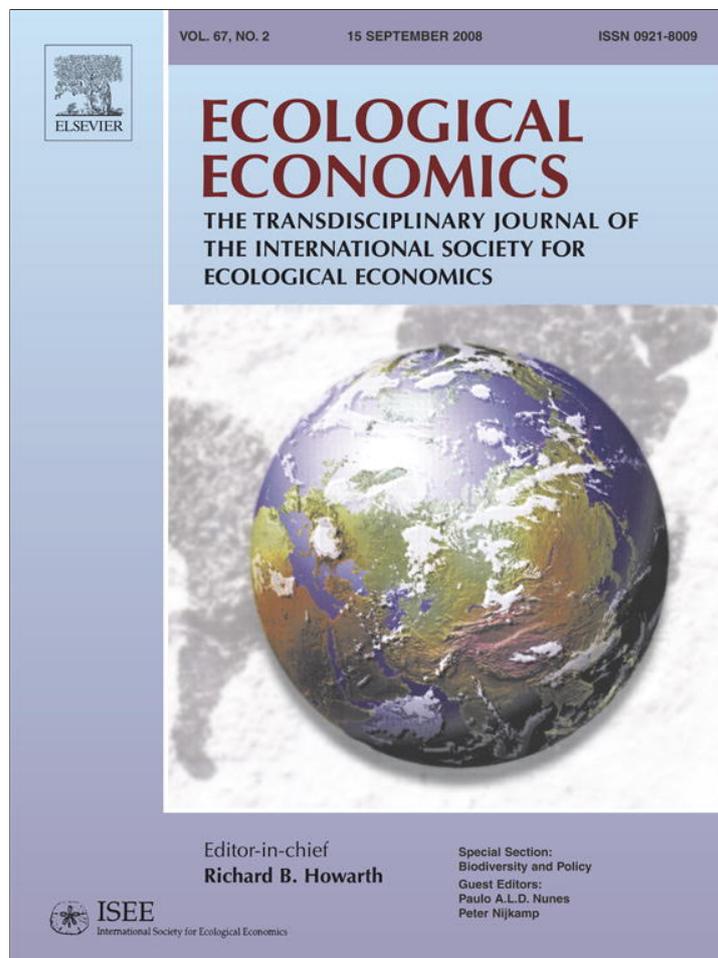


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## The value of conserving genetic resources for R&D: A survey

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### ABSTRACT

The value of genetic resources for R&D is placed within the framework of discussions concerning sustainability. We assess the extent to which society is able to invest now in order to prepare for future risks and uncertainties in the arrival of biological problems. Each of the approaches to valuation is discussed within this setting. Weitzman's approach to measurement is seen to be one that considers society's current objectives and information to be little relevant to future risks and uncertainties. Sedjo, Simpson and Reids' search-theoretic perspective is seen to reduce future uncertainties to highly tractable and known problems. Goeschl and Swanson's bio-technological approach also constrains the problem to be one without any real uncertainty, and focuses on the need to maintain genetic resources in order to maintain control over the problem. Kassari and Lasserre place uncertainty at the core of the problem, and assess the extent to which additional value is added by this feature. In sum all of the approaches to the problem evince a pessimism regarding the capacity of future technological change automatically to resolve these problems. Given this, the value of genetic resources depends on beliefs concerning the ability of current objectives to anticipate future risks and uncertainties.

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### 1. Introduction

Human society has relied upon the diversity of existing genetic resources for millennia, as a source of solutions to problems that arise in the biological arena. For example, in agriculture, when a crop has failed the surviving strains have signaled the presence of a solution concept, and this has guided plant breeders toward varieties that are successful in the existing environment (Evans, 1993). When a pest, pathogen or plague has passed through the human population, the primary source of remedies has been the set of chemicals found within the natural world (Anderson and May, 1991). These solution concepts have been identified and diffused, and have formed the foundation of the life sciences as we know them. These have been the values of genetic resources for the purposes of research and development in the past, and the question we are concerned with here is: What is the value of conserving existing genetic resources for R&D in the future?

One way to look at this problem is to consider it within the framework of those problems concerning the sustainability of the human enterprise. As society develops toward an ever larger population and an even more uniform biological base, our reliance upon biodiversity is potentially even more fine-tuned and knife-edged. Will the diversity of genetic resources remain a fundamental cornerstone for economic development? Will we continue to solve these biological problems in the future through accessing diversity, as we have done in the past? Will we be able to do so with an ever-dwindling supply of diversity? Who should bear the risks of a future filled with biological problems but relatively devoid of diversity, the current generation making the choices regarding diversity or the future generation solving the problems that arise?

In this survey we attempt to answer some of these questions in the context of a survey of the four different economic approaches that have been taken to these issues. Together these various approaches represent a wide range of

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perspectives on the way in which genetic resources might be conceived to be the solutions to tomorrow's problems. In sum the value of conserving genetic resources for R&D is something that depends crucially on whether current objectives are relevant to the solution of far-distant problems. Whether these resources have any value hinges in the first instance upon the necessity of genetic resources as the ultimate source of life science solutions. If we believe that this need exists, then the question concerns whether we can know anything now that enables us to distinguish between those resources that are more likely to be useful, and those that are not. The literature on valuing genetic resources makes clear that this is a critical question in the matter of the sustainability of the human enterprise.

In the remainder of this paper we turn in sequence to each of the four parts of this literature. We discuss and describe each method in turn, but against the background of assessing how each approach is relevant to the questions raised above. We wish to know how each of the various approaches describes the relevance of the current societal objectives in regard to genetic resource conservation, the sorts of technological assumptions embedded within the models and what the approach concludes in regard to the importance of these resources to the sustainability of human society.

## 2. Weitzman (1992, 1993, 1998) — The Noah's ark problem and the measurement of diversity

Starting with Oldfield (1989), the preservation of biological diversity has repeatedly been cast as a problem of supplying the broadest portfolio of biological options. In this sense, the value of any biological organism derives from the contribution it makes to the information or options within the entire set, rather than in respect to any particular individual value. What makes this concept difficult to operationalise is the problem of defining a meaningful measure of the stock of diversity, or the contribution of a single species to that stock. One solution to this problem can be found in the influential literature on diversity measures pioneered by Solow et al. (1993) and Weitzman (1992). Weitzman's work focuses on the question of how to measure diversity in a way that could serve as an objective in a traditional cost-benefit analysis framework of maximizing net benefits subject to a budget constraint. Much of his work concerns the development of alternative methods for conceptualising the value of genetic diversity qua diversity.

For this purpose Weitzman dedicates much of his effort to developing a measure of diversity. The building block of Weitzman's measure of diversity is the concept of pair-wise distance between two objects in a set. This measure of dissimilarity between an object  $i$  and a collection of objects  $S$  is:

$$d(i, S) = \min_{j \in S} d(i, j) \quad (1)$$

i.e. the distance to the set  $S$  is the distance to the 'closest relative' in the set. This difference should be analogous to a first difference or derivative of a 'diversity function' (to be defined) such that the marginal contribution of object  $i$  is:

$$V(S \cup i) - V(S) = d(i, S) \quad (2)$$

where  $V(\cdot)$  denotes a function uniquely quantifying diversity. The problem is to construct  $V(\cdot)$  such that it holds for all possible  $i$  and  $S$ . If the pair-wise distance measures between objects are known, then these are sufficient to construct a measure of diversity ('collective dissimilarity') of any set containing more than two objects. In fact, it permits the definition of a rigorous, but universal measure of 'diversity' as a scalar measure rooted in concepts of relatedness.

The important question for our purposes is: what is the measure of distance that is used to generate this index of diversity? Weitzman utilises the genetic relatedness of individual species by reference to a chemical measure: the amount of energy required to cause the DNA of different species to bind. The greater the amount of energy required, the less related are the chemical structures. Hence it is possible to develop a table of species relatedness by reference to chemical reactivity. Using this as a fundamental index of relatedness, he is then able to generate taxonomies of inter-species distance deriving from this measure, giving graphic representations of these diversity functions in addition to the tabular format. Thus, Weitzman is able to regenerate taxonomy from chemical information on basic genetic dissimilarity, and to use this taxonomy to encapsulate his notion of diversity.

Weitzman demonstrates the applicability of his concept of diversity functions for developing robust rules for conservation programs. In Weitzman (1993) he applies the framework to crane conservation. In the crane conservation problem the social objective is to maximise the size of the genetic space conserved under a given budget, where that space is generated by reference to his diversity function. He is able to list in both tabular form, and taxonomic trees, the information on relatedness relating to all extant crane species using his diversity functions.

Weitzman's first attempt at the problem is a fascinating effort to re-trace the steps of taxonomists, given new technologies for measuring genetic dissimilarity, and his policy efforts implicitly maximise the amount of diversity that is chemically quantifiable. This is an interesting attempt for the societal objective that it presumes, which is based on the concept of genetic isolation. It has long been argued that the concept of a species is that of a subset of the genepool that has become reproductively isolated. In this sense, the coevolution of that subset has resulted in a set of natural combinations, which are much more likely to be chemically reactive with one another than with others. Weitzman is using this notion of genetic isolation as the basis for his measure of distance. This assumes that a reduced level of basic chemical reactivity is a general indicator of important differences, and possibly an indicator of the amount of time that has passed since the two subsets of the genepool were contiguous. It is not clear that any of these assumptions need necessarily be true in every instance. It also is not at all apparent in what sense these differences are important, or even relevant, to any particular social objective. To a very real extent, this is an attempt to develop a measure of genetic diversity that is not necessarily related to societal objectives.

Weitzman addresses these issues regarding the relevance of his diversity measures in a later paper. In his analysis of the "Noah's Ark Problem" (1998), diversity functions are used to develop a ranking criterion for different species competing for scarce conservation resources. Here species face an inherent uncertainty concerning continuing existence, where  $P_i$  is the

probability of survival of species  $i$  (assumed to be independent between species). The loss of the value of a given species  $i$  is summarized by the loss of its direct utility ( $U_i$ ) and a coincidental loss in the value of its contribution to aggregate diversity  $V(\cdot)$ . Given uncertainty, the existence of the collection of  $Q \subseteq S$  species is probabilistic, which yields the expected aggregate value of individual species  $U(P)$  and the expected value of diversity they represent  $W(P)$  as:

$$U(P) = \sum_i P_i U_i \tag{3}$$

$$W(P) = \sum_{Q \subseteq S} \left( \prod_{j \in Q} P_j \right) \left( \prod_{k \in S \setminus Q} (1 - P_k) \right) V(Q) \tag{4}$$

Given this definition of the expected value of diversity, Weitzman then turns to demonstrating that expected value may be related to the information content of the stock of candidate species. To show this, Weitzman assumes that  $\varepsilon$  is the probability that any given species contains some useful information (used for example to develop a new drug to cure a deadly disease). It follows that the probability that at least one species among the set  $Q$  contains the useful information is  $H(Q, \varepsilon) = 1 - (1 - \varepsilon)^{V(Q)}$ . Here the value function for the diversity of the species is being related to a functional objective, viz. its marginal contribution to the solution of a biological problem. Weitzman defines the information content of diversity (defined as the probability that the set of  $Q$  species contains the useful information conditional on the existence of the species) as:  $I(P, \varepsilon) = \sum_{Q \subseteq S} \left( \prod_{j \in Q} P_j \right) \left( \prod_{k \in S \setminus Q} (1 - P_k) \right) H(Q, \varepsilon)$ . It follows that diversity is the first order approximation or the first derivative of the information content with respect to uncertainty, i.e.  $\frac{\partial I(P, \varepsilon)}{\partial \varepsilon} \Big|_{\varepsilon=0} = W(P)$ .

In other words, Weitzman justifies his reliance upon diversity measures by reference to the relationship between diversity and informational content, and an assumption that any increase in information (diversity) will contribute an equal amount to the potential solution of important societal problems. This last assumption requires a large leap of faith, but there is some merit in assuming that diversity exists for a function (past or present). Natural selection must ultimately dispose of any traits that serve no beneficial function, usually defined as being either the function of primary production or reproductive success. The analysis of coevolution demonstrates that there are additional traits, often termed secondary metabolites in higher plants, whose contribution to an organism is to compete with others. (Swanson, 1995) To the extent that genetic traits have been useful in competitions with other living organisms in the past, their continued existence might again serve a similar purpose if those competing strategies re-emerge. The question is how long useful traits of the past will be carried forward, before being washed out of the organism if not currently called into use. Of course it is also relevant to query whether society will value the particular competition or contest to which the trait is relevant, and the extent of that value. Society might feel one way about a trait that might be relevant to future competitions regarding wheat or maize, and another way altogether about one involving sweet clover. Not every evolutionary problem is a social problem, and those which are social problems might attract very different values. All of these issues are implicit within Weitzman's informational assumptions, but not really addressed.

Weitzman (1998) applies his new approach to the problem of ranking individual species for conservation. Society there faces the problem of conserving biological diversity by means of choosing the probability of survival  $P_i$  that maximizes the sum of the expected direct value of species and expected value of diversity  $U(P) + W(P)$  given the limited resources  $B$  allocated to the program. Preserving the diversity of species is costly ( $C$  is the cost of maintaining diversity) but conservation will increase the probability of survival of protected species. If species  $i$  is protected then its probability of survival is  $\bar{P}_i$  against  $\underline{P}_i$  otherwise, with  $0 \leq \underline{P}_i \leq \bar{P}_i \leq 1$ . Formally, the decision maker's problem is:

$$\begin{aligned} \max_{P_i} & U(P_i) + W(P_i) \\ \text{s.t.} & \sum_i C_i \left( \frac{P_i - \bar{P}_i}{\bar{P}_i - \underline{P}_i} \right) = B \\ & \underline{P}_i \leq P_i \leq \bar{P}_i \end{aligned} \tag{5}$$

Given the discontinuity in the likelihood of preservation, the policy solution is going to take the form of a corner solution. The solution to this problem is an extreme policy in which the resources are allocated to preserve some species and not at all to others. The choice of whether a species  $i$  should be preserved relies upon the so called Noah's ranking criterion, which is a simple ranking rule  $R_i$  where species  $i$  is preserved if  $R_i$  exceeds a certain threshold  $R^*$ , and not preserved otherwise. The ranking criterion  $R_i$  is written out as:

$$R_i = (D_i + U_i) \frac{\Delta P_i}{C_i} \tag{6}$$

This criterion incorporates information on the distinctiveness of a species  $D_i = \sum_{Q \subseteq S} \left( \prod_{j \in Q} P_j \right) \left( \prod_{k \in S \setminus Q} (1 - P_k) \right) d(i, Q)$ , and also on the direct utility of a species ( $U_i$ ), the increase in the probability of survival as a result of being conserved ( $\Delta P_i = \bar{P}_i - \underline{P}_i$ ) and the marginal cost of survivability gains ( $C_i$ ).

For our purposes the main contribution of Weitzman's approach lies in his definition of distinctiveness, and the measure used to give weight to a particular organism's contribution to the set's diversity. His arguments concerning the relationship between his diversity measures and broader notions of value (information, discovery) are not explicitly developed, and take the form of unexplained assumptions regarding genetic distinctiveness and inherent value. Weitzman's analysis delivers a path-breaking approach to the measurement of diversity qua diversity, although the specific nature of the links between diversity and social objectives and values remains open. This may or may not be an important limitation, depending on how well current objectives and values are predictive of the nature of future objectives and values in this realm. We will discuss this further in the sections below.

### 3. Simpson, Sedjo and Reid (SSR) (1996) — Search model approach to valuation

In an influential article on the value of bioprospecting, Simpson et al. (1996) develop a search-theoretic perspective on the problem, inspired by the approach found in the early paper by Brown and Swierzbinski (1988). They ground the value

of biodiversity in the activity of 'biodiversity prospecting' in an R&D-intensive industry. They deduce the marginal willingness to pay for an additional sample by reference to the potential value of adding another member to the set of genetic resources available for screening. The aim of their work is to quantify the willingness by private firms to invest in the conservation of biodiversity — when that value derives from the increased size of the potential sample group for purposes of achieving a specifically-defined outcome. Their problem reduces to a search across a given number of objects for the solution to a specific problem or specific number of problems, each object of which has an independent likelihood of providing the solution. The search model is not very closely rooted in the biological problem of conserving useful long-term survival strategies, but unlike Weitzman it makes a very specific link between genetic diversity and specific forms of social values.

The SSR approach is focused on the very private objective of firms seeking patents through random searches in natural habitats. The value of a marginal genetic resource within such a habitat is by reference to its contribution to the anticipated royalties from licensed sales after a successful search. Against this value is balanced the cost of undertaking another search and the prospect that earlier searches have already resolved the problem. The primary point of SSR is that, given a specified number of targets, the value of the marginal genetic resource must be declining on account of the decreasing likelihood that the solution has not previously been located and the increasing costliness of another search for the same target.

The typical model features a fixed probability  $p$  of identifying a valuable trait in any given screen of a sample from a pool (of genetic resources) where a successful screen gives rise to a product with fixed revenue  $R$ . The cost of screening a sample is fixed at level  $c$ . The expected value of a search over  $n$  samples  $V(n)$  can then be expressed as:

$$V(n) = pR - c + (1 - p)(pR - c) + (1 - p)^2(pR - c) + \dots + (1 - p)^{n-1}(pR - c). \quad (7)$$

This expression says that the total expected value of a search process is the sum of the expected payoffs until a sample is successful. In other words, if the first trial is successful the firm will receive an expected payoff of  $pR - c$ ; however, if the first trial fails with probability  $1 - p$  leading to a second trial which will also have an expected payoff of  $pR - c$ , and so on through the  $n$ th trial. The expected value of the pool of genetic resources is the sum of both those paths leading to early successes, and those paths that lead to much later ones (and hinging on the earlier observation of large numbers of failures). In effect the aggregate value of the sample pool derives from the aggregate measure of the "event tree" comprised of all events that can lead ultimately to successful screens; however, this event tree is extraordinarily unidimensional: the only path to success for any given genetic sample lies down a singular path of previous failures. Under this logic the marginal value  $v(n)$  of the  $(n+1)$ th sample is then its additional contribution to the total value of the search conditional on  $n$  unsuccessful previous trials. It represents the expected payoff of a successful  $(n+1)$ th sample given the failure of the  $n$  previous samples:

$$v(n) = V(n + 1) - V(n) = (pR - c)(1 - p)^n \quad (8)$$

In order to translate this static result into a dynamic context, SSR take the additional step of stating their assumption regarding the number of targets that exist in any given period as a constant ( $\lambda$ ); and then sum over time to determine the aggregate value of the marginal genetic resource. This results in the slightly modified expression below (where  $r$  is the relevant discount rate).

$$\sum_t v_t(n) = \frac{\lambda}{(1 + r)} (pR - c)(1 - p)^n \quad (9)$$

The problem as formulated in Eq. (9) generates several novel and relevant observations regarding the valuation of genetic resource sets for informational purposes, deriving from the general finding that the function mapping the probability of success in any single trial to the value of the marginal species (*ceteris paribus*) is single-peaked at fairly low probabilities and highly skewed to the right. This observation is interesting in several respects: First, it shows that sampling costs are an essential determinant of the marginal value of genetic resources, and studies that do not take these costs into account (e.g. see: Pearce and Puroshothoman, 1995; Farnsworth and Soejarto, 1985) are bound to over-estimate the marginal value significantly. Secondly, the fact that the marginal value of the species is not a monotonically increasing function of the probability of success brings an issue to the fore that had previously been overlooked by many researchers, namely the possibility of substitutability between genetic resources in searches for solutions. If there is significant redundancy within the stock of samples, a significant proportion of the samples can be discarded prior to screening with little loss of expected revenue since it is very likely that a success will be found within the remaining portion.

These points are then demonstrated in a practical example. Based on a number of reasonable assumptions regarding the market value of a product, the costs of screening, the maximum number of potential successes in a given search process and the independent likelihood of success in a given sample, Simpson et al. (1996) derive an upper bound for the willingness to pay (WTP) for the marginal sample for R&D purposes. They then translate this into a per-area WTP for conservation using the common MacArthur–Wilson approach of relating habitat size to the extant stock of biodiversity. Based on these computations, the maximum willingness to pay for biodiverse lands in Western Ecuador, one of the 'biodiversity hot spots', is just US\$20.63 per hectare. The rain forests of the Amazon elicit only US\$2.59 per hectare. This implies that most areas with even extraordinary biodiversity do not justify significant payments from the pharmaceutical industry for their preservation. The conclusion of Simpson et al. is that there is little reason to expect that the industrial use of genetic resources will result in significant payments for the conservation of marginal resources by private investors. This last point of SSR is probably true, and it is the most clear-cut result from the model and the examples given. Given the discount rates used by the private sector, and the limited objectives pursued by the private sector, it is very likely that the linear approach to search is legitimate in this context. A private sector may be unable to conceive of conservation values beyond one or two turns of the product cycle, i.e. possibly no more than

five or ten years, in which case its approach to search would be very limited and linear. However, using a privately motivated screening process as any sort of approximation to the social values of genetic resources may be problematic.

This limitation is addressed in *Craft and Simpson (2001)*, where they expand on this paper by considering the social value of biodiversity for R&D in terms of producer and consumer surplus as opposed to the private industry valuation alone. In this paper, they combine the search model with a product differentiation model in the spirit of *Salop (1980)*. Even though values may lie in a somewhat higher region, the fundamental logic of the private screening process remains. This means that the fundamental problem of truncating the search process also remains, in that the process is being motivated by private incentives and so short term planning horizons continue to apply. Hence the search process remains linear and uncomplicated, and the new values are simple additions to the previous ones.

The possible mismatch between private and social values is the first of three conceptual limitations of this approach to the problem of genetic resource valuation: 1) The private value of genetic resources for bioprospecting may be a poor proxy for their social value (see *Goeschl and Swanson*, below); 2) the assumption of equal but independent likelihoods of success in sampling processes may be both important and unlikely (see *Rausser and Small (2000)* for the argument and *Costello and Ward (2006)* for a critical review); and 3) the casting of the problem as the search for the solutions to a pre-determined number of problems is a highly simplified approach to technological innovation in the life sciences (see *Goeschl and Swanson, 2002*). In short, this search model fits well with the modeling of a limited and better-defined search processes, such as the search of a linear store front for a particular good or the search over a set of nearly-identical phone books for an address (or number of addresses). These search processes are clearly linear in nature, and the objectives are well-defined and the number of solution concepts is predictable and obviously countable. Its fit in a less well-defined setting requires further examination.

One assumption captures much of the linearity of this approach to search. It is the reduction of the underlying technological assumptions regarding the demand for search to a single constant,  $\lambda$ , the number of search targets. Fixing demand for searches in this way has a cost, in that processes that give rise to new targets are excluded from the analysis rather than being included at the core of the model. Two obvious sources of such ongoing demand come to mind. One is the exogenous and unpredictable consequences of environmental change that require new solutions to be found. The other is the process by which human society continues in its contest against pests and pathogens to gain ground in the life sciences (or not). It is known that pests and pathogens will continue to erode the solutions that humans put into place in the life sciences (*May and Dobson, 1986*), but the precise nature of the future problems that will be generated or the sequence in which they will arrive is unknown. In this case it is possible that searches that are unsuccessful for one purpose (or problem) might be right on point for a future one. It is also the case that any given solution will drive the future of the event tree, and the likelihood of future types of problems,

down certain pathways where entirely new samples are generated and new problems created. For these reasons the “event tree” which will constitute the future of genetic resource search is more likely to be bushy than linear in nature, and the aggregate value of any particular branch will evolve with the previous choices which have been made. The very stylised search process of SSR is not general enough to deal with these more complex futures but instead derives its estimates based upon its highly restrictive assumptions.

#### 4. *Goeschl and Swanson (G&S) (2002)* — The evolutionary contest and genetic resource values

This paper continues the investigation of genetic resource values within the context of patent-motivated search. In doing so, it develops a social framework for search that focuses on two issues: 1) the extent to which the search for biological solutions under a patent system matches up with social objectives regarding genetic resources; and 2) the extent to which the technological contest in the life sciences may be made a core part of the modeling of the value of genetic resources.

We will take the second issue first. *Goeschl and Swanson (2002)* commence with a simple observation from the agricultural R&D industry. In that sector, it is a stylized fact that a widely-used modern plant variety experiences declining yields in each of its years of usage, resulting in commercial obsolescence in a period of approximately five to ten years (*Heisey, 1990; Heisey and Brennan, 1991*). One reason is that in plant breeding, as in many other R&D-intensive sectors, innovators (plant breeders) are engaged in a contest of innovation against one another; the breakthrough of one can render the others' products commercially obsolete (‘creative destruction’). However, these innovators are also engaged in a contest against nature. The ongoing adaptation of the pests and pathogens to widely-applied innovations results in the obsolescence of plant varieties through adaptation (‘adaptive destruction’). Thus, the solution provided by R&D must necessarily be impermanent, and a flow of such problems will arrive predictably though the precise nature of each specific problem is unpredictable. In order to provide for a stock of information to address this predictable flow of problems, an important input into plant breeder R&D is the diversity of genetic resources (see: *Evenson et al., 1998*).

Based on this observation, *Goeschl and Swanson (2002)* develop a framework in which genetic resources are used in R&D at the base of an industry that addresses recurring problems of resistance, as in the pharmaceutical or plant breeding industries. The R&D process is one in which firms are engaging in a continuing contest of innovation against a background of both creative destruction (Schumpeterian competition) and adaptive destruction (natural selection and adaptation). The net effect of investment in R&D is to make progress in this contest relative to the rate of adaptation taking place within the biological sphere. Technological change is then conceptualised as an attempt to make progress up a ‘technology ladder’ against a background of biological change resulting in movement down the same ladder.

G&S propose a model in which the problem of conservation reduces to choosing between the proportion of global land

supplies used for conservation purposes ( $v$ ) versus the proportion used for intensive production  $F(1-v)$  in the production of final agricultural output ( $y$ ). The purpose of holding land for conservation is two-fold: it both increases the stock of genetic information available for search (thus increasing the arrival rate of innovations  $\phi i(v)$ ) and it also decreases the scale of application of the production technology (and thus decreases the rate of adaptation to the previous innovation  $a(v)$ ). The impact of human innovation net of biological adaptation determines the current stage of technology ( $A_s$ ), which is the number of steps of progress or regress away from the initial stage of technology ( $A_0$ ). Thus, the integration over the infinite horizon programme of land allocation generates a net present value of total production set forth in Eq (10) below that balances two factors: 1) the initial level of final good production and hence consumption (the numerator in (10) below); and 2) the trajectory of future growth in production given the net rate of innovation in the R&D sector (the denominator below). The numerator in Eq (10) represents the investment of resources into the initial level of production while the denominator represents investment of resources into sustainability (the growth trajectory emanating from that initial level of production). This expression therefore encapsulizes the reasons why society would choose to invest in conserving genetic resources for R&D, as a function of the choice of outcome in the technological contest between human society and its pests and pathogens.

$$U(y; v) = \frac{A_0 F(\cdot)}{r - [\phi i(v) - \lambda a(v)\gamma^{-1}](\gamma - 1)} \quad (10)$$

The design of genetic resource conservation policies balances the value of retaining and restraining future innovation capacities against the costs of current foregone consumption, i.e. the derivative of the above expression with respect to the marginal land allocation. In this framework the marginal value of land held for biodiversity, MVLB, is:

$$MVLB = \frac{[\phi i'(v) - \lambda a'(v)\gamma^{-1}](\gamma - 1)F'(\cdot)}{r - [\phi i(v) - \lambda a(v)\gamma^{-1}](\gamma - 1)} \quad (11)$$

which is the net present value of the net increase in productivity in terms of final output  $F$  from two sources: The first is  $\phi i'(v) > 0$ , the marginal increase in the rate of arrival of innovations by virtue of a greater amount of biodiverse land preserved. The second is  $\lambda a'(v)\gamma^{-1}$ , the marginal reduction in the rate of biological innovation on account of reduced selection pressure. The own discount rate applied in the denominator is the composite rate used by the social planner which takes into account the rate of technological and biological innovation. All of these costs and benefits are measured in terms of the step-size of innovation ( $\gamma$ ), which represents the gain or loss of one innovation within the system. The MVLB is then the integral across an infinite time horizon of the benefits from innovations lost if the genetic resource base is narrowed; its opportunity cost is the marginal value of one more unit of homogeneous production (net of the adaptation costs that this implies).

These values are stated in terms of social benefits from innovations in the life sciences sectors, and it is important to relate these to the manner in which private patent-based

incentive measures operate. This optimal allocation is likely to differ substantially from that of the patent-motivated firm. Because information flows freely once it is made available, a private firm will engage in research activities only if it is assured of reaping the benefits of its innovation. This benefit represents the private marginal value of biodiversity (MVBD<sub>p</sub>) which is the discounted expected value of the monopoly rent for the patent holder if one more unit of land is allocated to reserves.

$$MVBD_p = \phi i'(v) \cdot \frac{\gamma \frac{[F'(\cdot)]^2}{-F''(\cdot)}}{r + (n-1)\phi i(v) + \lambda a((n-1)v, g)} \quad (12)$$

The discount rate accounts both for the opportunity cost of capital  $r$  and the patent obsolescence due to technology change and biological adaptation. It appears that the social value of reserves for the purposes of R&D is systematically underestimated by private valuation. These valuations differ significantly because private firms fail to internalize several externalities. The clearest example of such an externality is the fact that biodiversity both slows the rate of adaptation and increases the rate of innovation, while only the latter can may be appropriated by the use of patents. The most important difference between patent-based objectives and societal objectives regarding genetic resource conservation is that firms engaged in a race to obtain patents focus primarily on the capacity to beat the incumbent and gain the current patent, whereas the appropriate societal objective is to make actual progress against the background of biological adaptation. For example, it is likely that a heavily-invested incumbent, with an assured future patent, would make no effort to make progress until such time as its patent was about to expire, even against a background of rapid adaptation and decline. And, in general, enhanced problems of adaptation and production decline will result in shorter patent lives, and thus reduce the rate of investment in innovation. In sum, the patent-based incentives for investment in genetic resources are both under-estimates and (in some of the most important cases) mis-targets. Therefore using the measures deriving from patent-based incentives to estimate the marginal value of biodiversity is probably inappropriate.

The G&S approach to the value of conserving genetic resources takes much from the SSR perspective on search, but adds a more specific set of technological assumptions. Genetic resources supply values both by enhancing social innovation and retarding biological adaptation. The assumption is that genetic resources contribute to the base of information available for search, and that innovations continue to arrive in a straightforward and continuous manner across time. In that sense the technology is not so different from SSR, except that problems and innovations are linked to the level of genetic resources. This is an important difference but it is also an indication that the two approaches (SSR and G&S) are more closely related to one another than they are to the others in the literature. At base, both assume that the question of conserving genetic resources is related to current societal objectives and the level of the anticipated flow of future problems. In these models the future path of problems is predictable in certain important respects, and this renders current conservation objectives and values determinate. Here

the diversity of genetic resources that should be retained is in direct proportion to that required to maintain optimal progress in the current technological contest. The models do not provide for uncertain or uncontrollable events within this technological contest, and so current objectives, values and requirements are adequate for the purpose of determining future needs.

### 5. Kassari and Lasserre (2004) real option approach — The importance of uncertainty

The purpose of this paper is to highlight the role of irreversibility and uncertainty in valuing biodiversity. The authors argue that if irreversibility and uncertainty are taken into account, substitutability among species will not be an obstacle to conservation as claimed by SSR but will in fact provide an additional rationale for the conservation of biodiversity. Indeed if the relative value of species used in addressing biological problems evolves across time in an unpredictable fashion, the valuable species today may prove to be ‘useless’ in the future and vice-versa. As a result even with perfect substitutability of the species, there is reason for preserving genetic diversity as insurance against the arrival of new information over time. This approach makes clear that the important issues concerning genetic resource conservation values are the ones involving real uncertainty. The assumptions about how future paths evolve determine what is valuable, and how these values change into the future. In this case the problem of genetic resource conservation is not linear (as in SSR) or known but cyclical (as in G&S) but rather Markovian: paths into the future that intersect and intertwine in a seemingly random and unpredictable manner.

To make their case, K&L develop a real option framework to arrive at a characterization of the insurance value of maintaining these values in the face of uncertainty about the future. For expositional convenience we focus on the modeling in respect to only two species. Suppose two perfectly substitutable species with a respective value  $v_1$  and  $v_2$ . Without loss of generality we assume  $v_1 > v_2$  implying that only species 1 will be used in the R&D industry. The problem for the decision maker is to decide whether to take costly measures to preserve both species, or to let the un-used species (here species 2) go extinct. While conservation is costly and amounts to  $C(v_1, v_2) = k(v_1 + v_2)$  (with  $k < 1$ ), the extinction of a species constitutes an irreversible loss. The values of both species evolve stochastically according to the geometric Brownian motion:  $dv_i = \alpha v_i dt + \sigma v_i dz$ , where  $\alpha$  is the deterministic rate of change in  $v_i$ ;  $dz$  is a Wiener process; and  $\sigma$  is the variability of the process. The stochasticity of the values reflects both endogenous and exogenous changes (tastes, new diseases, institutions). In addition, the return to the decision maker is  $R = \max(v_1, v_2) - k(v_1 + v_2)$ . In real option terms, the decision problem is whether to continue investing in the conservation of both species or to exercise the option of letting species 2 go extinct. The trade-off is that exercising the option surely saves conservation costs but it also disqualifies the decision maker from using species 2 in the future should there be a reversal in the species’ values, i.e. should  $v_2$  eventually exceed  $v_1$ . The decision problem is a recursive problem of optimal stopping nature and is typically represented

by a Bellman equation. Using Ito’s lemma, the payoff  $F_1(v_1, v_2)$  of holding on to species 2 in the continuation region can be written out as:

$$F_1(v_1, v_2) = v_2 \left( \frac{1-k}{r-\alpha} V_2 - \frac{k}{r-\alpha} \right) + v_2 (A_1 V_2^{\beta_1} + A_2 V_2^{\beta_2}) \equiv v_2 G_1(V_2) \tag{13}$$

where  $V_2 = \frac{v_1}{v_2}$ ;  $\beta_{1,2} = \frac{1}{2} \pm \sqrt{\frac{1}{4} + \frac{r-\alpha}{(1-\rho)\sigma^2}}$ ;  $A_1$  and  $A_2$  to be determined. The value  $F_1(v_1, v_2)$  has two components: the first term reflects the continuation of value associated with the preservation of both species; the second term reflects both the expected payoff of exercising the option at a later date, and the expected payoff of substituting species 2 for species 1 at some point in the future.

Let  $V(v_1)$ , the value of exercising the option in the stopping region.

$$V(v_1) = F_1(v_1, 0) = E_t \left[ \int_t^\infty e^{-r(s-t)} (1-k)v_1(s) ds \right] \tag{14}$$

The decision maker is indifferent between the conservation and extinction of species 2 along the frontier of the continuation and the stopping regions. As a consequence, exercising the option is optimal for any value  $v_2 < v_2^*(v_1)$  where  $v_2^*(v_1)$  satisfies  $F_1(v_1, v_2^*(v_1)) = V(v_1)$  and  $\frac{\partial F_1}{\partial v_2}(v_1, v_2^*(v_1)) = \frac{\partial V(v_1)}{\partial v_1}$ . Hence, whether the option is exercised is dictated by a trigger value ratio between the species  $V_2^* = \frac{v_1}{v_2^*(v_1)}$ . This shows that under uncertainty the ‘non-useful’ species 2 is conserved as long as its value exceeds a threshold (which is function of the value  $v_1$  of species 1). Above this threshold, the substitute species 2 is deemed an insurance policy against the future stochastic evolution of  $v_1$  and therefore will be preserved. These considerations lead to the derivation of the marginal value of biodiversity as the difference of retaining the option (at the cost of preservation) and disinvesting in the marginal species. The marginal value of species 2 is given by:

$$V_{m2}(v_1, v_2) = F_1(v_1, v_2) - V(v_1), v_2^*(v_1) < v_2 \leq v_1 \tag{15}$$

It is notable that when the two species are negatively correlated, the incentive for conservation is even greater because species 2 then constitutes good insurance against the reversal of the relative values. This effect is amplified by greater uncertainty, that is higher volatility  $\sigma$  in yields, as this results in a greater likelihood that paths will cross. One key conclusion from Kassari and Lasserre (2004) is that in a world in which conservation projects are carried out under uncertainty, substitutability in use works in exactly the opposite fashion from its description in Simpson et al. (1996). The closer the substitutability today, the more likely it is that the marginal species today will be called upon to replace the currently most preferred species. Substitutability is a reason for disinvestment only with respect to the probabilistic properties of the species. The higher the correlation of the stochastic processes, the lower the value of the optional species. But if the future movements of the paths are unknown or disassociated, then the fact of substitutability does not count against the conservation of the species.

The general point of K&L is that uncertainty regarding the paths of future values will require that additional real option

values be allocated in the present. So long as the manner in which different genetic resources will respond to new information is different, then the value of diversity is simply to maintain a broader portfolio of potential responses. In effect, if a reversal of the relative values of two substitutable species is possible and the loss of any given species is irreversible, then there is a clear incentive to preserve the non-used species given uncertainty.

In the very long run, the real option approach suggests that there is value in retaining any genetic resource. If it is known that R&D problems will arise in the future, but the precise nature of the problems that will arise in the distant future is unknown, then the real option approach generates values for all forms of diversity. The problem here is that the information set at any given point in time is necessarily incomplete. Any ranking of genetic resources against that set of information will necessarily be inaccurate, once biological circumstances change. For this reason there is value in retaining diversity qua diversity, without reference to the current information set. In this sense, K&L bring us back full circle to the Noah's ark problem of Weitzman. Given the indeterminacy of the future, there is added value to retaining the contribution of any given organism to diversity irrespective of any known relationship to any known human objective at the present time. The longest term objective requires the recognition that current objectives are based on current information.

## 6. Remarks on a framework for considering the values of conserving genetic resources for R&D

The question addressed in this survey is: how can society invest today to conserve the solutions that will ultimately be required in the biological problems that will arise? We have argued here that the question might best be considered within the framework of sustainability. In the first instance, genetic resource conservation is important for sustainable development if the following conditions are met: a) biological problems (pest, plagues, pathogens) will continue to arise at a fairly constant or increasing rate; b) the technological solutions to these problems are at present uncertain; but c) those technologies are such that genetic resources will continue to be an important source of solution concepts.

The different parts of the literature on genetic resource values demonstrate very different approaches to these conditions, although each commences from the assumption that the last condition is met. This places the literature squarely on the side of investigating the positive range of values, while it is possible that technologies based on resources other than genetic inputs might one day exist. We will return to this point below.

With regard to the first two conditions required for valuing genetic resources, the literature ranges dramatically regarding the capacity of society to foresee the nature of future problems and the importance of particular resources. The most optimistic in this regard is the search model of SSR. They have assumed a future in which there is a very specific and constant number of biological problems arriving in each period, which are then resolved with finality by reference to an identified set of genetic resources. In this situation the

technological assumptions indicate that everything is well-known, understood and under control. There is no uncertainty to deal with regarding future biological problems, and the nature of the problem remains nicely defined and clear-cut across the entire time horizon. The result is a constant and certain level of demand for genetic resources to deal with these problems, and the identity of the most useful resources is able to be determined by reference to today's social objectives.

This model is important for making clear what assumptions are necessary to get this sort of straightforward result. We have to assume that tomorrow's objectives and problems are closely related to today's (in order to make today's ranking of resources relevant for the future). And we have to assume that there is a stable process that generates these problems in a predictable fashion (resulting in a predictable number of problems of the same sort arising at each point in time). These assumptions are strong, and they indicate what is necessary to get to a deterministic result that both delimits and identifies the set of genetic resources we wish to conserve today.

The nearest model to SSR in this respect is probably G&S. In their approach the technologies and problems are also narrowly defined, and the uncertainty is limited to timing. The biological problems arrive in a precisely-specified although stochastic manner. This generates an easily controlled-for sort of uncertainty. Likewise the manner in which technologies respond to genetic resource conservation is similarly straightforward. The model does not distinguish between the contributions of differing genetic resources, but allows any conservation to have the same impact. This implies that current objectives always translate into the same amount of conservation effectiveness. Although there is some uncertainty regarding the timing of problems and innovations, there is not much variability within the model otherwise. In this sense, G&S provide a view of the future in which technological change is placed centre-stage, but the results are very similar to SSR. Genetic resource investments of a given level will provide solutions relevant to the future flow of biological problems. This means that the sets of genetic resources that are required in the future may be identified by reference to current objectives, and the levels of resources required are identifiable by reference to current technological requirements. Since the impacts of biological problems are finite and bounded, there is little important event uncertainty about future technological changes. The numbers are somewhat larger in the context of G&S (on account of the internalisation of externalities), but the basic message is the same: the value of genetic resource conservation is to provide solutions for a flow of incoming problems of a fairly well-understood and readily anticipated nature.

The real options approach of K&L provides an alternative view. It sees the problem as one of future uncertainties combined with current irreversibilities. The focus here is on the uncontrollable parts of the problem. Here the future potentially contains variability that is unforeseeable, and which renders current information and technology irrelevant to decision making for that future time. Implicitly the assumption is that there is no information available at the present time to inform us on how to invest in technologies that will be able to deal with incoming uncertainties. Hence, current information combined with current

objectives generates rankings that will not be suited to future environments (with different information and different objectives). There is an un-linking of the timeframes in this framework, in contrast to the role that technologies played in the other papers in linking decision making across time. SSR made a very simple link-up across time, and G&S made a slightly more complicated one, whereas K&L are assuming that we are unable to make this link. The information arriving in the future will generate surprises which our current objectives, information and technology cannot anticipate. This is a much more pessimistic view on the capacity for our current investments in technology to anticipate the nature of the future flow of biological problems, and places additional value on conserving genetic resources to fit whatever problem or technology that might someday arise.

Finally, the work by Weitzman provides the most pessimistic assessment regarding the capacity of current objectives and technologies to predict the sorts of investments required for future problem-solving. He starts from the logical conclusion implied by the real options framework, viz. that current objectives and technologies are irrelevant to the solution of future problems. Then the only thing that matters in preparing for the future is the maximising of diversity, given the available budget, and irrespective of current objectives. This implies that we not only do not have forward-looking objectives or technologies, but that these things are ultimately unknowable. In the face of total uncertainty of this nature, the only thing to do is to maximise genetic resources in a technology-neutral fashion.

In the final analysis, however, it is clear that all of these approaches can be criticized for falling on the same side of the fence in regard to technological beliefs. They all implicitly assume a role for genetic resources in the solution to future biological problems. It is important to recognise that it is possible that the future will build upon the base of information derived from natural resources, but develop down pathways that make use of the information while resorting to more basic building blocks (e.g. chemicals) in generating new solution concepts. The economic question then is: when does this backstop technology become so widely available as to render pre-existing technologies redundant?

In the case of the life sciences, it is apparent that there is both a large degree of uncertainty concerning the nature of the future problems arriving within the biological system, and a wide range of beliefs concerning the ability to forecast the technologies that will address these risks and hence uncertainty regarding the genetic resources required to deal with them. One way to resolve this debate is to enquire whether the current society is generating the problems for which solutions will be required. If, for example, the generation of an ever more uniform world with an increasingly reduced biological base results in an increasing rate of arrival or scale of risks in the life sciences, then it is arguable that the current generation should bear these risks as well as their uncertainties. Sustainability should require that the current development of an economy with increased risks requires that the future is handed the stocks of information and technology required to deal with them. When the nature of the technologies required to address these problems in the future remains uncertain, this implies an obligation on the current generation also to bear the risk of providing at least one form of technology and its necessary inputs. In this respect we agree with [Gollier et al \(2000\)](#) when they contend that “more scientific uncertainty as to the distribution of future

risk – that is a high variability in beliefs – should induce society to take stronger prevention measures today”. In this sense, providing inputs to go with existing technologies may be seen as an application of the precautionary principle, in the event that alternative technologies are not forthcoming.

In this regard, much of the question concerning sustainable development in this arena revolves upon the issue of which generation should bear the technological risks currently being created. The current values of genetic resource conservation would then derive from the responsibility of the current society to sustain current technologies and inputs for created risks, at least until such time as the new technologies for addressing biological problems are widely available.

In summary, we have attempted to address the basic question in this essay: How should society conceive of the problem regarding the conservation of genetic resources for R&D? Different readers might respond to this question differently, depending on: a) whether they consider current human objectives and technologies to be a sufficient basis for decision making concerning conservation of biodiversity, or not; and b) whether they are optimistic concerning the substitution of other technologies less reliant upon genetic resources for R&D, or not. As the answers to the above questions move from the positive to the negative, it becomes increasingly important to retain the broadest possible portfolio of diversity, a la Weitzman. If the reader's view on these problems is reasonably optimistic, then the values of conserving genetic resources for R&D becomes diminishingly small a la SSR.

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## 7. Conclusion

We have argued here that the appropriate framework for thinking about the value of genetic resources for R&D is the same as that used for thinking about long-term problems of sustainable development in the presence of uncertainty. ([Gollier et al., 2000](#); [Weitzman, 2000](#)) The questions concerning current values of these resources equates with those questions concerning capital substitution, technological change and the current economic response to future uncertain events. There is little doubt that the future will bring forth biological problems in the life sciences that are at least as critical as those faced in the past, and the question here concerns the sorts of factors of production, technologies and resources required to meet these challenges.

The models for thinking about these problems take very different approaches to these questions. Some (SSR and G&S) simply assume a deterministic and specific form of technological change that makes the problem straightforward to solve. At the other end of the spectrum (K&L and Weitzman) the assumption is that there is little provision that can be made now for all of the uncertainties involved concerning the flow of future problems. The former approach argues for maintaining a small and well-defined set of resources, while the latter advocates a broad and unspecified set.

There is a large area of unexplored territory between these polar possibilities that is available for future research. Which sorts of risks, hazards and uncertainties create the obligation to provide technologies, and which do not? Under what conditions should that obligation be released? How can we link current choices and outcomes to the importance of

specific technologies? How can we direct technological change in a way that assumes these risks? Addressing any of these questions would enable us to move away from one pole or the other, and instead consider how technological change might be directed toward the problems being created.

At the current stage of analysis, the valuation of genetic resources depends on the beliefs used to consider the problems concerned. An optimist would probably assume that future technologies will be flexible enough to make past reliance upon genetic resources irrelevant while a pessimist would assume the opposite. Who is right? It probably comes down to a question of which generation should bear the risk for the arrival of sufficiently flexible technologies to deal with the future problems being created. Since biological problems are clearly arising out of current human choices, we would argue that it makes sense for the current generation to bear this risk, if only to create the incentives for the current generation to work on the problem. Under this analysis and until such time as technologies render genetic resources irrelevant to future solutions, the current generation probably has an obligation to retain the broadest possible portfolio of genetic resources for R&D.

## REFERENCES

- Anderson, R.M., May, R.M. (1991): *Infectious Diseases of Humans. Dynamics and Control*. Oxford Science Publications. Oxford: Oxford University Press.
- Brown, G., Swierzbinski, J., 1988. Optimal genetic resources in the context of asymmetric public goods. In: Smith, V.K. (Ed.), *Environmental Resources and Applied Welfare Economics*. RFF, Washington, pp. 293–312.
- Costello, C., Ward, M., 2006. Search, bioprospecting, and biodiversity conservation. *Journal of Environmental Economics and Management* 52, 615–626.
- Craft, A.B., Simpson, R.D., 2001. The social value of biodiversity in new pharmaceutical product research. *Environmental and Resource Economics* 18, 1–17.
- Evans, L.T., 1993. *Crop Evolution, Adaptation and Yield*. Cambridge University Press, Cambridge.
- Evenson, R., Gollin, D., Santaniello, V. (Eds.), 1998. *Agricultural Values of Genetic Resources*. CABI, London.
- Farnsworth, N., Soejarto, D., 1985. Potential consequences of plant extinction in the United States on the current and future availability of prescription drugs. *Economic Botany* 39 (2), 231–240.
- Goeschl, T., Swanson, T., 2002. The social value of biodiversity for R&D. *Environmental and Resource Economics* 22, 477–504.
- Gollier, C., Jullien, B., Treich, N., 2000. Scientific progress and irreversibility: an economic interpretation of the 'Precautionary Principle'. *Journal of Public Economics* 75, 229–253.
- Accelerating the transfer of wheat breeding gains to farmers: a study of the dynamics of varietal replacement in Pakistan. In: Heisey, P.W. (Ed.), *CIMMYT Research Report No. 1*. CIMMYT, Mexico, D.F.
- Heisey, P.W., Brennan, J.P., 1991. An analytical model of farmers. Demand for replacement seed. *American Journal of Agricultural Economics* 73 (4), 1044–1052.
- Kassar, I., Lasserre, P., 2004. Species preservation and biodiversity value: a real options approach. *Journal of Environmental Economics and Management* 48, 857–879.
- May, R.M., Dobson, A.P., 1986. Population dynamics and the rate of evolution of pesticide resistance. *Pesticide Resistance Management*. NAS-NRC Publications, Washington D.C.
- Oldfield, M.L., 1989. *The Value of Conserving Genetic Resources*. Sinauer, Sunderland, MA.
- Pearce, D., Puroshothoman, P., 1995. The economic value of plant-based pharmaceuticals. In: Swanson, T. (Ed.), *Intellectual Property Rights and Biodiversity Conservation*. Cambridge University Press, Cambridge.
- Rausser, G.C., Small, A., 2000. Valuing research leads: bioprospecting and the conservation of genetic resources. *Journal of Political Economy* 108 (1), 173–206.
- Salop, S., 1980. Monopolistic competition with outside goods. *Bell Journal of Economics* 10, 141–156.
- Simpson, R.D., Sedjo, R.A., Reid, J.W., 1996. Valuing biodiversity for use in pharmaceutical research. *Journal of Political Economy* 104 (1), 163–185.
- Solow, A., Polasky, S., Broadus, J., 1993. On the measurement of biological diversity. *Journal of Environmental Economics and Management* 24 (1), 60–68.
- Swanson, T., 1995. *Intellectual Property Rights and Biodiversity Conservation*. Cambridge University Press, Cambridge.
- Weitzman, M., 1992. On diversity. *Quarterly Journal of Economics* 107 (2), 363–405.
- Weitzman, M., 1993. What to preserve? An application of diversity theory to crane preservation. *Quarterly Journal of Economics* 108 (1), 157–183.
- Weitzman, M., 1998. The Noah's ark problem. *Econometrica* 66 (6), 1279–1298.
- Weitzman, M., 2000. Economic profitability versus ecological entropy. *Quarterly Journal of Economics* 115 (1), 237–263.