

Belpasso Summer School

The Valuation of Diversity in Genetic Resources:

A Theoretical Survey

An Overview of Representative Approaches

1. Abstract Valuation: Genetic space as objective

2. Use Valuation: Informational Value of Diversity

2.1. *Production Function Approach*

2.2. *Search Approach* (single target search and complex searches)

2.3. *Endogenized Targets* (continuous search models)

3. Option Retention

1. Abstract Valuation: Genetic distance as policy objective

Proponents: Weitzman (1993, 1994)

Solow and Polasky (1992)

Essential Focus: Degrees of Diversity

Contribution: Translation of biological taxonomies into an optimization framework

Application Area: General

Figure 1: Evolutionary Tree



Society could then maximize an objective function of the format

$$\begin{aligned} \max \Phi(X) &= BX + U(X) \\ \text{subject to } CX &\leq M \end{aligned}$$

where X : vector of independent survival probability of each species

B : vector of species' individual direct net benefits

U : value of diversity function $V(\bullet)$ generated by X .

C : individual costs of diversity maintenance

M : budget constraint

Assumptions:

(1) Decision maker has **perfect information regarding diversity** in nature. This is perfect information regarding (a) the existing range of diversity in forms of species known to exist, and (b) the genetic make-up of all species identified in (a).

(2) It assumes policy **objective is space maximisation without regard to human welfare.**

2. Use Valuation: Informational Value

2.1. Production Function Approach: Measuring the Contribution of Genetic Resources to the production of some final output

Proponents: Gollin and Evenson (1993, 1995)

Oldfield (1989)

Essential Focus: Elasticity of Production with respect to input of GR

Empirical Estimation: New Plant Varieties Produced given Capital

Application Sector: Agriculture

Contribution: Robust, empirically measurable estimate of historical contribution of GR to output

Assumptions: Valuable traits are identically and independently distributed among the sample population.

$$N(\# \text{ New Useful Plant varieties}) = F(K, L, G)$$

2.2. Search Approach: Marginal Value of Probability of GR providing solution

Proponents: Simpson, Sedjo and Reid (1996)

Smale, Skovmand and Gollin (1998)

Essential Focus:

- Hit rates
- Marginal Value of GR as input

Application Sector: Pharmaceuticals; Agriculture

Contribution: Evaluation of GR from vantage point of expected private profits from research; willingness to invest in GR conservation

Assumption: 1) Targets are known and finite in number; and 2) traits are uniformly distributed throughout the sample population.

Typical Model:

Value of n samples: $V(n) = pR - c + (1-p)(pR - c) + (1-p)^2 (pR - c) + \dots$

Marginal Value: $v(n) = (pR - c) (1-p)^n$

where: R = value from hitting known target

p = likelihood of any one search realising "hit"

c = cost of one more search

n = number of searches

2.3. Search - Endogenized Targets

Proponents: Göschl and Swanson (1999)

Essential Focus:

- Division of Land between Production Sector and Reserve Sector
- Adaptive Response in Production Sector
- Epidemiological Buffers in Reserve Sector

Application Sector: Pharmaceuticals; Agriculture

Contribution: Evaluation of GR from vantage point of contribution of GR to continued growth

Assumptions: a) unknown and potentially infinite number of targets; and b) value of retained sample dependent on its disassociation from those used in production (non-uniform values).

Typical Model:

$$MVGR = \frac{[\phi i'(v) - \lambda a'(v)\gamma^{-1}](\gamma - 1)F(\bullet)}{r - [\phi i(v) - \lambda a(v)\gamma^{-1}](\gamma - 1)}$$

3. Real Options Approach (Kassar & Lasserre 2004)

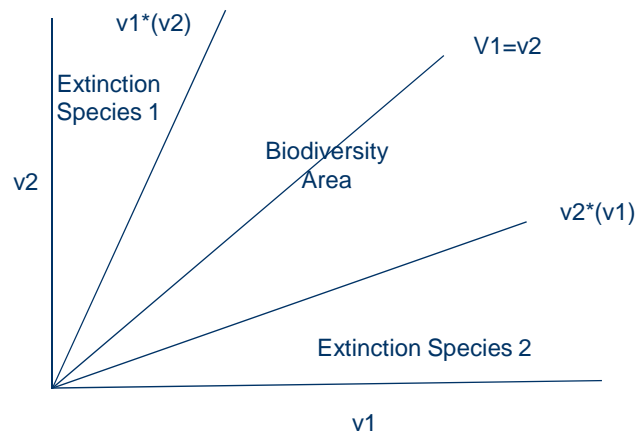
Value of conserving alternative species when one is already used in given function:

Important assumptions for species value:

- [A1] perfectly substitutable
- [A2/A3] costly and irreversible conversion
- known "targets"

Compares net expected value of preservation for $n(t)$ species with net expected value if one or more of $n(t)-1$ unexploited species are abandoned (Decision-maker rule)

Kassar/ Lasserre (2004) IV



Lecture Notes: A Survey of the Valuation Literature
(see Mare Sarr et. al., Ecological Economics)

1. The Innate Value of Diversity

Weitzman (1992, 1993) offers the most sophisticated approach to translating biologists' analysis of taxonomy into an optimization framework. Here, "diversity" is rigorously defined as a quantitative variable related to taxonomic concepts of relatedness. Weitzman assumes that there is perfect information about the genetic make-up of each species, an example of which is presented and explained below. Then we would like to define a measure of dissimilarity between a species j and a collection of species S which is

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

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

$$V(S \cup j) - V(S) = d(j, S)$$

where $V(\bullet)$ denotes a function uniquely quantifying diversity. The problem is to construct $V(\bullet)$ such that it holds for all possible j and S . It does hold if each j has an "ultrametric" relationship to all other elements contained in S , i.e. if the two greatest distances between any triple of elements are equal.

Take for example genetic distances of six primate species reported in table 5.1: These (ultrametric) distances are derived from experimental DNA comparisons between the species, i.e. grounded in biological data.

Table 1: Pair-wise genetic distance of 6 primate species

	1	2	3	4	5	6
1	0	126	250	357	532	532
2	126	0	250	357	532	532
3	250	250	0	357	532	532
4	357	357	357	0	532	532
5	532	532	532	532	0	126
6	532	532	532	532	126	0

This matrix can be transformed into an evolutionary tree where the diversity function would describe the total lengths of all its vertical branches. This tree is given in figure 1. In fact, all of these distance matrices, i.e. even non-ultrametric, can be approximated by a tree structure of this kind.

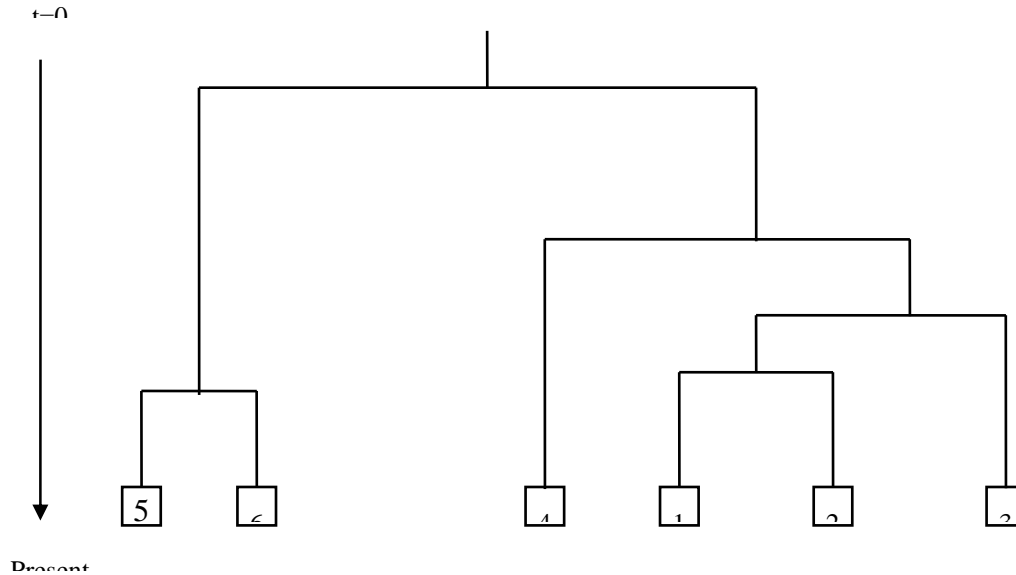
Society could then maximise an objective function of the format

$$\begin{aligned} \max \Phi(X) &= BX + U(X) \\ \text{subject to} \quad &CX \leq M \end{aligned} \quad (1)$$

where X : vector of independent survival probability of each of the 6 species
 B : vector of species' individual direct net benefits

U : value of diversity function $V(\bullet)$ generated by X .
 C : individual costs of diversity maintenance
 M : budget constraint

Figure 1: Evolutionary Tree



Implicit in this formalisation is that society has complete knowledge about the vector B , i.e. the relative value of diversity is known to the decision maker. Weitzman (1992) shows the diversity function to deliver a tractable algorithm for selecting the optimal set of species to be preserved. Essentially, Weitzman's approach looks backwards in time to the evolutionary tree and defines the optimal sequence of species elimination regarding the various branches of the tree.¹

There are two principal problems in Weitzman's approach as a tool for conservation analysis: Firstly, it assumes perfect information regarding diversity in nature. This is perfect information regarding not only the existing range of diversity in forms of species known to exist, but also the genetic make-up of all species identified in within that range. In the real world, both assumptions are not even approximately met. The actual number of extant life forms is unknown and only estimates are available, and the present and foreseeable state of genomic analysis of all species is insufficient both for developing diversity functions and solving the associated optimisation problem. Secondly, Weitzman's approach assumes perfect information on the relative net direct benefits of diversity, i.e. the vector B . As mentioned in the introduction to this chapter, this question is only beginning to be approached by science in attempts to conceive of the functional, ecological, economic, and existence values of different species. Once the vector B is completely known, the social planner would be in a position to quantify the direct social utility created by any arbitrary combination of elements from the entire diversity dendrite generated by evolution.

The policy implications of this exercise merit closer inspection: Equation (1) states that society's utility function is additively separable into the net direct benefit

¹ Weitzman (1993) applies this to crane preservation.

components from some array of species and the value of diversity of this array. This means that the first component $B X$ already captures all the direct net benefits that accrue to society from having a diversified set of biological assets. This begs the question what social preference the function $U(X)$ exactly captures and how it is made commensurate with the net direct benefits. What $U(X)$ captures is the “preference for diversity” per se, in absence of any tangible benefits. This means that diversity has to create utility over and above its net direct benefits and suggests that we can interpret $U(X)$ as a special form of existence value of a diverse set of elements. Utility functions can take any arbitrary form as long as the underlying preference ordering fulfils the basic tenets of rational choice. However, why would we expect society to have a preference ordering that gives rise to a utility function that accords value to a set of elements on no other ground than the fact that there is a certain amount of quantifiable diversity within the set? Diversity here is valued as an abstract concept as all its other direct benefits and the trade-offs between the individuals elements (as they are competing for space or other assets) are contained within B . This justification is likely to appeal to taxonomists, but it is difficult – again – to see a preference ordering that could accommodate a utility function of form (1).

Secondly, a diversity metric does not bring us closer to resolving the fundamental problem of commensurability between the value of diversity, $U(X)$, and the matrix of net benefits originating in the set of elements, $B X$. In the example of crane preservation (Weitzman 1993), this problem does not pose itself since cranes are attributed a net use benefit of zero such that $\Phi(X)=U(X)$. In most cases, a trade-off between the direct net benefits and diversity exists. Now the crux in the economic valuation of biodiversity is, as we have seen, how to methodologically, if not empirically, establish the comprehensive value of such a diverse stock, $\Phi(X)$. This means that even if we accept the condition of additive separability of the utility function into a net direct benefit component and a diversity component, we would need to an estimate of $\Phi(X)$ in order to establish the relative value of the function $U(X)$ to BX . This means that the separating out of the diversity component does little in the way of adding information to the structure of the problem that could help unravel the problem of valuation even if the matrix of net benefits B was perfectly known. In other words, there is an inherent identification problem in the way that the problem is set up using diversity metrics.

2. Production Function Approach

Evenson (1998) estimates the contribution of genetic resources to plant breeding in order to ascertain the value of diverse germplasm in agricultural R&D and to monetise these genetic resources. The contribution of this approach is that it delivers a robust and empirically measurable estimate of the historical contribution of genetic resources to plant breeding. This is done by specifying an "R&D production function", and then estimating the extent to which its various component parts have contributed to the past production of new information. An R&D production function in the context of plant breeding, for example, would have to consist of at least: i) the scientific input (human capital); ii) the technological input (physical capital); iii) the genetic resource input (natural capital). The theory of a production function states that increases in these various inputs would result in increases in the desired output: new modern plant varieties. (Evenson and Gollin 1998)

(Evenson 1995) applies this theoretical framework to conduct an empirical study which attempts to estimate the relative contribution of genetic resources in the R&D process in plant breeding. Here the R&D production function of new plant varieties N is specified as

$$N = f(L, K, G) \quad (2)$$

where L : level of input from human capital (scientists)
 K : level of input from physical capital (technology, machinery)
 G : level of input from genetic capital (biological diversity)

The empirical study is based upon the record of plant breeding at the International Rice Research Institute since 1960, and estimates the extent to which new varieties of rice were attributable to the various forms of investments. This study estimated that approximately 35% of the production of modern new rice varieties has been attributable to the genetic resource input into the R&D function. This implies that the inputs supplied by plant breeders in rice breeding (human and technological) generated no more than 65% of the useful information within modern plant varieties. The imputed present value of a single landrace accession according to this study was \$86-272 million. The imputed present value of one thousand accessions with no known history of use was \$100-350 million. Given that the initial stock of rice germplasm (in 1960) was 20,000 accessions, the added stock of germplasm since that time (about three times as many accessions) have been estimated to be responsible for fully 20% of the green revolution in rice production (Evenson 1998).²

This study gives an indication of the scale of the property rights failure outlined in the previous section. In the context of rice production, diverse germplasm contributes 35% of the “total input” required for the production of a new plant variety. Since the existing commercial varieties lose their resistance rapidly in the context of large-scale monocultural production, this implies that a large proportion of rice production is attributable to this one factor. The loss of this factor through inadequate investment would not constitute a small-scale inefficiency.³

3. Functions of Biodiversity

Clearly, biodiversity functions as an input into agriculture. This is because it is required to address the problem of built-in obsolescence in modern high yielding varieties. Essentially, any modern variety used extensively selects those pests and pathogens that thrive on it, and hence becomes increasingly subject to disease and decline with each year of use. (Heisey 1991) In agriculture, the same problem arises across space as well as across time, since disease and epidemics travel as epidemics do across space. Thus diversity can serve as a “firebreak” against epidemic contagiousness as well.

Weitzman (1998) sets forth the argument that a diversity of genetic resources plays an important role in the stabilisation of the production system. Too little diversity

² The studies conducted by Evenson et al. used as a measure of “genetic resource inputs” the number of plant varieties held within a public gene bank. Of course it is crucial that - for additional varieties to provide additional value - the varieties be dissimilar from those already held and be inclusive of proven resistance strategies (evolved in a natural system).

³ The inefficiency described here is that which would result if too many lands were converted to monoculture, leaving too little area for the generation of newly evolved genetic varieties in response to changes in the biological environment.

creates an unstable situation on account of the adaptive capacities of pests and pathogens; essentially, investing in narrowly defined monocultural systems of production selects primarily those pests and pathogens that are well-adapted to those resources. It is this adaptive pressure that creates instability in low-diversity production systems.

Biodiversity is also the source of solutions as well as the inhibitor of problems. Genetic resources evolved in differing environments contain differing information. Hence, if one genetic resource is not well-adapted to the current environment, it may be the case that another one has previously experience and adapted to it. (Swanson 1995b). This is the reason that a diversity of genetic resources can be expected to be the source of solution concepts, or information.

4. The Valuation of Information: Search-Theoretic Approach

In an influential article on the valuation of genetic resources, Simpson et al. (1996) develop a search-theoretic perspective on the problem that is inspired by (Brown and Goldstein 1984). They ground the value of biodiversity in the activity of “biodiversity prospecting” by an R&D intensive industry and deduce the marginal willingness to pay for an additional sample to be prospected when screening of samples is costly. The aim of their work is to quantify the willingness to invest of private firms in the conservation of biodiversity when the value of each sample is the outcome of a Bernoulli trial (the screen). In other words, they evaluate genetic resources from vantage point of expected private profits from research.

The typical model features a fixed probability p of identifying a valuable trait in a sample where valuable traits give rise to a product with fixed revenue R through a process of further R&D. The cost of screening a sample is fixed at level c . The expected value of a search over n samples can then be expressed as $V(n)$ which is

$$V(n) = pR - c + (1 - p)(pR - c) + (1 - p)^2(pR - c) + \dots \quad (3)$$

The marginal value of the n th sample is then

$$v(n) = (pR - c)(1 - p)^{n-1} \quad (4)$$

The empirical problem with the formulation in equation (4) is that the probability of a ‘hit’, p , is the most important parameter for estimating $v(n)$, but that data on p is notoriously difficult to obtain. Simpson et al. solve this dilemma by evaluating the expected value of the marginal species under the most optimistic conditions. One interesting finding is that the function mapping the probability of success in any single trial to the value of the marginal species is single-peaked and strongly skewed to the right. This means that once the probability of a successful trial is such that the expected marginal value of a trial exceeds the cost of the trial, the value will rise very rapidly to its maximum value and then decrease again rapidly. This observation is crucial as it shows several points: Sampling costs are an essential determinant of the marginal value, and studies that do not take these costs into account (such as Pearce and Puroshothamon 1995) are bound to overestimate the marginal value significantly. Secondly, the fact that the marginal value of the species is not a monotonously increasing function of the probability of success in the Bernoulli trial brings an issue to the fore that had previously been overlooked by many researchers, namely the presence of substitutability between species.

The degree of relative scarcity of “successful” traits is one of the key elements in the search-theoretic perspective: More than one sample can be a “success” in the Bernoulli trial, such that once a trial has been successful, there is no further need for sampling.⁴ If substitutability is very scarce, i.e. the probability of success is very low, then the marginal value is depressed since the expected revenue from the marginal trial is too low to warrant a high volume of trials. If substitutability is not scarce, then the expected revenue from the marginal trial is too low to warrant a high volume since it is very likely that a success has occurred already. In other words, if there is much 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.

Based on a number of reasonable assumptions regarding the market value of a product and other parameters, Simpson et al. derive an upper bound for the willingness to pay for the marginal sample and translate this into an 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 maximal willingness to pay for a hectare of biodiverse lands in Western Ecuador, one of the „biodiversity hot spots“, is US\$20,63. The rainforests 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 their preservation by private investors.⁵

5. The R&D Approach

a) *Brown and Swierzbinski*

Brown and Swierzbinski (1988) consider the effects that market and institutional imperfections in the production of knowledge have on biodiversity as a input into the R&D industry. The source of imperfections in their model are spill-overs from the R&D process of one firm to others and a monopolistic market structure.⁶ Despite the firms not being connected on the demand side, the combined working of monopolistic output decisions and spill-overs from R&D lead to sub-optimal R&D expenditures compared to the social optimum. Since biodiversity is an input factor into the production of knowledge, derived demand for biodiversity is below its optimal level. This lack of demand translates into insufficient investment in the preservation of biodiversity.

⁴ The biological equivalent is that there may be abundance of species with very similar genetic make-up and that the same bio-active compound (that results in a “success” in the screen) can be produced by species of completely different genetic structure.

⁵ This search-theoretic approach has been considerably refined in order to include differences in the value of individual hits (Gollin, Smale and Skovmand 1998) or situations in which the assumption of independence between the probability distribution of individual traits is violated (Simpson and Sedjo 1998).

⁶ The monopolistic market structure is intended to capture the effects of a patent system that excludes competitors from producing substitutes for a firm’s product.

What is interesting in this model is that this dilemma cannot be rectified through a private property rights in biodiversity because the fundamental source of imperfection is located further down the vertical industry, namely in the final goods sector. Secondly, the focus on the spill-over of R&D externalities between different firms into the input market provides the missing link between static models of biodiversity valuation and a growth-oriented analysis. The reason is that the spill-overs invoked by Brown and Swierzbinski are not only the source of imperfections in the input market, but also the source of constant or increasing returns to scale in innovation at the social level. The endogenous growth literature argues that the temporary availability of monopolistic rents from successful R&D offers an endogenous incentive for firms to engage in productivity-improving research. These monopolies are at the same time unable to capture all the rents from R&D such that there are spill-overs to other producers in the form of technological progress and in the end spill-overs to society at large.

b) Goschl and Swanson

Once it is accepted that genetic resources are of importance for their contribution to R&D, then it is necessary to see how this value arises and flows into the economy. Goschl and Swanson (mimeo) assess genetic resources' contribution to an economy as both stability enhancing diversity, as well as the sources of flows of information for new solutions.

G&S argue that the essential importance of genetic resources in R&D is their dual "reserve role": a) lands invested in diverse genetic resources act as a "brake" against the epidemiological impact of increased uniformity in the economy; and b) lands invested in diverse genetic resources act as a "bank" across which to search for solutions to newly arising biological problems.

The assumptions underlying this approach are that 1) there is a potentially infinite number of biological problems or targets on account of the potential for biological resources to evolve around solution concepts; and 2) diverse genetic resources are uniformly valuable, because they serve both the search function and the brake function. Anything that is not part of the uniform production system acts as a potential stabiliser on the problems arising on account of uniformity.

The approach essentially builds an underlying biological model, upon which the search model sits. This gives clear expressions for not just the search value of the genetic resources, but also the source of those values.

In addition, this approach gives rise to comparative statics for addressing how the incentive system (e.g. patents) works in the context of biological problems (where solution concepts are necessarily time-limited). It points to the likelihood that patents (based on a duration of revenue flows) will have perverse impacts in contexts where biological forces are likely to erode a solution's durability. The following figures demonstrate how incentive systems work relative to the social optimum, in the face of varying biological forces. In short, when solutions are eroded (due to evolutionary resistance) a patent system gives poor (and sometimes perverse) incentives.

Figure 1: Share of reserves for varying rate of biological adaptation

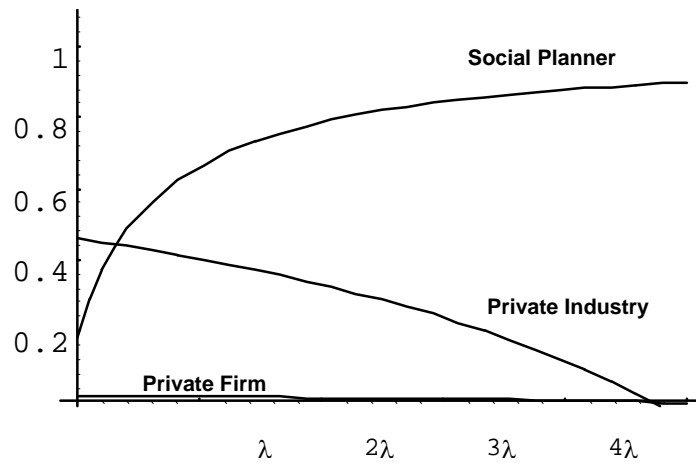
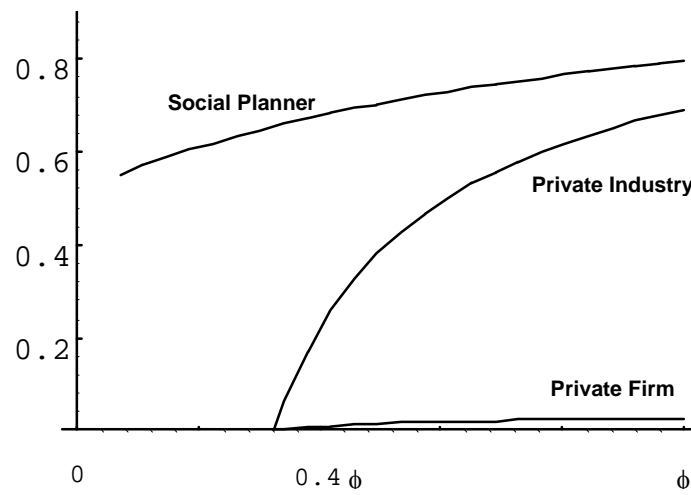


Figure 2: Share of reserves for varying rate of technological innovation



4. Real Options Approach

The final strand of literature to be considered is the real options approach, which considers the potential value of conserving a backup option. The question considered here faces the issue of redundancy squarely, and asks: what value is there to retaining known options that are currently second-best?

The approach to this question considers the possible paths of evolution of value that might cause one options to switch ranks (in terms of valuation), and the real option value is the likelihood of a material change in ranking times the value of the retained option. Kassar and Lasserre (2004) demonstrate this "real option" approach to valuing one species that is currently redundant, but a potentially valuable asset in some potential futures.

Then the role of "biodiversity" (a larger set of retained options) is that it allows the decision maker to react **flexibly** if dominance pattern of values (v_i and v_k) changes. For this reason, the abandonment rule for allowing any given extinction is defined relative to value of other species, i.e. disinvestment in v_i is a function of v_k . (see the diagram in the figures above). In the extreme regions, the value of one species dominates the other in most possible states of the world, but in intermediate regions, the values of the species can potentially switch ranks.

**The Values of Biological Diversity:
Belpasso Summer School -
Tim Swanson**

Survey of Lecture:

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