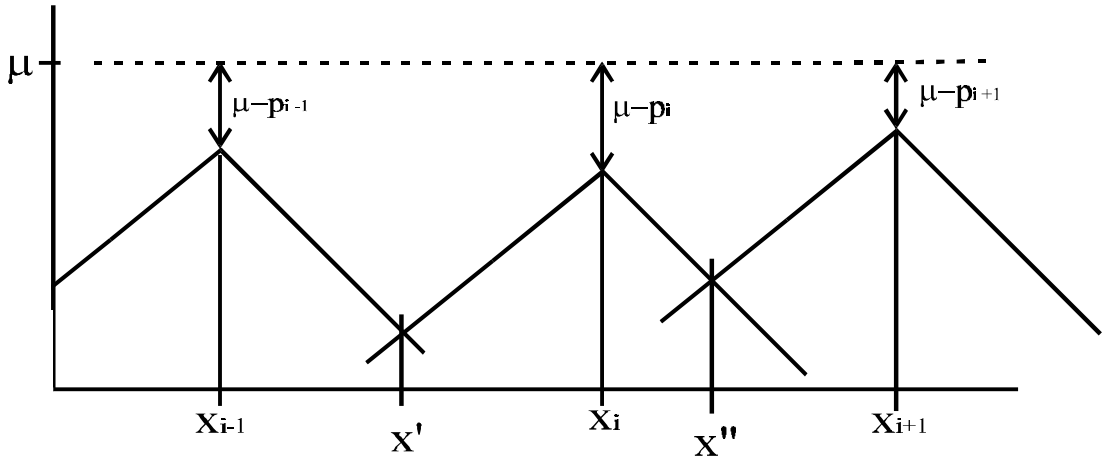
We will use Salop's (1979) model of product differentiation. We will suppose that consumers are distributed uniformly around a circle of unit circumference. Each point on the circle represents both a consumer and the drug that would provide the greatest utility to that consumer. The greater is the distance from a particular consumer on the circle to a particular drug on the circle, the lower is the utility of the drug to the consumer.

Let us arbitrarily define a starting point on the circle, and measure distances clockwise from this origin. Suppose that each consumer has a unit demand for at most one drug. Then we can define the net utility experienced by a consumer at a distance x from the starting point of the circle when she consumes the drug whose location is at a distance x' from the starting point as $U(x, x') - p'$, where p' is the amount the consumer would pay to consume a unit of the drug whose location is at x'. As in the Salop paper, suppose that $U(x, x') = m - \gamma|x-x'|$, where m and γ are positive constants. We will suppose also that there is a constant marginal production cost c.

Figure 1 shows the location of m products randomly distributed around a circle of unit circumference. Note that we normalize the location of the first product to a position that could be denoted as either 0 (the beginning) or 1 (the end) of the circle. In Figure 2 we have "straightened out" a segment of the circle. There are three drugs at locations x_{i-1}, x_i, and x_{i+1} along this segment. Suppose that the prices for which these drugs sell are p_{i-1}, p_i, and p_{i+1},

Figure 1 is available from the authors at
Resources for the Future

Figure 2
Pricing among adjacent products



respectively. Let us also assume for now that each drug is associated with a separate and independent firm. Suppose that firm *i*, in making its pricing decision, only takes account of the prices charged for products *i*-1 and *i*+1; that is, only adjacent products directly constrain prices (although, since products adjacent to the products adjacent to drug *i* affect the prices p_{i-1} and p_{i+1}, the prices of these more distant products have *indirect* effects on p_i). This assumption, that each firm considers the prices charged by both of its neighbors, is not always valid. The model resulting from this assumption has some appealing properties, however, so we will defer a discussion of what happens when the assumption is violated, and a defense of employing the model despite these shortcomings, to the appendix.

We can identify a point x' between x_{i-1} and x_i such that the consumer at x' is indifferent between purchasing a unit of drug from firm *i*-1 or a unit of drug from firm *i*. At this point,

$$\mu - p_{i-1} - \gamma(x' - x_{i-1}) = \mu - p_i - \gamma(x_i - x').$$

Solving for x', we have

$$x' = \frac{p_i - p_{i-1}}{2\gamma} + \frac{x_{i-1} + x_i}{2}. \qquad (1)$$

Similarly, we can identify a point x'' between x_i and x_{i+1} such that the consumer at x'' is indifferent between purchasing a unit of drug i or a unit of drug i+1. Proceeding as above, we have

$$x'' = \frac{p_{i+1} - p_i}{2\gamma} + \frac{x_i + x_{i+1}}{2}. \qquad (2)$$

Figure 2 depicts the analysis underlying expressions (1) and (2) graphically. A consumer located at the point x_i (or x_{i-1}, or x_{i+1}) would realize net utility $\mu - p_i$ (or p_{i-1}, or p_{i+1}, respectively) if she chooses to purchase product i. The utility of other consumers not located exactly coincident with a particular product declines linearly at a rate γ in their distance from the product. The extent of a firm's sales are determined by the points of intersection of these downward-sloping willingness-to-pay lines, labeled x' and x'' in Figure 2.

Firm i's total demand is, then, $(x_i - x') + (x'' - x_i) = x'' - x'$. Firm i will choose a price p_i so as to maximize its profits given the prices chosen by the providers of adjacent products (who in turn choose their prices optimally, etc.). Since the constant marginal cost of producing all products is c, firm i's problem is to

$$\max_{p_i} \pi = (p_i - c)\left(\frac{p_{i+1} + p_{i-1} - 2p_i}{2\gamma} + \frac{x_{i+1} - x_{i-1}}{2}\right).$$

The first-order condition for maximization of profit from drug i is

$$-\frac{2p_i}{\gamma} + \frac{c}{\gamma} + \frac{p_{i+1} + p_{i-1}}{2\gamma} + \frac{x_{i+1} - x_{i-1}}{2} = 0,$$

which we may restate in the form of a best-response function in price space as

$$p_i = \frac{p_{i+1} + p_{i-1}}{4} + \frac{\gamma(x_{i+1} - x_{i-1})}{4} + \frac{c}{2}. \qquad (3)$$

Using (3), that we can restate the optimand as

$$\pi_i = \left[\frac{p_{i+1} + p_{i-1}}{4} + \frac{\gamma(x_{i+1} - x_{i-1})}{4} - \frac{c}{2}\right]\left[\frac{p_{i+1} + p_{i-1}}{4\gamma} + \frac{(x_{i+1} - x_{i-1})}{4} - \frac{c}{2\gamma}\right]$$
$$= \frac{(p_i - c)^2}{\gamma}. \qquad (4)$$

Thus, for any location x_i and adjoining market boundaries x' and x'', sales of drug i are

$$q_i = x'' - x' = \frac{p_i - c}{\gamma}. \quad (5)$$

Since we have normalized the circumference of the circle to one, we have

$$\sum_{i=1}^{m} q_i = 1 = \frac{1}{\gamma}\left(\sum_{i=1}^{m} p_i - mc\right),$$

or

$$\sum_{i=1}^{m} p_i = \gamma + mc. \quad (6)$$

Consider next the utility resulting from the discovery of some set of m drugs. As was the case in thinking about the pricing decisions of a firm located at a position x_i, we need to think about the decisions of consumers both to the left and to the right of x_i. Adopting from expressions (1) and (2) the notation x' and x'' for the postions of, respectively, the most distant consumer to the left of x_i and the most distant customer to the right of x_i who purchase product i, total consumer surplus for all consumers on the interval (x', x'') is

$$CS_i = \int_{x'}^{x_i} \left[\mu - p_i - \gamma(x_i - x)\right]dx + \int_{x_i}^{x''} \left[\mu - p_i - \gamma(x - x_i)\right]dx.$$

Integrating the above, we have

$$CS_i = (\mu - p_i)(x'' - x') - \frac{\gamma}{2}\left[(x_i - x')^2 + (x'' - x_i)^2\right].$$

Using (5) and completing the square in the second term, we have

$$CS_i = (\mu - p_i)\frac{p_i - c}{\gamma} - \frac{(p_i - c)^2}{2\gamma} + \gamma(x'' - x_i)(x_i - x').$$

Since consumer's costs of purchase are the same as producers' revenues, social welfare accruing to both the consumers on the interval (x', x'') and the firm that serves them is

$$W_i = CS_i + \pi_i = (\mu - c)\frac{(p_i - c)}{\gamma} - \frac{(p_i - c)^2}{2\gamma} + \gamma(x'' - x_i)(x_i - x').$$

Note that we can write $x'' - x_i = (p_i - c)/2\gamma + d_i$ and $x_i - x' = (p_i - c)/2\gamma - d_i$ for some d_i. Thus we have

$$W_i = (\mu - c)\frac{(p_i - c)}{\gamma} - \frac{(p_i - c)^2}{2\gamma} + \frac{(p_i - c)^2}{4\gamma} - \gamma d_i^2 .$$

Summing over all products *i* and all consumers, we have, using (6),

$$W = \sum_{i=1}^{m} W_i = \mu - c - \sum_{i=1}^{m} \frac{(p_i - c)^2}{4\gamma} - \gamma \sum_{i=1}^{m} d_i^2 . \tag{7}$$

From (4), we know that the first summation on the right-hand side is one-quarter of the industry profit. Further analytical results are difficult to derive, but extensive numerical examples establish that (see Figures 3-5 and the appendix), to at least a very good approximation:

$$E\left(\sum_{i=1}^{m} \frac{(p_i - c)^2}{\gamma} \right) = \frac{\tilde{\pi}}{m} \tag{8}$$

and

$$E\left(\gamma \sum_{i=1}^{m} d_i^2 \right) = \frac{\tilde{\pi}}{6m}, \tag{9}$$

where $\tilde{\pi}$ is a constant, and all expectations are taken over the joint distribution of the vector of product locations **x** conditioned on *m* products being discovered.

Substituting (8) and (9) into (7), we have

$$E(W) = \mu - c - \frac{5}{12}\frac{\tilde{\pi}}{m}. \tag{10}$$

II. UNCERTAINTY IN THE NUMBER OF PRODUCTS DISCOVERED

There are two sources of uncertainty in the model. The first is the uncertainty regarding where around the circle any of *m* products is located. The second concerns *m* itself: how many commercial products will be discovered?

To model the distribution of the number of products developed, we will suppose that there is a probability ϕ that any species tested at random will yield *some* product.[5] We will

---

[5] This assumption is somewhat problematic, as some species yield two or more commercial products (see, e.g., Farnworth, 1988), and we are implicitly assuming that any species is the source of, at the most, one commercial product. These products are often closely related in use, however, so we might reasonably regard them as a single product for the purposes of so schematic a model. Our results would also not differ greatly if we regarded each species as the potential source of some number of pharmaceutical products.

suppose that all species have the same ϕ *ex ante*, and that success in new product development is statistically independent between species. The other parameter that determines the distribution of the number of new product discoveries is the number of research opportunities–in our context, the number of species–over which a search may be conducted. We will denote the number of species by *n*. Thus the number of new product discoveries is binomially distributed with parameters *n* and ϕ.

The consideration of uncertainty in the number of drugs brings up an element not addressed in the previous analysis. We are assuming that all species are tested for their pharmaceutical potential. This will, presumably, involve a fixed cost. Let us denote this cost by *z*. We could abuse notation slightly by using *z* to denote the expectation of a random variable, under the assumption that the distribution of *z* is independent of that of *m*. Total social welfare is, then, consumer surplus plus variable profits less testing costs, *z*.[6]

Thus the expectation of welfare is[7]

$$E(W) = \sum_{m=1}^{n}\left(\mu - c - \frac{5}{12}\frac{\tilde{\rho}}{m}\right)\frac{n!}{m!(n-m)!}\phi^{m}(1-\phi)^{(n-m)} - nz$$

$$= \mu - c - \frac{5\tilde{\rho}}{12}\sum_{m=1}^{n}\frac{1}{m}\frac{n!}{m!(n-m)!}\phi^{m}(1-\phi)^{(n-m)} - nz$$

The summation in the third term of the second line above may be somewhat difficult to reduce, but we can approximate it by noting from a Taylor series expansion about the expectation of *m* that

$$\frac{1}{m} = \frac{1}{E(m)} - \frac{(m - E(m))}{E(m)^2} + \frac{(m - E(m))^2}{E(m)^3} - \frac{(m - E(m))^3}{E(m)^4} + \frac{(m - E(m))^4}{E(m)^5} - \ldots$$

For $n\phi$ large relative to $[n\phi(1-\phi)]^{1/2}$ the binomial distribution is approximately symmetric, implying that odd-order moments are approximately zero. In addition, the probability mass on

---

[6] We might also include fixed costs of product introduction, given that a new product is in fact discovered. In the interests of clarity, however, we will abstract from these costs.

[7] The competitive industry model is used here, even for m = 1 or 2. This convenience compromises the analysis very little since the probability mass at those points is extremely small. See the appendix for further details on these cases.

relatively large or relatively small values of *m* will be small. Thus, taking expectations over the Taylor series summation above and truncating it after its fourth term we have[8]

$$\sum_{m=1}^{n} \frac{1}{m} \frac{n!}{m!(n-m)!} \phi^{m}(1-\phi)^{(n-m)} \approx \sum_{m=1}^{n} \left[\frac{1}{E(m)} + \frac{(m-E(m))^{2}}{E(m)^{3}} \right] \frac{n!}{m!(n-m)!} \phi^{m}(1-\phi)^{(n-m)}$$

$$= \frac{1}{E(m)} + \frac{Var(m)}{E(m)^{3}}.$$

(Mood, Graybill, and Boes, 1974).

Since we are assuming that *m* is drawn from a binomial distribution b(*n*, ϕ),

E(*m*) = *n*ϕ,

Var(*m*) = *n*ϕ (1 - ϕ).

Combining our results, then, we have

$$E(W) \approx \mu - c - \frac{5\tilde{\rho}}{12} \left[\frac{1 + (n-1)\phi}{n^{2}\phi^{2}} \right] - nz.$$

The relevant question for performing economic valuation is how much is a species worth on the margin, i.e., by how much does a small change in *n* reduce welfare. It will be somewhat easier to manipulate expressions into a useful form if we invoke another approximation, ignoring the integer problem and differentiating with respect to *n* rather than taking a discrete difference. Differentiating, we find

$$\frac{\partial E(W)}{\partial n} \approx \frac{5}{12} \frac{\tilde{\rho}}{n} \left[\frac{n\phi + 2(1-\phi)}{n^{2}\phi^{2}} \right] - z.$$

Consider next the limits on *z*. If a researcher is willing to incur the costs of testing a species for its pharmaceutical potential, it must be the case that the expected payoff is greater than *z*. The expected payoff to a researcher is the probability that she develops a commercial product times her expected profits. Her profits depend on the number of other researchers who also develop commercial products. Thus the expected payoff to a single researcher is

---

[8] The binomial distribution of *m* actually includes a positive probability that *m* = 0, but this event can be ignored with little consequence; see appendix.

$$\phi\tilde{\pi}\sum_{m=0}^{n-1}\frac{1}{(m+1)^2}\frac{(n-1)!}{m!(n-m-1)}\phi^m(1-\phi)^{(n-m-1)} = \frac{\tilde{\pi}}{n}\sum_{m=1}^{n}\frac{1}{m}\frac{n!}{m!(n-m)!}\phi^m(1-\phi)^{(n-m)}.$$

Note that the right-hand side of the above expression is simply 1/*n* times expected industry profit.

Maintaining our assumption that *z* is constant (or, at least, that *z* is statistically independent of *m*), let us denote by τ the ratio of total R&D expenditure, *nz*, to expected profit. It is immediate, then, that we must have $0 \le \tau \le 1$.

Note next that expected industry profits[9] are

$$E(\pi) = \tilde{\pi}\sum_{m=1}^{n}\frac{1}{m}\frac{n!}{m!(n-m)!}\phi^m(1-\phi)^{(n-m)} \approx \tilde{\pi}\left[\frac{n\phi+(1-\phi)}{n^2\phi^2}\right]. \qquad (11)$$

Thus, if we divide the derivative of expected welfare with respect to number of species by E(π), we have

$$\frac{E(\partial W/\partial n)}{E(\pi)} \approx \frac{5}{12n}\frac{n\phi+2(1-\phi)}{n\phi+(1-\phi)} - \frac{\tau}{n}.$$

Any reasonable estimate of the expected number of potential pharmaceutical products that might be derived from natural sources would be in the many hundreds, if not thousands. Thus, $n\phi$ should be a large enough number that $\frac{n\phi+2(1-\phi)}{n\phi+(1-\phi)} \approx 1$. To a reasonable approximation, then,

$$\frac{E(\partial W/\partial n)}{E(\pi)} \approx \frac{5-12\tau}{12n}. \qquad (12)$$

Note that the expected social value of the marginal species need not be positive. If R&D costs are high enough, excessive effort and expense may be put into exploration.

III. RELATING THE MODEL TO PHARMACEUTICAL INDUSTRY DATA

While it is a highly speculative exercise to calibrate a model as stylized as that we have presented above to real-world data, some useful insights emerge. Let us suppose, unrealistically, that pharmaceutical researchers were starting from a "clean slate." That is, suppose that search

---

[9] Note now that the expectation is taken with respect to the number of successful products discovered.

were undertaken simultaneously among all species for products of commercial value. We will calibrate the private and social values that might be expected to be generated as a result of such a search by looking at existing industry statistics.

From (12), social surplus would be no greater than 5/12n times expected industry profits. Let us sketch out a rough estimate of industry profits. Annual expenditures on pharmaceutical products in the 23 OECD countries excluding Japan is approximately $175 billion; see Table 1[10] (PRMA, 1996; data for Japan were not listed). These countries account for about three-fifths of world product (World Bank, 1995). Thus, if we assume that expenditures on pharmaceutical products are in the same proportion to income in the rest of the world as they are in the OECD countries -- an assumption we think is generous -- we would arrive at a world-wide figure of some $300 billion per year in pharmaceutical product sales. Discounted at about three percent per year, we might suppose that a figure on the order of ten trillion dollars might be a reasonable estimate of the expected present value of all future pharmaceutical product sales.

Using data from pharmaceutical companies on which publicly filed financial information is available, we find that production costs vary between roughly one quarter and four tenths of firm sales (see Table 2). We might also regard at least some portion of marketing and administration expenses as variable costs, both because sales might be expected to be proportional to product advertising and promotion, and because we have streamlined our theoretical model by not including as a component of social cost the set-up costs of new products.[11] Thus we might

---

[10] In nine of the twenty-three countries data on expenditures on pharmaceutical products were not given separately from expenditures on health care. In these cases, we have extrapolated by supposing that expenditures on pharmaceutical products are in the same proportion to total health care expenditures as the average of the ratios for countries for which data is available in both categories.

[11] Arguably, these costs should have been included in our model, but we feel that they would have complicated the exposition without adding much insight. We might also note in passing, comparing the figures for the different companies listed in Table 2, that it seems likely that different companies have different definitions of production costs and sales and administrative expenses. Those reporting higher values for the former report lower values for the latter. This suggests to us that there may not always be a sharp distinction between the two.

Table 1:
Health and pharmaceutical expenditure data for OECD countries
(Japan not available; all figures in millions of dollars)

	Gross domestic product	Expenditures on health care	Expenditures on pharmaceutical products
Australia*	$310,184	$26,366	$3,714
Austria	152,671	14,198	1,525
Belgium	194,498	16,143	2,689
Canada	555,494	56,660	8,578
Denmark	100,351	6,724	760
Finland*	78,448	6,903	972
France	1,076,457	105,493	17,750
Germany	1,353,638	116,413	21,503
Greece*	90,925	5,183	730
Iceland	4,976	413	54
Ireland	48,991	3,282	458
Italy	1,020,292	86,725	15,649
Luxembourg*	10,977	757	107
Netherlands	269,134	23,415	2,564
Norway*	83,720	6,865	967
New Zealand	53,291	4,103	659
Portugal*	118,490	8,650	1,218
Spain*	520,273	37,980	5,350
Sweden	147,184	11,039	1,406
Switzerland*	161,152	15,954	2,247
Turkey*	324,011	8,748	1,232
United Kingdom	981,892	69,714	10,389
United States	6,270,957	884,205	74,956

* Data on pharmaceutical product expenditures was unavailable for these countries. It has been imputed assuming that the ratio pharmaceutical product expenditure to total health care expenditure is the average of that for the countries for which full data was available.

Source: 1993 figures for Organization for Economic Cooperation and Development member nations (excluding Japan), electronically retrieved from PRMA (1996).

Table 2:
Financial Statistics of Major Pharmaceutical companies
(Millions of dollars)

	Pharmacia Upjohn	Pfizer	Merck & Company	Rhône-Poulenc Rorer	Total of these four companies
Net sales	6,704	8,281	14,970	4,175	34,130
Production costs	1,822	1,919	5,962	1,371	11,074
Marketing and administrative costs	2,617	3,251	3,178	1,512	10,558
Research and development costs	1,254	1,139	1,231	600	4,224

Source: 1994 Annual Reports electronically retrieved from SEC (1996).

suppose that industry profits gross of R&D would run to some forty percent of total sales, leaving us with a figure of about four trillion dollars. If we take ten millions species as a lower bound estimate of the total number of species on which pharmaceutical research can be performed (Wilson, 1992; p. 134), expression (12) implies a maximum social value of the marginal species of about $170,000.

We emphasize that this is an upper bound on the maximum social value, as we have as yet included no estimate of the costs of R&D. Here we have a still more difficult time relating our model to the real data, as the observed patterns of R&D spending are at odds with our depiction of R&D as an expense incurred only once, before any products are marketed.

Let us suspend credulity a little longer, however. Note first that our model requires that costs of R&D be less than five-twelfths of the expected payoff in order for the marginal species to be of positive social value at all. It seems entirely possible that the value of the marginal species would be negative, given a suboptimal market structure *vis-à-vis* the allocation of research and development effort and expenditure. To generate an estimate, however, let us make another heroic assumption. Suppose that current R&D expenditures can

be regarded as "installments" in a long-term plan to discover all required pharmaceutical compounds. Then total R&D costs would be the net present value of pursuing this program. U.S. Company-financed research and development by member companies of the Pharmaceutical Researchers and Manufacturers Association is estimated at $14.3 billion per year;[12] U.S. companies account for almost one-third of all pharmaceutical research and development in the world (PRMA, 1996). Thus, annual world pharmaceutical industry research and development is around $45 billion. Discounting this figure at the same three percent as we used for revenues and profits above, we find a total net present value of R&D expenditures of about $1. 5 trillion. This implies a value for t in expression (12) of about one-third, and an implied social value of the marginal species of about $33,000.

IV. IMPLICATIONS FOR POLICY

There are two levels at which the policy implications of this research are important. The first concerns the global sacrifices that might be justified in order to save biodiversity for its value in new pharmaceutical product research. It may seem reasonable to be concerned about the loss of biodiversity as a source of new pharmaceutical products in a world in which health care constitutes a large share of national product. The share is over ten percent in some of the more developed countries (see Table 1). What does the figure we have derived above imply about the economy-wide relative importance of biodiversity loss?

Obviously, the loss of one species at a value of $33,000 is not of great consequence. Let us consider the consequences of more catastrophic losses of biodiversity. Suppose that we are faced with the impending loss of twenty-five percent of all species. Let $\pi(n)$ be the expected industry profit when there are n species with which to conduct pharmaceutical research. Then, using (12), the expected value of the loss of twenty-five percent of all species would be $\int_{7,500,000}^{10,000,000} \frac{5-12t}{12n}\pi(n)dn$

[12] This figure is for U. S. PRMA member companies, but members account for the great majority of U. S. pharmaceutical research and sales.

Given the numbers of species involved and the number of pharmaceutical products in existence, we can reasonably approximate $\pi(n)$ from (11) as $\pi(n) \approx \tilde{p}/n\phi$. Thus the integral above is approximately

$$\frac{5-12\tau}{12}\frac{\tilde{p}}{n\phi}\Bigg|_{7,500,000}^{10,000,000} = \frac{5-12\tau}{12}p(10,000,000)\left(1 - \frac{10,000,000}{7,500,000}\right)$$

Using the figures of $\tau \approx 1/3$ and $\pi(10,000,000) \approx$ \$4 trillion above, we find that the net present value of the expected loss of welfare from these species extinctions would be on the order of \$111 billion. This is not a loss to be taken lightly, but it is only about 0.4% of an annual world product estimated to be on the order of \$25 trillion (World Bank, 1995), and is only about 0.01 percent of the world product when annualized at the same discount rate as we have applied above.

What sort of calamity might result in the loss of one quarter of the world's species? While few biologists have hazarded precise estimates, many fear that greenhouse-gas induced climate change could have profound effects on biodiversity (McNeely, *et al*., 1995). While the uncertainties are still extreme, let us suppose that the costs of greenhouse gas emission stabilization are between 0.8 and 2.2% of gross world product (Hourcade, *et al*., 1996). The costs of reducing global climate change (and, hence, presumably, biodiversity loss) would appear to be about two orders of magnitude greater than the benefit of preserving biological diversity for use in new pharmaceutical product research.

The loss of biological diversity due to climate change is more a prospective concern than a currently documented fact. Another source of potential biodiversity loss is already proceeding at an alarming rate, however. This is the destruction of habitat–largely by the conversion of forest land to agricultural use–that is occurring at a rapid pace in the developing tropical nations (see Pearce and Moran, 1994, p. 10, and the sources cited therein). Other papers have argued that the *private* incentives to preserve habitat containing endangered biodiversity for the purpose of using that biodiversity in new product research are modest at best (Simpson, Sedjo, and Reid, 1996; Simpson and Sedjo, 1996a). As we have emphasized, however, these results deal solely with private incentives: the incentives arising from the profit

motives of researchers, rather than the combination of profit and consumer surplus that constitute social welfare. An open question remains, then, as to whether society (or, more likely in practice, the wealthier nations of the world) ought to subsidize the preservation of biologically rich habitats.

It can be extremely difficult to translate our results on the value of the marginal species into an estimate of the social value of preserving particularly threatened habitat. Let us attempt to do so, however, while at the same time warning the reader that we must work with a very broad brush. Our defense must be again that the data will only allow us to generate order-of-magnitude estimates. Our procedure is to follow Simpson, Sedjo and Reid (1996) in taking the eighteen "biodiversity hot spots" identified by Norman Myers (1988, 1990) and assuming that: 1) the number of plant species in an area is determined by the theory of island biogeography; and 2) the total number of endemic species of all taxa is proportional to the number of plant species.

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

$$n_i = \alpha_i A_i^{\beta},$$

where α_i is a constant that measures the species richness potential of an area and β a constant whose value is approximately 0.25 (McArthur and Wilson, 1967). To infer the social value of the marginal hectare of land for biodiversity prospecting, we multiply the figure we derived above for the social value of the marginal species by the derivative of the number of species in a habitat area with respect to the size of the area. This derivative is

$$\frac{\partial n_i}{\partial A} = \beta \alpha_i A_i^{\beta-1} = \beta \frac{\alpha_i A_i^{\beta}}{A_i} = \beta D_i, \qquad (12)$$

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

The assumption that the number of species in all taxa in a particular area is proportional to the number in any one taxon in that area is particularly heroic, but it at least gives us a basis

for rough estimates. These estimates are reported in Table 3. The social values for habitat preservation among these biodiversity "hotspots" range from a little less than thirty to a little less than 3000 dollars per hectare.

We have, arguably, now reached the point where the imprecisions in our work render us unable to make any policy-relevant pronouncements, but let us venture a couple nonetheless. First, there are reasons to suppose (see the following section) that we have been generous in constructing our estimates. Thus, the simple fact that we do not get astronomical figures for any area, and modest figures for the "cooler" of even these "hot spots" suggests that a broad international policy of subsidizing habitat preservation could not be justified solely on this basis. Our second observation is that there may well be some areas in which such subsidization could be appropriate. This is, in fact, almost tautological in some instances. Some areas continue to support high biodiversity precisely because they are so remote, unpopulated, and generally inhospitable to human occupation as to be valueless for other uses. Thus, to the extent that there is *some* value to be realized by leaving such lands as repositories of biodiversity, the needs of new product research constitute an argument for their preservation. Again, however, it seems doubtful that this argument will be compelling when property values in alternative uses are high.[13]

---

[13] Let us offer two additional observations. The first concerns property values. As we noted in the text, property values probably are negligible in some biodiverse areas. On the other hand, however, some threatened biota are located in areas of high population density, great pressure, for alternative uses, and consequently, high property values. Atlantic coast Brazil (the seventh "hot spot" in Table 3)and Central Chile (the seventeenth "hot spot") include the largest cities of those countries. The California floristic province, (the eighteenth "hot spot") includes major metropolitan areas of California and northern Mexico (Wilson, 1992; pp. 260-269). While one does not want to generalize from admittedly casual empiricism, one of the authors was surprised to discover on a recent research mission that land in Southwestern Sri Lanka could sell for tens of thousands of dollars per hectare (admittedly, however, this may be due in large part to restrictions on the sale and use of other plots of land in the area).

Our second observation is that land values may be highest in those biodiverse areas that also boast sufficient physical and intellectual infrastructure to attract pharmaceutical researchers. Thus, while very backward areas may not face great pressures for conversion, they also may not be attractive locations for biodiversity prospecting. Perhaps, then, biodiversity prospecting will be a more financially attractive use of land in the more developed of the biodiversity-rich areas. (We are grateful to Anthony Artuso for stimulating conversations on this issue.)

Table 3:
Social value of the marginal hectare of land for use in biodiversity prospecting

"Hot spot"	Present forest area (1000s of hectares)	Number of plant species	Implied total number of species	Proportion of endemics	Density of endemics per hectare	Value of the marginal hectare
Western Ecuador	250	8,750	350,000	0.25	0.35000	$2,888
Southwestern Sri Lanka	70	1,000	40,000	0.50	0.28571	2,357
New Caledonia	150	888	35,520	0.89	0.21075	1,739
Madagascar	1,000	3,550	142,000	0.82	0.11644	961
Western Ghats of India	800	4,050	162,000	0.40	0.08100	668
Philippines	800	3,595	143,800	0.44	0.07909	652
Atlantic Coast Brazil	2,000	7,500	300,000	0.50	0.07500	619
Uplands of western Amazonia	3,500	15,383	615,320	0.25	0.04395	363
Tanzania	600	1,600	64,000	0.33	0.03520	290
Cape Floristic Province of South Africa	8,900	8,600	344,000	0.73	0.02822	233
Peninsular Malaysia	2,600	5,799	231,960	0.28	0.02498	206
Southwestern Australia	5,470	3,630	145,200	0.78	0.02070	171
Ivory Coast	400	2,770	110,800	0.07	0.01939	160
Northern Borneo	6,400	6,856	274,240	0.39	0.01671	138
Eastern Himalayas	5,300	5,655	226,200	0.39	0.01664	137
Colombian Choco	7,200	9,212	368,480	0.25	0.01279	106
Central Chile	4,600	2,900	116,000	0.50	0.01261	104
California Floristic Province	24,600	4,450	178,000	0.48	0.00347	29

Sources: Myers (1988, 1990); Simpson, Sedjo, and Reid (1996), and authors' calculations.

V. HOW UNREALISTIC IS THE MODEL?

As we have emphasized above, we have chosen to work with a model that is much more tractable than it is realistic. Since we are suggesting a strong conclusion–that biological diversity is not of great social value as a source of new pharmaceutical products–we are obliged to justify our conclusion by anticipating a number of objections. As we have noted above, there are also some technical details and assumptions which we have relegated to an appendix. In this section, we will deal with some more general issues.

We might say that the value of the marginal species depends on two things. First, by how much does the existence of an additional species increase the probability with which a useful product is found? Second, when a new product is found, by how much is social welfare increased as a result of its introduction? Our conclusion that the social value of the marginal species is small is based on the argument that the marginal species adds little probability to the event that an additional product is found in those states of the world in which useful products are rare. Let us now ask to what extent the generation of this conclusion in our model is an artifact of the assumptions we have made. We can think of generalizations along two lines, the first being the forms of the social welfare and probability density functions, and the second being the timing of product demands and discovery.

Generalizing the Functional Forms

We have chosen our generalization of the Salop model because it is (numerically, if not necessarily analytically) tractable. There were, of course, other alternatives. Examples include Perloff and Salop's (1985) random-utility specification and Dixit and Stiglitz's (1977) model, in which each consumer purchases some of each available product. The relative advantage of the circular-product-space specification we have adopted is that it affords a straightforward way of describing a market with differentiated products in which consumers choose among products based on their relative efficacy for their needs. This seems a not unreasonable general description of the pharmaceutical market: customers generally choose (or are prescribed) that drug that best treats their condition, and the degree to which the prices of other products affect

willingness to pay for the particular product chosen depends on substitutability between products. The Salop model also facilitates calibration with available aggregate data.

Having said this, though, there is no particular reason to suppose that competition takes place along only one dimension, or that disutility is linear in some measure of distance. Salop developed his original model to illustrate a point: that there may be excessive entry in a monopolistically competitive equilibrium. That we find that there may be excessive research under uncertainty is an artifact of the specification, and there is no reason to suppose that it necessarily generalizes.

What does seem obvious, however, is that any model in which uncertain R&D is likely to lead to a relatively large number of products will describe a situation in which there is competition between products. This implies two things. First, the introduction of an additional product will result in a transfer of benefits from the producers of existing products to consumers and the producer of the new product. The second implication of the expected number of products to be developed being relatively large is that it is unlikely that any one product will command a local monopoly, or, equivalently, that there is any large segment of consumers who are unserved–however inadequately–by at least some existing product. If the most substantial social benefits of new product creation arise from the advent of products to meet previously unmet demands, not the reshuffling of consumers between products that are more or less effective for their particular needs, a model that presumes that all consumers are served will not assign high values to additional products.

On this point there is some merit to the objection that we have essentially assumed our conclusion. By supposing that expression (3) is valid–that each product is in price competition with its two closest neighbors, in contrast to alternative market structures characterized by local monopolies or duopolies–we are assuming that new products attract customers from existing products, rather than meeting previously unmet demands. Our defense to this objection is empirical. Even if a new drug proves to be vastly superior to existing treatments, it is generally the case that the new drug displaces some existing product. Aspirin does not cure AIDS, but it is helpful for at least some of the symptoms.

It might also be objected that the assumption of a uniform distribution of product locations around the circle is unrealistic. This does not, however, seem an unreasonable assumption *ex ante*. Researchers do not necessarily put their effort into those projects in which they believe their chances of success to be greatest, but rather, into those in which they think it most probable that they will be successful *and their rivals will not* (see, e.g., Dasgupta and Maskin 1987). We have abstracted from a great deal of real-world detail, but this is one instance in which we might expect a consideration we have not modeled–the choice of area in which to do research–to support our choice to model a uniform distribution of products around the circle. Related to this issue is our assumption that each species is implicitly assigned to an independent firm. In the real world, of course, pharmaceutical research organizations are often relatively large, and one company may sell dozens of products. It does not seem unreasonable, however, to assume that the different products of a single firm are either so close together as to treat as the same product, or sufficiently far apart as to have little influence on joint pricing decisions.

The final consideration in the form of the welfare objective concerns the use of the consumer-surplus-plus-profit concept. We might well expect income effects to be important in this context–a very ill person might be willing to part with virtually all his wealth to obtain a cure. At the level of generality at which we are working, however, we doubt that this oversight greatly biases our results. Another consideration is the distribution of income. Society might assign a greater value to provision of medicines to the world's poor than is indicated by their ability to pay for such drugs. This observation begs the usual question as to why, if we feel this way, we do not act in accordance with our sentiments and give the poor enough wealth to afford the medicines or other necessities they require. It also might be noted that the nutritional and health problems of developing countries can, by and large, be treated with products that are relatively common and cheap. Discovering new products is unlikely to help when the real problem involves distributing existing ones.

Timing

We have made restrictively specific assumptions about the welfare function and the probability distribution, but we have ignored the matter of timing altogether. Implicitly, we have assumed that all species are tested in a single period. In the real world, of course, the testing of natural products for their pharmaceutical potential is an ongoing process. Different species are tested at different times for the same purpose, and the same species is tested at different times for different purposes. The set of conditions for which treatments are sought changes over time as new diseases are identified, population and wealth increase, and demographic characteristics change.

We could make some concession to dynamics by supposing that all products have an equal, finite, useful life. This might be the situation if, for example, disease organisms develop resistance to drugs over time. Then we could consider a process under which researchers test all n species at time zero and identify and market m_0 products. These products "expire" at time 1, at which time the n species are again tested, and m_1 products are identified. These products "expire" at time 2, m_2 products are identified, and so forth *ad infinitum*. This process is also not particularly realistic, but it suggests that a somewhat more realistic process, while being more difficult to model, would not give qualitatively different results.

Potentially more problematic is the fact that the size of the circle, as we have represented the extent of the market in our model, does not stay constant over time. It may well grow with wealth and demographic changes. Again, however, it would seem that we might capture these differences by adjusting the discount rate to reflect an increase in expected sales over time. It seems unlikely either that indefinite rapid growth in demand for pharmaceutical products is possible or that such a growth-adjusted long-term discount rate could be small enough to produce a dramatic inflation in our estimate of the social value of the marginal species.

We also have not modeled uncertainty in the appearance or intensity of new product demands. Such uncertainty introduces considerations of option pricing: biodiversity is an asset whose value fluctuates stochastically and whose extinction is irreversible. It is well

known that the properly calculated price of such an asset exceeds the expected value of the returns to which it gives rise (see, e.g., Dixit and Pindyck, 1994). Again, however, we must ask whether this fact really makes much difference. While there is certainly temporal variation in the demand for new products, aggregate variation is not unbounded. It seems highly unlikely that the option premium would be large enough to change our results drastically.

Three other dynamic considerations lead us to believe that the very rough estimates we have ventured above greatly *over*estimate the social value of the marginal species. The first of these considerations can be appreciated by returning to the issue of why our description of the research process is so unrealistic. In the real world, pharmaceutical researchers do not test all species simultaneously. Rather, they choose some to test initially, proceed to further testing with those among the first batch tested that appear most promising, and select another group for initial testing. It is estimated that less than one percent of all plant species have been tested for their medicinal properties (Bankson, 1996). In a world in which testing is proceeding at so slow a rate, it can reasonably be argued that the marginal species would not even come into a laboratory for several generations[14] –and hence, that its discounted present value would be correspondingly lower.[15] In a recent paper in which it is easier to model a dynamic sampling strategy than it is in this case, in which product differentiation matters, Simpson and Sedjo (1996a) argue that the marginal species is of little private value; if it were, researchers would make greater haste to test it. Unless it could be argued that extensive public investment should

---

[14] One can, of course, argue that researchers test the most promising species first, and hence that the value of the marginal *promising* species is substantially greater than we have suggested. If we are considering arguments for conserving biological diversity more generally, however, we should not distinguish between species that are promising or unpromising with respect to their pharmaceutical research potential. Moreover, it is not always clear that researchers test the most promising or the most easily available natural products. Sample collection in the relatively stable nation of Costa Rica is certainly a more attractive proposition than would be, for example, collection amid the civil strife in Burundi.

[15] This observation begs the questions of whether the rate at which testing takes place is socially optimally *vis-à-vis* the social benefits arising from the provision of new products. While the literature on innovation in patent races is mixed, there appears to be no reason to suppose that innovative effort is too slow in general (see Reinganum, 198, and the literature cited there).

be undertaken to increase the pace of pharmaceutical research, we believe that this argument is also compelling in considering social values.[16]

The second dynamic consideration that may argue that our figures are overestimates is that, over time, the range of substitutable research opportunities grows. The *n* species in the denominator of expression (12) may be augmented by technological progress. Advances in synthetic chemistry provide substitutes for natural product leads. Moreover, synthetic chemistry supplements natural product leads. Naturally occurring molecules can be used as blueprints for the creation of less toxic, more effective related compounds. Rather than having to find an organic source that meets their needs exactly, pharmaceutical researchers can, increasingly, modify naturally occurring substances into novel forms.

The final reason for which our procedure likely produces an overestimate of the value of biodiversity in new pharmaceutical product research is simply that we do not take into account the fact that many products have already been discovered. While it is true, as we noted above, that the need for new products is always expanding as drug-resistant microorganisms evolve and demographic conditions change, much of the existing stock of natural-product-based medicines remains effective, and provides starting points for the synthesis of other compounds.

VI. CONCLUSION

We have considered the social incentives for the conservation of biodiversity for use in new pharmaceutical product research. While it is extremely difficult to generate accurate estimates of such values, and we are reluctant to defend the figures we report as more than order-of-magnitude estimates, we believe that these results have some important policy implications. The first is that one cannot defend expensive policies for biodiversity

---

[16] This begs the question as to whether such publicly financed investments ought be made. While arguments have been made along these lines (see Mendelsohn and Balick, 1995; Artuso, 1996), this strikes us as a "small tail wagging a big dog." Simpson and Sedjo (1996b) have argued that such efforts are unlikely to be cost-effective.

preservation–preventing climate change by reducing greenhouse gas emissions, for example–by appeal to the value of biodiversity for use in new pharmaceutical product research. The second implication is that, while biodiversity prospecting might motivate conserving some threatened biota, the incentives are not great enough to motivate the preservation of all such endangered habitats.

Let us conclude with two final thoughts. The first concerns the uses and limits of economic research. It is often, and rightly, pointed out that the preservation of biodiversity is an exceedingly complex issue, fraught with uncertainties. Biologists have difficulty estimating even the number of living species to within an order of magnitude,[17] and the relationships between biodiversity, climate change, and habitat destruction are very poorly understood. Regrettably, the response to this uncertainty is all too often a throwing up of hands, and unwillingness to attempt any analysis whatsoever of the values involved. While we do not pretend to any great accuracy, the analysis we have done suggests that at least one set of arguments is *not* compelling as a motivation for expensive biodiversity conservation efforts. Some economists do not find this result surprising; as we said in the introduction, it is an instance of the diamonds and water paradox. We believe that it is useful to conduct this sort of formal analysis as best we can, however. It is at least helps to focus the debate on the more relevant questions.

This leads us to our second thought. The bottom line of our research is not that biodiversity is not valuable. There are many other commercial, ecological, esthetic, and even spiritual reasons for which it may be. We do not claim to have considered any of these beyond the narrow focus of new product values. We also believe, however, that the costs of maintaining biodiversity at the levels some advocates suggest also raise profound questions. The answers to these questions may be found, at least in part, by applying the tools of

---

[17] This imprecision has implications for the reliability of our estimates of the value of the marginal species. We would argue, however, first that we have been conservative in the estimate we have used for the number of species, and second that the number of species cancels in our calculation of value of the marginal hectare of habitat.

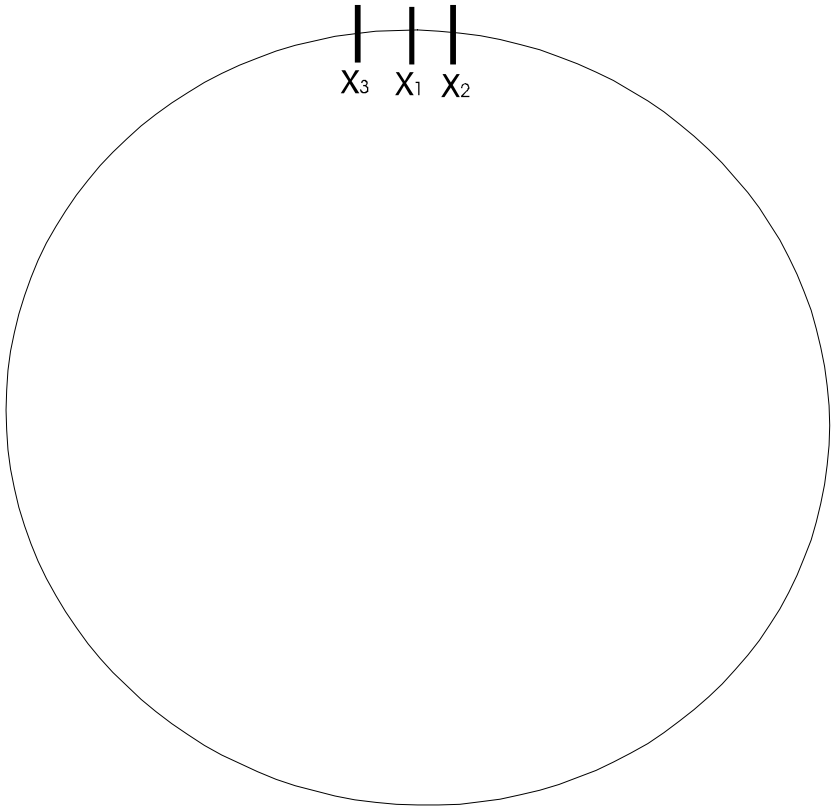
economics analysis to the other values of biodiversity in a fashion analogous to what we have done here.

Figure 3 is available from the authors at Resources for the Future

Figure 4 is available from the authors at Resources for the Future

Figure 5 is available from the authors at Resources for the Future

Figure 6
An example in which products are clustered too closely together



APPENDIX

THE CALCULATION OF PRICES

We can write the system of equations represented by (3) in matrix notation as

$$\boldsymbol{p} = \frac{1}{4}\begin{pmatrix} 0 & 1 & 0 & 0 & \cdots & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & \cdots & 0 & 1 & 0 \end{pmatrix}\boldsymbol{p} + \frac{\gamma}{4}\begin{pmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \cdots & -1 & 0 & 1 \\ 1 & 0 & 0 & 0 & \cdots & 0 & -1 & 0 \end{pmatrix}\boldsymbol{x},$$

where **p** is an *m*-vector of product prices and **x** is an *m*-vector of product locations. We set the first component of **x** equal to 1. The remaining *m*-1 components of **x** are ascending, as each successive component denotes a greater clockwise distance around the circle from the starting point.

We will conserve space in what follows by denoting the first matrix above as **A** and the second as **B**. Let **I** be the *m*-dimensioned identity matrix. Then we can rearrange our solution for ***p*** above as

$$\boldsymbol{p} = \frac{\gamma}{4}\left[\boldsymbol{I} - \frac{1}{4}\boldsymbol{A}\right]^{-1}\boldsymbol{B}\boldsymbol{x}. \qquad \text{(A1)}$$

It would be possible to solve (A1) analytically for **p**, but working through the arithmetic is a daunting exercise. We have, instead, adopted a numerical procedure. First, for any given value of *m*, it is easy to compute the nonstochastic part of expression (A1), $\frac{\gamma}{4}\left[\boldsymbol{I} - \frac{1}{4}\boldsymbol{A}\right]^{-1}\boldsymbol{B}$. A vector of product locations, **x**, can be generated by taking *m*-1 draws from a uniform distribution on the support [0, 1], ordering them from least to greatest, and concatenating them with a first element of 1. Doing so, we generated a random vector **p**.

Having the vector **p**, we calculate the sum of profits, and the sum of the squared d_i terms. We then repeated this procedure 100 times each for $m = 3, 4, 5, \ldots, 100$. Doing so,

we obtained average values of the sum of profits and $\sum_{i=1}^{m} d_i^2$, which we take to be close approximations to the expectations of the sum of profits and of $\sum_{i=1}^{m} d_i^2$. These averages are depicted in Figures 3 and 4. Moreover, by comparing the expected sum of profits to the expectation of $\sum_{i=1}^{m} d_i^2$, we see that the latter is, with only relatively small variations, one-sixth of the former (Figure 5).

DISTRIBUTIONS UNDER WHICH (3) DOES NOT HOLD

We have assumed throughout that equilibrium behavior is described by equation (3). This presumes, however, that products are arrayed "not too asymmetrically" around the circle, in a way we will make precise momentarily. Expression (3) embodies the assumption that the price charged for a product depends on the price of *both* the product immediately to its right and the price of the product immediately to its left. If products are either too close together or too far apart, this assumption may not be valid.

To illustrate the possibilities, consider a case in which it is easy to calculate equilibrium prices explicitly. Suppose that there are only three products. Fix the position of product one at the top of the circle, and let the postions of products 2 and 3 be given by x_2 and x_3, respectively. From (3)

$$p_1 = \frac{p_2 + p_3}{4} + \frac{\gamma(x_2 + 1 - x_3)}{4} + \frac{c}{2}$$

Adding and subtracting $p_1/4$ and using (6), we have

$$p_1 = \frac{\gamma(2 + x_2 - x_3)}{5} + c\,.$$

Similarly,

$$p_2 = \frac{\gamma(1 + x_3)}{5} + c\,,$$

and

$$p_3 = \frac{\gamma(2 - x_2)}{5} + c\,.$$

Equilibrium behavior is "normal" if the three products are not distributed "too asymmerically" around the circle. Consider, for example, a symmetric distribution of the three products around the circle. Then each sells for a price $p_i = \gamma/3 + c$. It can be shown that each would have to charge a price lower than marginal cost if it were to capture its rivals' customers.

Consider, however, the situation depicted in Figure 6. In this case, all three products are clustered together. Intuitively, the equilibrium concept should be Bertrand rivalry among (almost) undifferentiated products. The prediction of the model, however, is that the price of products 2 and 3 would be $2\gamma/5 + c$, while product 1 would sell for $\gamma/5 + c$. Not only does this require that firms at (almost) the same location charge discretely different prices, it suggests that products 2 and 3 would sell for prices at which all consumers would prefer to buy 1!

This type of result is relatively unusual, however (given our assumption that product locations are drawn from a uniform distribution). Under the assumptions of our model, product i completely supplants product i-1 if and only if, at prices p_i and p_{i-1} a consumer at position x_{i-1} would prefer to buy product i. This condition may be put as

$$\mu - p_i - \gamma(x_i - x_{i-1}) \geq \mu - p_{i-1},$$

or

$$p_i \leq p_{i-1} + \gamma(x_i - x_{i-1}). \qquad \text{(A2)}$$

We have demonstrated that it is possible to identify product configurations in which our equilibrium concept is invalid. Such configurations are more the exception than the rule, however. To see why, sum expression (A2) over all m product locations, using (6), to find that, in aggregate,

$$\gamma + mc < 2\gamma + mc.$$

"On average," then, condition (A2) holds. We have investigated this phenomenon extensively using randomly generated vectors of product locations, and determined that situations in which the use of expression (3) is not appropriate are relatively uncommon.[18]

---

18 There is another consideration. Even if a set of products is not arrayed so as to give inherently implausible results in a putative equilibrium, we should still check if it would prove profitable to lower price below the level

They do, however, occur, so we ought to explain why we continue to use the model. First, such exceptions to the application of (3) as we observe tend to affect only a small region of the circle,[19] at least when there are many products. *Whatever* the pricing rules followed for regions in which the application of (3) is invalid, pricing elsewhere will be little different. Second, we might suppose that sellers have some influence on the perceived differentiation of their products. It might not be unreasonable to suppose that sellers would choose to invest enough in differentiating advertising, marketing, etc., as to restore some well-ordered equilibrium. Third, we might suppose, especially in the industry that we are investigating, that legal (e. g., patent) or other barriers exist to prevent the simultaneous sale of extremely similar products. If this were the case, using our model would overstate the value of the marginal species, which seems the appropriate bias to accept, given our general conclusions. Finally, such a simple and stylized model should not be taken too seriously. It suffices for our purpose that we generate generally plausible forms for demands, profits, and welfare. We certainly do not claim that our model is literally true, only that it provides a useful way of approaching our problem. While it may be inconsistent in minor specifics, it does not seem unreasonable as a stylized description of how products compete, how numbers matter, and how uncertainty enters.

MONOPOLY AND DUOPOLY OUTCOMES

We have just seen that the equilibrium solution embodied in (3) may not be valid when products are clustered too tightly together. It may also not hold when there are too few products around the circle, and/or products are too far apart. Of course, if only one commercial product were developed, the firm providing that product would be a monopolist, and if only two products were developed, the firms providing them would be duopolists. We

---

determined by ( ). By lowering price sufficiently, the firm can induce a discontinuous increase in demand (see the discussion of "supercompetitive" regions in Salop, 1979, for tha analog in the symmetric case). In extensive numerical exercises, we have not found this to be a concern.

[19] It can be demonstrated analytically that the effects of proximity among products, and hence, prices, in one region of the circle tends to drop off rapidly as we move around the circle.

ignore these possibilities when working with the model in the text. Hundreds, if not thousands, of pharmaceutical products have been, or could be, developed from natural sources (see Farnsworth, 1988; Mendelsohn and Balick, 1995). This being the case, we can approximate the binomial distribution very closely by a normal distribution with mean $n\phi$ and variance $n\phi(1-\phi)$. Taking even a conservative estimate[20] of $n\phi$ to be on the order of 100, the standard deviation would be approximately ten. The probability that $m = 1$ would then be on the order of 10^{-42}. The probability that exactly two products would be discovered is only slightly greater. [21] Thus, we are not affecting the results appreciably by ignoring the the special forms that obtain in the monopoly and the duopoly cases. In fact, as we will argue below, we would not affect the results appreciably by ignoring all outcomes in which there are a relatively small number of products. To give an example, if the expected number of products to be developed, $n\phi$, were 100, the cumulative probabilty of finding fifty or fewer products would be less than 3×10^{-7}.

De facto monopoly or duopoly outcomes could also arise when there are more than one or two products. This would occur if γ, the parameter denoting the disutility of consuming more distant products, were large enough relative to μ, the maximum willingness to pay. Suppose that only one product were available, and that it is located at position zero on the circle. Then demand for the product is determined by the point at which consumer willingness to pay is zero, that is the position x where $\mu - p - \gamma x = 0$; i. e., $x = \frac{\mu - p}{\gamma}$. Maximizing

---

[20] Since ϕ is a small number, the ratio of the mean to the standard deviation of the normal approximation is $n\phi/\sqrt{(n\phi)}$. Thus, the number of standard deviations separating zero from the mean, $n\phi$, increases as the square root of our estimate of $n\phi$.

[21] The probability that exactly one hit is realized in a collection of size n is $n\phi(1-\phi)^{n-1} = \exp[\ln(n\phi) + (n-1)\ln(1-\phi)] \approx n\phi \exp[-(n-1)\phi] \approx n\phi \exp(-n\phi)$, where the first approximation is made under the assumption that ϕ is small, and the second under the assumption that ϕ is small and n is large. $100e^{-100} = 3.76 \times 10^{-42}$. The probability that exactly two hits are realized is, to a close approximation for large n, small ϕ, and $n\phi = 100$, fifty times the probability of one hit.

profit, $2(p-c)\frac{\mu - p}{\gamma}$ (since the monopolist sells to consumers at a distance up to *x* both to the right and to the left), with respect to *p*, we have $p^m = \frac{\mu + c}{2}$, and $x = \frac{\mu + c}{2\gamma}$. A sufficient condition for a monopolist to choose to serve the entire circle is, then, that $x \geq 1/2$, i. e., that $\gamma \leq \mu + c$.

More generally, a sufficient (but stronger than necessary) condition for no product to have a monopoly position is that the space between adjacent products be no greater than $\frac{\mu + c}{2\gamma}$. As the expected number of products becomes large, the expectation that the distance between any two products is large enough to generate monopoly (or, *a fortiori*, duopoly) power vanishes.

REFERENCES

Aylward, Bruce A. 1993. "A Case Study of Pharmaceutical Prospecting," Part III of Bruce A. Aylward, Jaime Echeverria, Liza Fendt, and Edward B. Barbier, *The Economic Value of Species Information and its Role in Biodiversity Conservation: Case Studies of Costa Rica's National Biodiversity Institute and Pharmaceutical Prospecting*, Report to the Swedish International Development Authority.

Artuso, Anthony. 1994. "An Economic and Policy Analysis of Biodiversity Prospecting," Ph.D. dissertation, Cornell University.

Artuso, Anthony. 1996. "Economic Analysis of Biodiversity as a Source of Pharmaceuticals," in *Biodiversity, Biotechnology, and Sustainable Development in Health and Agriculture: Emerging Connections* edited by Julie M. Feinsilver. Washington: Pan American Health Organization.

Bankson, Ross. 1996. "Biodiversity Work Pushes Alternative Livelihoods in Protected Areas," *USAID Developments*, vol. 2, no. 3 (Spring), p. 3.

Brown Jr., Gardner, and Jon H. Goldstein. 1984. "A Model for Valuing Endangered Species," *Journal of Environmental Economics and Management*, **11**, pp. 303-309.

Dasgupta, Partha, and Eric Maskin. 1987. "The Simple Economics of Research Portfolios," *Economic Journal* **97** (September), pp. 581-595.

Dixit, Avinash K., and Robert S. Pindyck. 1994. *Investment Under Uncertainty* (Princeton, N.J., Princeton University Press).

Dixit, Avinash K., and Joeseph Stiglitz. 1977. "Monopolistic Competition and Optimum Product Diversity," *American Economic Review* **67**, pp. 297-308.

Farnsworth, Norman R. 1988. "Screening Plants for New Medicines," in E.O. Wilson and Frances M. Peter, eds., *Biodiversity* (Washington, D.C., National Academy Press).

Hourcade, J. C., et al. 1996. "A Review of Mitigation Cost Studies,"Chapter 9 in James P. Bruce, Hoesung Lee, and Erik F. Haites, eds., *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge, Cambridge University Press), pp. 297-366.

MacArthur, R., and E.O. Wilson. 1967. *The Theory of Island Biogeography* (Princeton, N.J., Princeton University Press).

McNeely, Jeffrey A., Madhav Gadgil, Christian Levèque, Christine Padoch, and Kent Redford. 1995. "Human Influences on Biodiversity," Chapter 11 in Vernon H. Heywood, ed., *Global Biodiversity Assessment* (Cambridge, Cambridge University Press).

Mendelsohn, Robert, and Michael J. Balick. 1995. "The Value of Undiscovered Pharmaceuticals in Tropical Forests," *Economic Botany*, 49 (June), pp. 223-228.

Mood, Alexander M., Franklin A. Graybill, and Duane C. Boes. 1974. *Introduction to the Theory of Statistics*, third edition (New York, N.Y., McGraw-Hill).

Myers, Norman. 1988. "Threatened Biotas: 'Hot Spots' in Tropical Forests," *The Environmentalist*, **8**, pp. 187-208.

Myers, Norman. 1990. "The Biodiversity Challenge: Expanded Hot-Spots Analysis," *The Environmentalist*, **10**, pp. 243-256.

Pearce, David, and Seema Puroshothamon. 1992. "Preserving Biological Diversity: The Economic Value of Pharmaceutical Plants," Discussion Paper 92-27, CSERGE, London.

Perloff, Jeffrey, and Stephen Salop. 1985. "Equilibrium with Product Differentiation," *Review of Economic Studies*, **52**, pp. 107-120.

Pharmaceutical Researchers and Manufacturers Association (PRMA). 1996. http address: `www.phrma.org/facts/data/oecd.html`.

Polasky, Steven, and Andrew Solow. 1995. "On the Value of a Collection of Species," *Journal of Environmental Economics and Management*, **29**, pp. 298-303.

Principe, Peter. 1989. *The Economic Value of Biodiversity Among Medicinal Plants* (Paris, OECD).

Reid, Walter V., Sarah A. Laird, Carrie A. Meyer, Rodrigo Gamez, Ana Sittenfeld, Daniel H. Janzen, Michael A. Gollin, and Calestous Juma. 1993. "A New Lease on Life," Chapter 1 in Walter V. Reid, Sarah A. Laird, Carrie A. Meyer, Rodrigo Gamez, Ana Sittenfeld, Daniel H. Janzen, Michael A. Gollin, and Calestous Juma, eds., *Biodiversity Prospecting: Using Genetic Resources for Sustainable Development* (Washington, D.C., World Resources Institute).

Reinganum, Jennifer F. 1989. "The Timing of Innovation: Research, Development, and Diffusion," Chapter 14 in Richard L. Schmalansee and Robert D. Willig, eds., *Handbook of Industrial Organization, Volume I* (Amsterdam: North Holland).

Rubin, Steven M., and Stanwood C. Fish. 1994. "Biodiversity Prospecting: Using Innovative Contractual Provisions to Foster Ethnobotanical Knowledge, Technology, and Conservation," *Colorado Journal of International Environmental Law and Policy*, **5**, pp. 23-58.

Salop, Stephen. 1980. "Monopolistic Competition with Outside Goods," *Bell Journal of Economics*, **10**, pp. 141-156.

Simpson, R. David and Roger A. Sedjo. 1996a. "Valuation of Biodiversity for Use in New Product Research in a Model of Sequential Search," Discussion Paper 96-27, Resources for the Future, Washington, D.C., July.

Simpson, R. David, and Roger A. Sedjo. 1996b. "Investments in Biodiversity Prospecting and Incentives for Conservation," Discussion Paper 96-14, Resources for the Future, Washington, D.C., May

Simpson, R. David, Roger A. Sedjo, and John W. Reid. "Valuing Biodiversity for Use in Pharmaceutical Research," *Journal of Political Economy* **104** (February, 1996), 163-185.

Solow, Andrew, Stephen Polasky, and James Broadus, "On the Measurement of Biological Diversity." *Journal of Environmental Economics and Management* **24** (1993). 60-68.

Solow, Andrew and Stephen Polasky, "Measuring Biological Diversity," *Environmental and Ecological Statistics* **1** (1994), 95-107.

United States Securities and Exchange Commission Archives (SEC), http address: *www.sec.gov/archives/edgar/data*, 1996.

Weitzman, Martin L., "On Diversity," *Quarterly Journal of Economics* **CVII** (1992), 363-406.

Weitzman, Martin L, "What to Preserve? An Application of Diversity Theory to Crane Conservation," *Quarterly Journal of Economics* **CVIII** (1993), 157-84.

Wilson, Edward O., "The Current State of Biological Diversity," in *Biodiversity*, edited by E.O. Wilson and Frances M. Peter. Washington: National Academy Press, 1988.

Wilson, Edward O., *The Diversity of Life*. Cambridge: Belknap, 1992.

World Bank (International Bank for Reconstruction and Development), *World Development Report 1995: Workers in an Integrating World*. Oxford: Oxford University Press, 1995.