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Resources for the Future

"Biodiversity prospecting" has been touted as a mechanism for both discovering new pharmaceutical products and saving endangered ecosystems. It is unclear what values may arise from such activities, however. Evidence from transactions is incomplete and existing theoretical models are flawed. We calculate an upper bound on the value of the "marginal species." Even under favorable assumptions this bound is modest. Slightly modified assumptions lead to drastically lower estimates. We extend our findings to the value of the marginal hectare of habitat and find that the incentives for habitat conservation generated by private pharmaceutical research are also, at best, very modest.

I. Introduction

There has been considerable recent interest in "biodiversity prospecting," the search for chemicals produced by wild organisms. In nature, these compounds are employed to escape predators, capture prey, enhance reproductive success, and fight infection. These chemical compounds might be of considerable commercial value if adapted to industrial, agricultural, and, particularly, pharmaceutical applications.

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Biodiversity prospecting has also been touted as a tool for conservation. It has been argued that incentives for the preservation of areas in which biological 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 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" in biodiversity prospecting. A number of studies, including those of Farnsworth and Soejarto (1985), Principe (1989), McAllister (1991), Harvard Business School (1992), Pearce and Puroshothamon (1992), Aylward (1993), and Artuso (1994), have adopted a straightforward approach to valuing biodiversity for pharmaceutical research. These authors have multiplied an estimate of the probability of discovering a commercially valuable substance by the value of a discovery. Results of these exercises range from as little as $44 per untested species in situ (Aylward 1993) to as much as $23.7 million (Principe 1989).

The more careful of these studies are useful in that they incorporate detailed treatments of the benefits of new product discovery. We believe the method underlying all these studies to be flawed, however. Existing work takes little account of scarcity. Redundant resources are not scarce and hence do not have great value. 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.

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 Weitzman (1992, 1993), Solow, Polasky, and Broadus (1993), and Solow and Polasky (1994). In these papers the authors measure biological diversity in terms of the genetic "distance" between related species;[1] in fact, Weitzman (1992) and Solow and Polasky (1994) show how their proposed measures of diversity can be related to the incremental probability of discovering 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

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

may be said to be more or less diverse than another.[2] In our work, we accept current taxonomic practice as the appropriate measure; we suppose that all species within a particular taxon are "equally different." We then ask by how much *value* is augmented by increasing the number of species that may be tested in new drug research.

Valuation methods based on the work of these other authors will prove more useful as better information concerning the genetic constitutions of species becomes available. Our simpler approach is closer to practical application, however. Biologists estimate there to be between 10 million and 100 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 Solow et al. simply cannot be performed on a broad scale with existing data and computational limitations. In our work we treat each 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.

We provide some background information on biodiversity prospecting in Section II. We then turn in Section III to a discussion of possible sources of redundancy in biodiversity prospecting. Our main results are presented in Sections IV–VI. 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 hectare of habitat on which it exists. We demonstrate that this upper bound is relatively modest even under very optimistic assumptions and that the value of the marginal species falls off very rapidly if the probability of discovery differs from the one that 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 Section VII, but we can summarize here by saying that we do not believe that a more realistic treatment would change our results much.

We state our conclusions in Section VIII, but we should emphasize one point now. This paper is concerned solely with pharmaceutical researchers' willingness to pay for biodiversity as an input into com-

[2] A more recent paper by Polasky and Solow (in press) does deal with valuation issues. That paper does not address values on the margin, however, and does not incorporate any costs of prospecting. It also appears to have been written in part to address perceived omissions in earlier versions of our work.

mercial products.[3] Biodiversity may give rise to a number of other ecological, moral, and aesthetic values that are not captured in market transactions. Our point is not that biodiversity is not valuable. If biodiversity *is* determined to have great value, however, the international community should be seeking other mechanisms to finance its conservation.

II. The Use of Biodiversity in Pharmaceutical Research

Natural organisms' genetic codes contain 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 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 to recognize that nature has perfected chemicals that synthetic chemists might never dream up (Reid et al. 1993).

These considerations indicate that genetic resources are nonrival goods. Property rights in them have typically not been well established (see Sedjo 1992; see also Chichilnisky 1993; Vogel 1993). The seminal contributions of Coase (1960) and Demsetz (1967) (see also Barzel 1989) 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 defining property rights exceed the costs of their enforcement. The legal and institutional treatment of indigenous genetic resources is, in fact, changing. The Biodiversity Convention (United Nations Environment Program 1992) prepared for the 1992 United Nations Conference on Environment and Development in Rio de Janeiro and recently signed by the United States guarantees states

[3] We emphasize here that we are considering private, rather than social, incentives to engage in biodiversity prospecting. While we shall consider the implications of broadening our focus later in the paper, we devote most of our attention to private incentives. Much of the conservation advocacy literature promotes the establishment of private biodiversity prospecting schemes; an important policy issue is, then, whether such schemes are likely to generate much money for conservation.

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 agreements is probably the one 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 promises of substantial royalties in the event of new product discovery (Sittenfeld and Gámez 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 whether collectors have (or should have) legal title to the samples they sell. Observed prices might, then, be misleadingly low.

The second reason why observed prices may be misleading is that they generally also reflect a measure of compensation for collection and processing effort and expertise. Sample collection is typically a much more difficult process than it may seem. 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. Some or all of these steps are now performed by sellers of samples. Payments made for samples may, then, reflect compensation for collection and processing and taxonomic expertise rather than rents for the materials themselves.[4]

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

[4] The Merck-INBio agreement illustrates this point. Of the million dollar up-front payment, less than 10 percent was designated for conservation activities. The remainder went for equipment purchases and to defray INBio's expenses (Sittenfeld and Gámez 1993).

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. Moreover, it can take 10 or more years from the time a useful lead is identified until commercial sales of a resulting product begin, so there is little evidence of the outcomes of existing arrangements. For these reasons, most attempts to estimate the value of biodiversity for pharmaceutical research have been based on inferences from indicators other than observed transactions.

III. Value and Redundancy in Indigenous Genetic Resources

In this paper we seek to determine the value of biodiversity 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 then determine from this demand curve the willingness to pay for the "marginal species"[5] and, by extension, the marginal hectare of threatened habitat.

In deriving this demand curve, we must consider the likelihood not only 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 may be effective but is identical or inferior to an existing treatment has 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 of continuing research on others.

The essence of the argument we shall make 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 must be very small. We shall treat these issues more formally below; we note in passing, however, that there are several reasons why genetic resources may be

[5] For want of a better index, we shall treat "species" as the basic units of genetic differentiation. It would be inaccurate to suppose that all species are separated by the same degree of genetic variation. It is common, however, to consider the species as the basic unit of both biological diversity (Wilson 1992) and economic value.

relatively redundant. First, 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). To give a recent example, the discovery of the anticancer drug taxol in the Pacific yew of western North America has set pharmaceutical researchers looking for similar compounds in its old-world relatives (see, e.g., Chase 1991). 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. 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 call medicinal redundancy. Different therapeutic mechanisms may be effective in treating the same 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 (Reid et al. 1993), synthesis from nonorganic sources may also yield substitutes for natural product leads.

IV. A Simple Model

In this section we derive a simple demand function for biodiversity in pharmaceutical research, determine the 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. The intuition behind our results is easily grasped by considering extreme cases. If all species are promising sources of leads, most would be redundant and the marginal species close to valueless. If no species are likely sources of leads, it is unlikely that two or more will prove redundant but also unlikely that *any* species will prove to have value. Increasing the likelihood of success with any species has two offsetting effects on the value of the marginal species: it increases the expected payoff in the event the species is tested, but it also decreases the expected payoff inasmuch as it is more likely that another equally valuable species is discovered first. By identifying the probability of success at which these effects are balanced, we can derive an upper bound on the value of the marginal species. As the number of species available for testing increases, this upper bound declines.

We begin with a very simple model. Suppose that medical research-

ers have identified a need for a new product. A new product, if successfully developed, will earn net revenue of R. Revenue 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 R & D 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

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

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

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

We shall 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, we must have $pR - c > 0$ if any sampling is deemed

worthwhile; on the other hand, as p becomes larger, the magnitude of $(1 - p)^n$ declines more quickly than that 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 the one that 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 possible 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

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

when p is chosen to maximize $v(n)$. Heuristically, the first term to the right of the equal sign in the first line of (3) reflects the loss in marginal value associated with the increased likelihood that a successful test will be conducted before the last species is tested. The second term reflects the gain in value associated with the increased expected payoff from testing the last available species, conditional on no earlier discovery.

The second-order condition for a maximum requires that

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

As the satisfaction of the first-order condition requires that the expression in 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 $p^*R - c = (R - c)/(n + 1)$, or

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

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

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

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

The approximation $[n/(n + 1)]^n \approx 1/e$ (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

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

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 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 is that $(R - c)/R$ 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 $K = (c/p)[1 - (1 - p)^n]$. 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

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

and the maximum value of the marginal species is approximately

$$v^*(n) \approx \frac{R - c}{n + 1}e^{-\Pi/(\Pi - K)}. \tag{7}$$

As K approaches Π, $v^*(n)$ again approaches zero. In short, the value of the marginal species can be high only if the expected aggre-

gate profitability of the research venture is high. In figure 1 we illustrate this relationship.[6]

It also bears mentioning both that the marginal species takes on its maximum value at a probability relatively close to the one 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 profitable in expectation only if $pR - c > 0$, that is, $p > c/R$. Our statements about relative closeness may be made more concise if we define a basic unit

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

Note that μ is necessarily less than $1/(n+1)$.

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,

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

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,

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

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 $\mu < 1/(n+1)$; thus, on an interval of length less than $10/(n+1)$, $v(n)$ varies from zero to its maximum value to $10e^{-9} = 0.0012$ times its maximum value. The probability p^* is greater than $1/(n+1)$. 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.

[6] The curve in fig. 1 quickly approaches a linear relationship; recall from (7) that

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

For $\Pi \gg K$, the exponential expression asymptotes to e^{-1}.

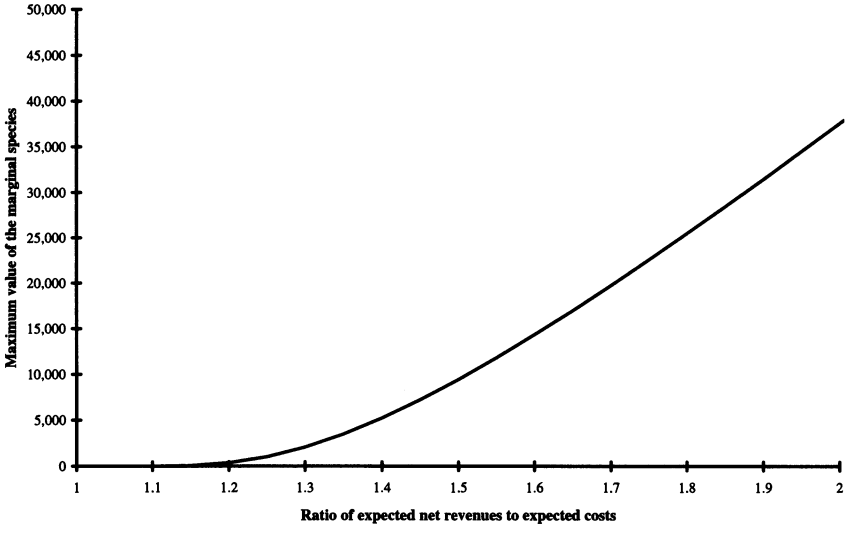

FIG. 1.—Maximum value of the marginal species as a function of the ratio of expected revenues to expected costs in a new product research program.

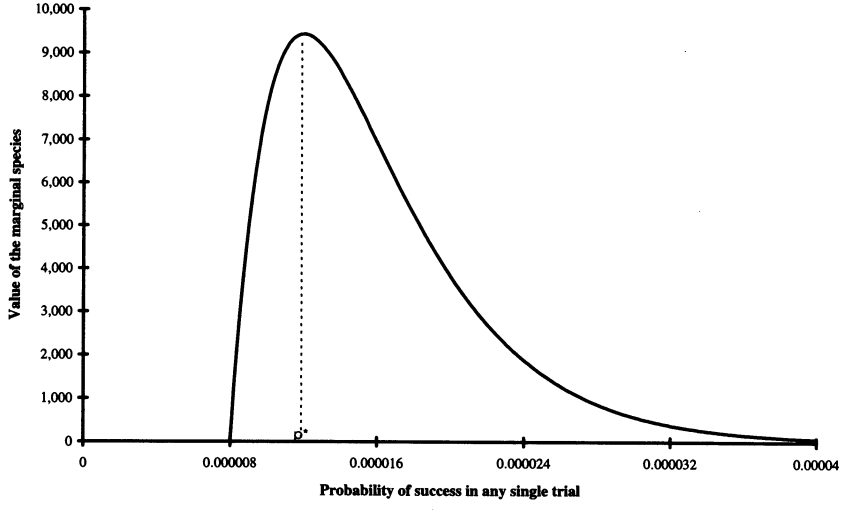

FIG. 2.—Value of the marginal species as a function of the probability of success in any single trial.

V. Some Specific Examples

It is impossible to estimate the value of the 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 necessarily imprecise, there are reasons to believe that even our upper-bound estimates will be optimistic.

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 biodiversity prospecting as a conservation strategy stems from an unrealistic view of the number of products to be generated from prospecting activities. 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;[7] 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.

We shall suppose that there exists 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, as demographic characteristics change and the health needs of certain groups become more important, or as new technologies are developed. We label these as potential products since 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 shall suppose that λ remains constant over time: 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 R & D costs denoted by R_{jt}. Similarly, we could say that the cost of evaluating the potential of the ith species for its use in deriving the jth 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

[7] Conversations with researchers suggest that 100 or fewer tests are typically done on species for their pharmaceutical potential.

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

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

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 10 million species. *The "base case" estimate we report below would have been reduced by 41 orders of magnitude if we had assumed that all 10 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 anticancer drugs vincristine, vinblastine, and taxol are all derived from higher plants. There are estimated to be at least 250,000 species of higher plants (Myers 1988; Wilson 1992).[8]

Between 1981 and 1993 the U.S. Food and Drug Administration approved an average of 23.8 new drugs per year (annual reports of the Pharmaceutical Manufacturers Assoc., 1982–94). 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 compounds first approved in the United States and subsequently sold to the rest of the world, as well as drugs already sold elsewhere but just being approved in the United States, 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 shall assume that 10 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, $1 - (1 - p)^n$.

DiMasi et al. (1991) estimate pharmaceutical R & D expenditures per successfully derived product to be $231 million. A recent report

[8] Farnsworth (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.

TABLE 1

NEW DRUG APPROVALS

Year	Number of 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.

suggests that "a reasonable upper bound" on the figure is $359 million (Office of Technology Assessment 1993). We shall assume a value of $300 million for our calculations. In our notation, the expected R & D cost per successful product developed would be expressed as

$$\frac{c}{p} = \frac{K}{1 - (1 - p)^n}.$$

We shall adopt what seems to us a generous assumption, that the expected return to a new product research effort is 50 percent.[9] If the expected cost per successful product developed is $300 million, then we shall suppose that the expected net revenue is $R = \$450$ million. Finally, we shall suppose that pharmaceutical firms discount future returns at 10 percent per year.

The results of an exercise based on expression (6) and these assumptions are summarized in table 2. 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 12 in a million. Over an entire collection of 250,000 species from which to sample, the probability of making a hit is slightly over 95 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.

[9] This assumption seems a generous estimate on the basis of reported revenues, costs, and R & D expenditures of major pharmaceutical firms, although these data are admittedly difficult to interpret.

TABLE 2

PARAMETER VALUES AND RESULTANT VALUE OF THE MARGINAL SPECIES FOR THE BASE SCENARIO

Number of species	250,000
Expected number of new products	10
Cost of developing a new product	$300,000,000
Revenue to cost ratio	1.50
Discount rate	.10
Revenue	$450,000,000
c	$3,600
p^*	.000012
Probability of a hit	.9502
λ	10.52
Value of the marginal species	$9,431.16

NOTE.—Variables are defined in the text.

We must emphasize that these estimates are extremely sensitive to changes in assumptions, however. Recall that we have evaluated the marginal species at the probability of success that maximizes its value. The results reported in table 2 indicate that $p^* = .000012$. If we continue to assume that $c = \$3,600$ and $R = \$450,000,000$ but allow p to vary, we may get very different results. We must have $p \geq .000008$ 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 .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 50 percent. If we assumed instead that expected net revenues exceed expected costs per successful product by 25 percent, the value of the marginal species would be only $1,017.53; if expected net revenues exceed expected costs per successful product by 10 percent, the value of the marginal species would be $2.20.[10]

[10] These examples beg the question of what would happen if the margin were higher than 50 percent. One answer is that returns are ultimately limited by demand, and even if evaluation costs were negligible relative to revenues in the event of a new product discovery, the upper bound might well still be modest given the number of species available for testing. Another consideration is that, in the interest of brevity, we have not modeled investments in processing capacity and the timing of R & D. If we were to do so, we would expect that high expected returns to prospecting activities would not exist: a firm—or its competitors—could hasten the research process by making new investments in testing capacity.

We shall 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 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 necessarily has 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 Habitats

We have concentrated to this point on efforts to evaluate the worth of the "marginal species." We are, perhaps, past due in defining this concept and justifying its importance. Economists should be familiar with the notion of valuing resources on the margin but may be uncomfortable with applying marginal analysis in an ecological context. How can one identify the marginal element of a large and complex ecosystem?

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 shall employ a widely used model in the ecological literature, advanced by Preston (1960, 1962) and incorporated by MacArthur and Wilson (1967) in their influential theory of island biogeography. Because habitat disturbances may not be as devastating as island biogeography implicitly assumes (see, e.g., Lugo, Parrotta, and Brown 1993), the model is likely also to incorporate an upward bias in estimates of value.

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

$$n_i = \alpha_i A_i^Z, \tag{11}$$

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., Preston 1962; MacArthur and Wilson 1967; Wilson 1988).

To infer the maximum possible value for the marginal hectare of land for biodiversity 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_i:

$$\frac{\partial n}{\partial A} = Z\alpha_i A_i^{Z-1} = Z\frac{\alpha_i A_i^Z}{A_i} = ZD_i, \tag{12}$$

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

We can combine expression (12) with our earlier results presented in table 2 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 3 we have entered data on Myers's (1988, 1990) 18 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

It is, of course, impossible to derive precise estimates of the values arising from an activity as speculative as biodiversity prospecting. Our simple model does not begin to do justice to the real-world complexities involved. On balance, however, we believe that it is reasonable to argue that a consideration of such complexities would, if anything, lower our upper-bound estimates. Consider, for example, the omission of discounting from our model. In a world in which it might take years, or even decades, for the marginal species to become the subject of testing, values might be considerably lower. Similarly, an incorporation of Bayesian updating might drive the value of the marginal species to zero: researchers might well quit in discouragement after testing hundreds of thousands of species with no success.

The most obvious omissions of our model concern heterogeneity of species and statistical dependence between tests. Incorporating these features would require the solution of difficult search models, but we doubt that our results would change much if we adopted a more sophisticated procedure. It is, of course, true that pharmaceutical researchers do not generally conduct random searches; rather, they begin searching in the most promising taxa. We might simply regard part of the "testing" process as determining whether or not potential

TABLE 3

MAXIMUM WILLINGNESS TO PAY TO PRESERVE A HECTARE OF LAND IN 18 BIODIVERSITY HOT SPOTS

Hot Spots	Present Forest Area (1,000 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	.25	.00875	$20.63
Southwestern Sri Lanka	70	1,000	.50	.00714	$16.84
New Caledonia	150	888	.89	.00527	$12.43
Madagascar	1,000	3,550	.82	.00291	$6.86
Western Ghats of India	800	4,050	.40	.00203	$4.77
Philippines	800	3,595	.44	.00198	$4.66
Atlantic Coast Brazil	2,000	7,500	.50	.00188	$4.42
Uplands of western Amazonia	3,500	15,383	.25	.00110	$2.59
Tanzania	600	1,600	.33	.00088	$2.07
Cape Floristic province of South Africa	8,900	8,600	.73	.00071	$1.66
Peninsular Malaysia	2,600	5,799	.28	.00062	$1.47
Southwestern Australia	5,470	3,630	.78	.00052	$1.22
Ivory Coast	400	2,770	.07	.00048	$1.14
Northern Borneo	6,400	6,856	.39	.00042	$0.99
Eastern Himalayas	5,300	5,655	.39	.00042	$0.98
Colombian Choco	7,200	9,212	.25	.00032	$0.75
Central Chile	4,600	2,900	.50	.00032	$0.74
California Floristic province	24,600	4,450	.48	.00009	$0.20

SOURCE.—Myers (1988, 1990) and authors' calculations.

samples are in promising taxa, however. With respect to statistical dependence, results in the limiting case are obvious. If the efficacies of any two species were perfectly correlated, they would be redundant. More generally, some species may constitute "guideposts" pointing toward promising relatives. It may well be the case, however, that if any substantial number of species are closely enough related to be useful guideposts, researchers would be unlikely to regret the loss of any one species.

Two other issues merit consideration. The first concerns option value. It is well known (see, e.g., Pindyck 1991) that, under uncertainty, irreversible (dis)investments should not be made until the expected value of their exercise exceeds the opportunity cost by a positive margin. The extinction of a species is an irreversible event. If we consider the overall stochastic variability of new product demand, however, we doubt that option considerations would substantially increase what are, in all likelihood, very small values.[11]

Our final remark relates to the distinction we mentioned above between private and social benefits from biodiversity prospecting. As we said above (n. 3), we have concentrated on private incentives since many policy issues involve defining and exploiting the willingness of private companies to pay for access to biodiversity for new product research. Social incentives for biodiversity preservation might be considerably greater: consumer surplus from new product development could well exceed profits by a large margin. Even if this is the case, however, values on the margin will still be low if the number of candidate species is large. We regard our example in the section above as a reductio ad absurdum, a demonstration that even under extraordinarily optimistic assumptions, private willingness to pay will be, at best, modest. A consideration of social willingness to pay for the marginal species when there are tens of millions of possibilities for search, alternative avenues of pharmaceutical investigation open, a positive cost of sample evaluation, and some uncertainty with regard to the probability of success in any individual test could well yield negligible estimates of marginal value to society even when overall demand is great.

[11] Another consideration concerns advances in science. The invention of processes that radically reduce sampling costs might increase our upper-bound estimates of value considerably. At the same time, however, such scientific advances might well increase the range of living organisms over which biodiversity prospecting could be conducted (consequently reducing the value of the marginal species) and enhance the capabilities of synthetic chemists to develop products without reference to natural leads (we are grateful to an anonymous referee for noting these implications).

VIII. Conclusions

We have developed a simple model of the demand for biological diversity 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.

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 postulate moderate values for the conservation incentives provided by biodiversity 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 minuscule. This view seems to be consistent with information concerning observed transactions. This subject should be studied further, but we would not expect a reversal of the conclusion of our analysis: the private value of the marginal species for use in pharmaceutical research and, by extension, the incentive to conserve the marginal hectare of threatened habitat are negligible.

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

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