Definitions of Biodiversity and Measures of Its Value

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Abstract

The destruction of natural habitats has prompted concerns about the loss of biological diversity. Regrettably, however, there is no consensus among either biologists or economists on the most meaningful measures of biodiversity. Fundamentally different definitions are useful in asking fundamentally different questions. Considerable attention has been given to the value of diversity in search models. A measure of "aggregate variability" is appropriate to such models. Values derived from search models tend to be well behaved; they exhibit diminishing returns in diversity. In contrast, a definition of diversity as "relative abundance" is more appropriate to more complex objective functions. Values derived in these models are not necessarily well behaved. The differences between diversity values arising in search models and those arising from more general objectives are demonstrated. An example shows that "consistency tests" applied to measures of valuation may not be useful when diversity per se is being valued.

Key Words: Biological diversity; biodiversity; diversity index, abundance; search; variability, consistency; contingent valuation; diminishing returns; increasing returns

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Introduction

In recent years a great deal of interest has surfaced in the quantification and valuation of biological diversity. The interest is largely motivated by findings from natural scientists that biodiversity is imperiled by human activities (e.g., Wilson 1992), especially the destruction of natural habitats (e.g., Primack 2000). Biodiversity has, however, proved both difficult to define in practice and difficult to relate to human welfare.

Definition and valuation are closely related, of course. We cannot speak meaningfully of valuation without having some notion of what it is that is being valued. On the other hand, a definition that cannot be related to human values may propose "distinctions without differences." This paper considers both definition and valuation. Two types of definitions have been proposed in the literature of both ecology and economics. The first concerns aggregate variability; the second, relative abundance.

The two types of definitions lend themselves to two types of valuation exercises. The first considers the contributions of variation to the achievement of a particular objective. The search for new or improved products is the canonical example. The second valuation approach considers the contributions of many components to an objective that may depend on the quantities of each and the interactions among them.

In the first type of exercise, biodiversity can often be thought of as a "thing" that may vary in scalar fashion, as opposed to a collection of not necessarily commensurable things. Value functions are typically well behaved, in the sense that value exhibits diminishing returns in diversity. Results can be far less clear-cut in the second type of exercise. Received theory provides little guidance on how value may respond to diversity, and there is no assurance of diminishing returns in the number of dimensions in which quantities can vary. Common sense may suggest that problems are well behaved, but the view that this is generally the case would seem to be an axiom rather than a theorem.

The next section of this paper presents a brief discussion of some proposed definitions of diversity. In the following section, one common instance of valuation is discussed: the value of diversity in the search for a new product. After that, we consider a broader notion of the value of diversity in general systems of preference. Some comparisons are drawn across the two topics. A simple example illustrates the broad range of possibilities in the more general setting. It is demonstrated that no conclusions can be drawn regarding diminishing returns *a priori*. The next-to-last section presents one practical implication of that principle: tests of the consistency of stated preferences (see Diamond 1996) are not necessarily applicable to instances in which diversity is truly the subject of inquiry. A final section discusses some broader issues.

I. Defining Diversity

Defining *biological diversity* as "the total variability of life on earth" (Heywood et al. 1995, 5) is admirably compact but far too inclusive to be of much practical use. In practice, biologists generally resort to the expedient of defining *diversity* as "number of species." A species is, in relatively informal usage, "a population whose members are able to interbreed freely under natural conditions" (Wilson 1992, 38). As the qualifiers "freely" and "natural" suggest, the concept is elastic. One survey offers no fewer than eight definitions of *species,* including five variants of the biological species concept Wilson was summarizing (Bisby et al. 1995). Expediency is the most compelling argument for settling on the admittedly fuzzy notion of *species* as the "fundamental unit"—the title of E.O. Wilson's (1992) fourth chapter. "One can argue that for the whole of species diversity to be built on such an uncertain unit as the species is very unsatisfactory. It is, however, the best: the only unit that we have!" (Bisby et al. 1995, 44).

The authors of the passage just quoted would almost certainly not object to the qualification that the species is the "only unit" currently operational for measuring the total variability of life forms across the globe.[1] There is widespread agreement that not all species are created equal. The sole remaining representatives of otherwise extinct genera are recognized to represent greater diversity than would one species from among many exemplars of a copious genus.[2] Vane-Wright et al. (1991; see also May 1990) propose that taxonomic level be a lexicographic preference: given a choice between saving one species of a genus with many

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[1] And even at that, one does well to recall that biologists estimate that 90% of extant species may be as yet unclassified (Wilson 1992).

[2] Life forms are classified at seven taxonomic levels, from general to specific: kingdom, phylum, class, family, order, genus, and species.

surviving representatives and the single surviving species of a particular genus, the latter would trump the former.

There is now near-uniform agreement that not all species can be maintained given the many needs of a human population at six billion and growing and the political realities that growth implies. Although there may be somewhat less agreement that the tools of economics can be brought to bear on the problem, those tools have begun to be applied, and applied to some considerable effect. Martin Weitzman in particular has, in a series of papers (1992, 1993, 1998; see also Solow et al. 1993 and Nehring and Puppe forthcoming) developed and applied an index by which diversity can be measured.

Weitzman's index is developed from measures of pairwise distance. It can be informally, if not wholly adequately, described as arising from an evolutionary tree. The diversity of a set of species can be summarized as the sum of the lengths of the branches in its evolutionary tree.[3] Weitzman demonstrates that this measure of diversity has a number of appealing properties and interpretations. Among the latter is the example of a search problem. Greater diversity, by Weitzman's measure, is equivalent to greater likelihood of success in search; the measure proposed by Nehring and Puppe (forthcoming) is similar in this respect. If the length of evolutionary branches denotes the cumulative number of genetic mutations that have occurred since descent from a common ancestor, the measure of diversity can be related to the probability that a set of a certain diversity contains an instance of a genetic attribute not found in the common ancestor.

This search-theoretic notion of diversity has been employed in applied work on the valuation of biodiversity for use in new product development. Using the species as a basic and invariant unit of diversity, Simpson et al. (1996) calibrate a simple model of search to pharmaceutical industry data in deriving the value of the "marginal species" with respect to its contribution to new product development (see also Rausser and Small 2000). In a sense, such search models are the canonical application of distinctiveness-based diversity measures to economic valuation.

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[3] As suggested, this is not wholly accurate. All extant branches of an evolutionary tree necessarily terminate at a common point: the present. Different rates of mutation could result in different terminal points more generally.

Both natural and social scientists would agree that diversity may be important for a multitude of purposes above and beyond the discovery of new and improved products, however. The diversity of an ecosystem may affect its resilience and productivity (see, e.g., Tilman et al. 1994; Naeem et al. 1999). The presence or absence of representative elements may not be sufficient to assure performance. Their relative abundance is important as well.

Let x_i be the population (or biomass, or other relevant attribute) of species *i*. Define the relative abundance of species *i* as $s_i = x_i \Big/ \sum_{i=1}^{N} x_i$. Biologists calculate measures of relative abundance, such as the Simpson (1949) index,

$$D^S = \sum_{i=1}^{N} 1 \big/ s_i^{\,2} \,,$$

and the Shannon-Weaver (1949), or entropy, index,

$$D^{S-W} = -\sum_{i=1}^{N} s_i \ln s_i \,.$$ [4](1)

Economists have also begun to explore the implications of relative abundance. Weitzman (2000) demonstrates that the Shannon-Weaver index may be interpreted as the resistance of a cropping system (as the foremost example) to catastrophic collapse. We will return to Weitzman's result, as the Shannon-Weaver index also emerges as the solution to some other optimization problems. First, however, let us consider diversity-as-distinctiveness and valuation in search models.

II. Diversity and Search

In search models the objective is to find the "best"—by some criterion—element of a set. Suppose that the diversity of the set can be measured by an index *N* and that the value of any particular element is given by a random variable θ. The "best" element of a set indexed by *N* is its greatest order statistic; call it $\hat{\theta}$. Let the support of θ be Θ and the cumulative distribution of $\hat{\theta}$ given *N* $G(\hat{\theta} \mid N)$. Then if the expectation exists,

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[4] Compare also Hayri Önal's (1997) proposed "structural diversity index,"

$$D^{SDI} = 1 - \frac{1}{n-1} \sum_{i<j} \left| s_i - s_j \right| .$$

$$E\left(\hat{\theta} \mid N\right) = \int\limits_{\Theta} \left[1 - G\left(\theta \mid N\right)\right] d\theta \text{ .(2)}$$

Concerns about biodiversity conservation are most constructively addressed by considering marginal values, and hence the value of "marginal diversity" would, in this formulation, be

$$v(N) = E\left(\hat{\theta} \mid N\right) - E\left(\hat{\theta} \mid N-1\right) = \int\limits_{\Theta} \left[G\left(\theta \mid N-1\right) - G\left(\theta \mid N\right)\right] d\theta \text{ .(3)}$$

The marginal value, v(N), is, of course, positive. One can do no worse in finding the best when there are more leads over which to conduct the search. More formally, the distribution conditioned on N is first-order stochastically dominant relative to that conditioned on N – 1.

Economic experience leads us to expect diminishing returns. A reasonable measure of diversity for use in this context might be one in which diversity is the equivalent number of "identically different" independent leads one might pursue. Suppose, then, that the values to which each of *N* entities gives rise are independently and identically distributed. In this case $G(\theta| N) = F(\theta)^{N}$, where $F(\theta)$ is the cumulative density for any one θ, and

$$v(N) = \int\limits_{\Theta} \left[1 - F(\theta)\right] F(\theta)^{N-1} d\theta \text{ .(4)}$$

It will be more revealing to work with an approximation. The expectation of $\hat{\theta}$ can be approximated from

$$1 - F\left[E\left(\hat{\theta} \mid N\right)\right] \approx 1/N \text{ (5)}$$

David (1981) derives the expression. Abstracting from the integer constraint on N and differentiating both sides with respect to N,

$$\frac{\partial E\left(\hat{\theta} \mid N\right)}{\partial N} \approx \frac{1}{f\left[E\left(\hat{\theta} \mid N\right)\right] N^2},$$

or, using (5),

$$\frac{\partial E\left(\hat{\theta} \mid N\right)}{\partial N} \approx \frac{1}{N} \frac{1 - F\left(E\left(\hat{\theta} \mid N\right)\right)}{f\left[E\left(\hat{\theta} \mid N\right)\right]} \text{ .(6)}$$

The second fraction on the right-hand side is the inverse of the "hazard rate." That is, it is the inverse of the probability that some event occurs (in this instance, some particular value of θ is the greatest observed) given that the event has not yet occurred. Expression (6) is easily calculated for a number of distributions and is of some practical use in real-world problems.[5] If the support of θ is finite, $\partial E(\hat{\theta}|\mathrm{N})/\partial N$ must vanish as N grows large. It also vanishes for common distributions on infinite supports, such as the normal and the exponential.

III. Preferences for Diversity

A different situation arises when diversity enters into a more complicated objective. Consider a situation in which a consumer derives benefits from N goods. Suppose that production of the N goods is constrained by some resource or resources; one cannot enjoy unlimited quantities of each. We have described a situation in which the quantities of the N goods the consumer enjoys could be determined from a knowledge of their actual (if the goods are allocated in markets) or virtual (if the consumer has no choice concerning the levels of their provision) prices and the expenditure function $e(\mathbf{p}, u)$, where $\mathbf{p}$ is an N-vector of prices and u the level of utility the consumer enjoys in some reference state.

In this case "diversity" might be measured by the number of goods available to the consumer. Two examples come to mind. Consider a farmer with a fixed area in which she can plant crops. The diversity available to her is the variety of seeds from which she can choose. Alternatively, consider a consumer who derives satisfaction—perhaps "existence value"—from the continuing presence of wild species in a park area. The diversity he enjoys might be changed by a species reintroduction program, such as the controversial reintroduction of wolves into Yellowstone National Park. Note that in this case also, the presence of some population of one species will affect the populations of others. Those animals on which wolves prey may be supported at lower populations, and/or the populations of those predators with which wolves compete would be reduced.

To lose access or enjoyment of some element of diversity is equivalent to having that element's price increase without bound. A natural measure of the welfare loss from the elimination of one element of diversity is the increase in expenditure required to produce some reference level of utility if the price of the Nth element increased without bound. Some notation

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[5] A number of biological traits are normally distributed: the central limit theorem applies to the independent contributions of genes combined at random. Hence expression (6) might describe the expected contribution of a "marginal individual" to a program of clonal propagation.

can be simplified in what follows by choosing units such that the price of all goods is one in the *status quo ante*—that is, before we conduct the thought experiment of allowing the price of the *N*th to increase. Denote by $\mathbf{1}_j$ a *j*-vector whose elements are all ones. Then the measure proposed for the welfare loss experienced when the *N*th element of diversity is lost is

$$v(N) = e(\mathbf{1}_{N-1}, \infty, u) - e(\mathbf{1}_{N-1}, p_N, u).(7)$$

Equivalently,

$$v(N) = \int_1^\infty \frac{\partial e(\mathbf{1}_{N-1}, p, u)}{\partial p} dp = \int_1^\infty x_N(\mathbf{1}_{N-1}, p, u) dp ,(8)$$

where the second equality results from applying Shephard's Lemma.

There is a certain formal similarity between expressions (2) and (8). It may be illuminating to compare and contrast them further. As a first step in doing so, note an interesting characterization of the compensated demand for the *N*th good. Suppose that with income *M* a consumer achieves utility u^0 by purchasing the *N*-vector of goods $\mathbf{x}$ when all prices are one. Define

$$x_N^0 = x_N(\mathbf{1}_N, u^0) = x_N(\mathbf{1}_N, M);$$

that is, compensated demand equals Marshallian demand at the *status quo ante.* Now note that

$$F(p) = 1 - \frac{x_N(\mathbf{1}_{N-1}, p, u^0)}{x_N^0} (9)$$

is an admissible cumulative probability function on the support [1, ∞). That is, X(1) = 0, limρ → ∞ X(ρ) = 1 , and its derivative can be interpreted as a probability density function:

$$\frac{\partial F(p)}{\partial p} = -\frac{\partial x_N(\mathbf{1}_{N-1}, p, u^0)/\partial p}{x_N^0} \geq 0 ,$$

as compensated demands are downward sloping.

Now we can define the "expectation" of p_N as

$$E(p_N) = -\int_1^\infty \frac{p \partial x_N(\mathbf{1}_{N-1}, p, u^0)/\partial p}{x_N^0} dp .(10)$$

Integrating by parts,

$$E(p_N) = -\left.\frac{p x_N(\mathbf{1}_{N-1}, p, u^0)}{x_N^0}\right|_1^\infty + \int_1^\infty \frac{x_N(\mathbf{1}_{N-1}, p, u^0)}{x_N^0} dp .$$

The first term on the right-hand side of the equal sign vanishes in the limit if the Nth good is not essential. If this is the case, the first term is simply 1·xN0/ xN0 = 1, and

$$v(N) \;=\; \int_1^\infty x_N\left(\mathbf{1}_{N-1},\; p,\; u^0\right)dp \;=\; \left[E\left(p_N\right) - 1\right]x_N^0 \,(11)$$

Although this analysis is somewhat contrived, it has a certain intuitive appeal. The value of incremental diversity is determined by a relatively simple summary measure—the excess of “expected” over equilibrium price—times the equilibrium quantity.

Now compare expressions (11) and (2). In the search problem the *total* value of a set of diversity *N* is an expectation. In (11), it is the *incremental* value that is related to the “expectation”—the value of the marginal species. Heuristically, we might expect that with more diversity available, better substitutes are available, and hence that the compensated demand for the marginal element of diversity would decline at any given price. It is possible, however, that for sufficiently strong complementarity among elements the right-hand side of (11) would be increasing in *N*.

IV. A Simple Example

Possibilities can be illustrated with a simple example. Suppose first that “production possibilities” are summarized by

$$\sum_{i=1}^{N} x_i \;\leq\; 1 .(12)$$

Again, one might appeal to the concrete examples of land devoted to crops or populations (or biomasses) of populations of organisms in fixed reserve areas. Prices are, in this case, wholly determined by this production relationship. In equilibrium the price of everything is one, as the opportunity cost of increasing any component is just the space of which it deprives others. Suppose further that all elements enter symmetrically into an objective function $U(x_1, x_2,\ldots, x_N)$. The solution to the problem of maximizing $U(\mathbf{x})$ subject to (12) is obviously $x_i = 1/N$ for all *i*.

To be still more concrete, suppose utility takes the constant elasticity of substitution form

$$U \;=\; \left(x_1^\rho + x_2^\rho + \ldots + x_N^\rho\right)^{\frac{1}{\rho}} .(13)$$

Then the utility afforded by N elements of diversity under our assumptions can be written as

$$U(N) \ = \ N^{\frac{1-\rho}{\rho}}.^{6} \ (14)$$

If one component of utility were constrained to be zero, utility will remain well defined for ρ > 0. That is, when ρ > 0, goods are not essential. Put in another way, the expenditure function corresponding to (14) is, in a corresponding reduced-form notation,

$$e(N, u) \ = \ uN^{\frac{\rho-1}{\rho}}.(15)$$

Abstracting from the integer nature of N, note that the following two conditions are equivalent:

$$\frac{U_{NN}N}{U_N} \ = \ 1-2\rho \ > \ 0 \ \text{and} \ \frac{e_N N}{e(N, u)} \ = \ \frac{\rho-1}{\rho} \ < \ -1 \ (16)$$

Each is satisfied if ρ < ½ (more completely, we should say 0 < ρ < ½, as for ρ ≤ 0, expenditure is not well defined).

Even if goods are not essential, then, anomalous behavior can occur. Marginal utility need not be declining and the value ascribed to diversity may be increasing as more and more of it is accumulating. Although these facts are relatively well known in other literatures (see, e.g., Krugman 1987, 1998; Romer 1990), they also have implications for the valuation of biological diversity.

V. Consistency Tests on Willingness to Pay

It has proved extremely difficult to place a value on biodiversity. The complexities involved in inferring, for example, the marginal products of services provided by diverse natural ecosystems are daunting. Moreover, few elements of biodiversity are transacted in existing markets, so there are no prices from which to infer valuations.

In this information-poor environment, economists (and sometimes others) have resorted to the expedient of asking for stated preferences rather than observing revealed preference.

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[6] It is interesting to note a special case. In the limit as ρ approaches zero, $U(\mathbf{x})$ is a Cobb-Douglas function. The optimized function is then of the form $U(\mathbf{x}) \ = \ \Pi x_i^{x_i}$, or $\ln U(\mathbf{x}) \ = \Sigma x_i \ln x_i$. That is, it is of the form of the Shannon-Weaver index.

Willingness to pay for the conservation of endangered species is one example of such preference elicitation. The results of such exercises are controversial and deemed unreliable by many. For example, Gardner Brown and Jason Shogren summarize the results of 18 studies of willingness to pay to preserve different species. The results, as the authors report, indicate that "the average person was willing to pay about $1000 to protect 18 different species" (Brown and Shogren 1998, 12). To quote the authors again, "Many will find these figures suspiciously high."

Many commentators have found the results of such contingent valuation studies "suspiciously high." If the studies record economically meaningful data, they argue, the data should be consistent with the tenets of received consumer theory. One way in which it has been alleged that contingent valuation studies are not consistent with received theory is in demonstrating "embedding" effects. Respondents often do not show as much sensitivity to the scope of the changes they are being asked to value as theory might suggest that they should (see, e.g, Kahneman and Knetsch 1992).

Following Peter Diamond (1996), consider a test of the consistency of contingent valuation responses that may evidence "embedding." Contingent valuation surveys are typically designed to elicit willingness to pay for the good or service in question. Willingness to pay is a Marshallian, as opposed to a Hicksian, notion. That is, it is predicated on the ability to pay as constrained by income, rather than an implicit property right that would entitle the respondent to maintain her utility at a constant level.

Thus, willingness to pay must satisfy an "adding up" condition. Consider a proposed change in the provision of some good *or goods* (the distinction will become important momentarily) that can be decomposed into two phases. Suppose that the initial level of provision is q^0, there is an initial change from q^0 to q^1, and following that, a second change from q^1 to q^2. The qs are to be interpreted liberally. They may refer to different levels of a scalar, or they may refer to vectors. Suppose that $q^0 > q^1 > q^2$, where the inequality sign is to be interpreted in the sense of "greater in at least one component and no less in any" if applied to vectors.

The willingness to pay to avoid a decline from q^0 to q^2, conditional on initial income M, can be decomposed into two parts. It is the willingness to pay to avoid a decline from q^0 to q^1 conditional on M, plus the willingness to pay to avoid the decline from q^1 to q^2 *conditional on initial income less willingness to pay to avoid the first change*. That is,

$$w\left(q^0, q^2, M\right) = w\left(q^0, q^1, M\right) + w\left[q^1, q^2, M - w\left(q^0, q^1, M\right)\right]. \tag{17}$$

Following Diamond, the implications of (17) can be made more transparent by adding and subtracting $w(q^1, q^2, M)$:

$$\begin{aligned} w\left(q^0, q^2, M\right) = {} & w\left(q^0, q^1, M\right) + w\left(q^1, q^2, M\right) - \\ & \left(w\left(q^1, q^2, M\right) - w\left[q^1, q^2, M - w\left(q^0, q^1, M\right)\right]\right). \end{aligned} \tag{18}$$

The term on the second line of (18) is an income effect. We can use the definition of a partial derivative and approximate

$$w\left(q^0, q^2, M\right) \approx w\left(q^0, q^1, M\right) - w\left(q^1, q^2, M\right) - \frac{\partial w\left(q^1, q^2, M\right)}{\partial M} w\left(q^0, q^1, M\right),$$

or

$$\frac{w\left(q^0, q^2, M\right)}{w\left(q^0, q^1, M\right)} \approx 1 + \frac{w\left(q^1, q^2, M\right)}{w\left(q^0, q^1, M\right)} - \frac{\partial w\left(q^1, q^2, M\right)}{\partial M}. \tag{19}$$

Consider a situation in which the change from q^0 to q^2 is twice as severe (assuming there is some meaningful sense in which such changes can be measured) as that from q^0 to q^1. Then Diamond argues that unless the income effects captured in the final term of (19) are far stronger than are typically observed, the willingness to pay to avoid the change from q^0 to q^2 should be approximately twice that of willingness to pay to avoid the change of half the magnitude. A pivotal consideration here is that the second term on the right-hand side of (19) not be less than one. In the case of a scalar q, it should not be. Diminishing returns in q are sufficient to assure that $W(q^1, q^2, M) > W(q^0, q^1, M)$.

As the discussion in the previous sections makes plain, though, things can be considerably more problematic when the qs measure not differences in the level of a *thing*, but rather, differences in the *numbers* of things in existence. An example establishes the point. Replace q in our analysis with N, the number of species supported in, say, a wildlife reserve. Suppose that in a natural equilibrium, all of N species will be supported in equal populations in the reserve, and that a survey respondent derives some satisfaction from their existence as given by expression (14) above.

Suppose further that $U(N)$ is itself a component of a larger utility function. Suppose that the collection of species in the reserve is a public good; everyone can benefit from it, but not everyone necessarily has to pay for its maintenance. Suppose that the utility derived from private goods (given some set of prices that we will suppress on the assumption that they are not affected by policy in the wildlife reserve) can be expressed as a function of money income, M. Let indirect utility as a function of numbers of species in the reserve and money income be of the CES form

$$v(n,\ M) \ = \ \left(N^{\frac{1-\rho}{\rho}\phi} + M^{\phi} \right)^{1/\phi} . (20)$$

Willingness to pay to avert the loss of one species, w = w(N, N – 1, M), is defined implicitly by

$$v(N-1,\ M) \ \equiv \ v(N,\ M\ -\ w). (21)$$

In our case, (21) may be written as

$$\left((N-1)^{\frac{1-\rho}{\rho}\phi} + M^{\phi} \right)^{1/\phi} \ = \ \left(N^{\frac{1-\rho}{\rho}\phi} + (M-w)^{\phi} \right)^{1/\phi},$$

or

$$(N-1)^{\frac{1-\rho}{\rho}\phi} + M^{\phi} \ = \ N^{\frac{1-\rho}{\rho}\phi} + (M-w)^{\phi} . (22)$$

Abstract from the integer constraint and differentiate totally with respect to N:

$$\frac{1-\rho}{\rho}\phi(N-1)^{\left[\frac{1-\rho}{\rho}\phi-1\right]} \ = \ \frac{1-\rho}{\rho}\phi N^{\frac{1-\rho}{\rho}\phi-1} - \phi(M-w)^{\phi-1}\frac{\partial w}{\partial N},$$

or

$$\frac{\partial w}{\partial N} \ = \ \frac{1-\rho}{\rho(M-w)^{\phi-1}}\left[N^{\frac{1-\rho}{\rho}\phi-1} - (N-1)^{\frac{1-\rho}{\rho}\phi-1} \right] . (23)$$

The first fraction to the right-hand side of the equal sign is positive, since $\rho > 0$ if we are to have a meaningful comparison (i.e., if the imperiled component of diversity is not essential). Note also that since $\phi < 1$, the increment in willingness to pay would necessarily approach zero if willingness to pay were to approach income. Willingness to pay could be increasing in *N*, then, if

$$\phi \ > \ \frac{\rho}{1-\rho} . (24)$$

Since ϕ must be less than one if the overall utility function is to be well behaved, condition (24) also requires that $\rho < ½$. Briefly, if the components of diversity are sufficiently complementary with one another and sufficiently substitutable for market goods, the "adding up" test for consistency may have little power.

VI. Implications for the Valuation of Biodiversity

The sections above have made three main points. First, there is no consensus among either biologists or economists about the most meaningful measures of biodiversity for use in policy analysis. Fundamentally different definitions are useful in asking fundamentally different questions. This leads to the second point: models focusing on biodiversity for its contributions to search provide very different results concerning marginal values than would those raising more general concerns. This in turn leads to the third point: received economic theory provides few guidelines for how the value of diversity "ought" to behave. Diminishing returns with respect to increases in the individual components do not necessarily imply anything about returns to diversity per se. Thus, to use the example presented in the previous section, "consistency" tests have little power to identify credible value estimates.

The last point may not surprise the reader of other literatures in economics. The Dixit-Stiglitz (1977) model of product differentiation—essentially a model of CES preferences (or production technologies) with imperfect competition—has been used in the international trade (Krugman 1987), endogenous growth (Romer 1990), and "new economic geography" (Krugman 1998) literatures. In each, the implications are similar to those developed here. Potentially increasing returns in variety induce nonconvexities, with interesting and often novel policy implications.

Even though one of the authors who himself has most productively applied the Dixit-Stiglitz approach calls it "a very restrictive, indeed in some respects, silly model" (Krugman 1998, 164), this statement might be taken to concern its properties in extreme cases rather than the plausibility of the qualitative predictions arising from its application. Indeed, such modeling approaches came into being in response to empirical anomalies that conventional approaches could not explain: in international trade, cross-shipping in similar commodities; in growth theory, the failure of incomes to converge across nations; and in economic geography, the inability of simple theory to explain the most obvious of facts, that people and economic activity tend to cluster in cities.

There are at present no similarly striking anomalies with regard to biodiversity. There is, for example, little evidence that ecosystems teeming with natural diversity are more productive in any economically meaningful sense (and even the assertion that they are more "productive" in the biological sense of the term is subject to hot and occasionally hostile debate; see Naeem et al. 1999 and Wardle et al. 2000). Such effects, if they are to be found at all, may be identified only in the fullness of time—an observation that begs vexing questions concerning intertemporal allocation, fairness, and discounting.

One does not have to strain credulity to posit circumstances under which complementarities among components of diversity could be strong enough to generate nonconvexities. The debate among ecologists mentioned in the previous paragraph now hinges on the question of whether more diverse systems "overyield"—that is, whether organisms in complex communities produce more than would the same constituent elements, constrained by the same total resources, but operating in isolation. Moreover, even the least tangible of human satisfactions might admit some complementarity among the elements providing them. Perhaps it is not unreasonable for a contingent valuation survey respondent to say that she would attach more value to reintroducing, say, both wolves and moose, to a wildlife refuge. One might attach existence values not only to species but to ongoing interactions among them. It is not surprising that one of the more eloquent defenders of contingent valuation takes some pains to point out that questions may be asked about changes involving the quantities of very different entities (Smith 1997).

It is, in a way, dismaying that theory admits such variation in possible values. The observation that consistency tests do not necessarily preclude results that some find implausible does not necessarily imply that such results are to be taken at face value. There will continue to be controversy concerning the validity of the maintained hypotheses. In contingent valuation studies, are the questions eliciting truthful responses from well-informed respondents? More generally, are the preferences and/or processes derived from diverse natural ecosystems well enough understood that people can evaluate the importance of interactions between components of diversity? This is likely to remain an area of active, and controversial, research far into the future.

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