

AN ABSTRACT OF THE THESIS OF

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*This thesis investigates the incentives for the conservation of biodiversity with multiple decision-makers by comparing the market equilibrium solution to the social optimum under different assumptions. Geographic land areas are modeled to permit two conflicting uses: conservation of biodiversity or conversion of the land for some economic activity. Two main models are developed. The first model makes use of a downward-sloping demand curve for biodiversity. This demand can represent the partial or total economic value of biodiversity, or more tangibly, the harvest demand for a given rare species. The market equilibrium will provide less of the species than would be socially optimal because of the oligopolistic structure of the supply side of the market. The second model assumes a "blueprint" demand function for biodiversity where species are seen as genetic and chemical "lead" or "blueprint" resources for industrial use. In the static model, rent can be obtained only if a unique landowner possesses the species of value, otherwise the demanding industry will bid the price down until no rent is captured. In this case, the market equilibrium of conservation is socially optimal. In a dynamic model, however, this result is not obtained. The multiple stage model reveals a dynamic externality. Further modeling and comparison with real world data are needed to appreciate the importance of this divergence of results. The problem of imperfect substitute species is investigated, and too much conservation can occur in the "blueprint" case from society's point of view.*

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**Economic Incentives for the Conservation of Biodiversity with Multiple Decision-Makers**

by

**Nancy Bergeron**

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Nancy Bergeron, Author

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# **Economic Incentives for the Conservation of Biodiversity with Multiple Decision-Makers**

## **INTRODUCTION**

This thesis investigates incentives for the conservation of biodiversity with multiple decision-makers by comparing private equilibria to social optima under different assumptions.

Human population pressure and economic development cause natural habitat destruction which in turn is widely recognized as the single most important cause of loss of biodiversity through the extinction of species. As the rate of extinction of species is believed to be accelerating (Wilson, 1988, 1992), individuals, firms and governments realize the increasing value of the remaining biodiversity. It may be difficult, however, to conserve species because landowners may not have the proper incentives to conserve. In the U.S.A. for example, it is believed that more than half of the species listed as threatened or endangered occur primarily on private land (Defenders of Wildlife). In this national context, regulation and coercion might be an effective means of conservation, as long as there is limited perverse economic consequences from it. Otherwise, the lack of public support for policy might jeopardize the conservation of biodiversity. If the consequences of conservation are important, regulation and compensation for the loss of economic opportunity is warranted. If the value of a species or a collection of species is known, either through open market operations or through some valuation method, then some payment could be made by a government or an international agency for the biodiversity

conserved by decision-makers. This last scheme is applicable at the national and global scales.

Regulation has been used in the United States of America under the Endangered Species Act (ESA or Act hereafter) on public and private land, where endangered and threatened species critical habitat is protected. It has been argued that coerced conservation on private land could perhaps be interpreted as a "taking" in the context of property rights, for which government should compensate the private landowners (Innes; Stroup; Polasky, Doremus and Rettig). The ESA is in the process of being reauthorized, and many have called for economic incentives for conservation to be added to the current law (Defenders of Wildlife). Private landowners in the national context are the decision-makers on which this research focuses.

In the global context, nation-states where biodiversity-rich tropical rainforests are found are the multiple decision-makers of interest. The 1992 UN Convention on Biological Diversity is an international agreement which recognizes the value of genetic material. The Convention creates the possibility of monetary transfers for wild samples by attributing the property rights of genetic resources to nation-states where they are found. Such samples are of particular interest for the pharmaceutical industry. There are of course other global values to tropical biodiversity. Following the signature of the Convention by more than 150 countries, some international agreements have been made for pharmaceutical research as well as for Park conservation. Much remains to be done however, and more research is needed in order for policies to trigger economically efficient outcomes. This thesis is an effort in that direction.

My general objective is to investigate incentives for the *in situ* conservation of biodiversity by multiple decision-makers. The specific objectives are:

- (i) under different assumptions, compare the optimizing equilibria of decision-makers with the social optima;
- (ii) suggest policies that will give the right incentives to landowners so that the social optima occur.

The procedures for this research are straightforward. Partial equilibrium game theoretic modeling will be used to elicit the equilibrium and optimal outcomes under different assumptions. Two main models are developed, along with some extensions. The first model makes use of a downward-sloping demand curve for biodiversity. This demand can represent the partial or total economic value of biodiversity, or more tangibly, the harvest demand for a given rare species. The second model assumes a "blueprint" demand function for biodiversity where species are seen as genetic and chemical "lead" or "blueprint" resources for industrial use. Following the conclusions of the comparisons between private equilibria and social optima, an attempt will be made to interpret the results and suggest policies that will give the right incentives to multiple decision-makers for the realization of the social optima.

The next chapter reviews the literature and the theory pertinent to this research. Then follows the gist of the thesis, the chapter on Models, Results and Policy Implications. The last chapter offers a general discussion of the thesis and ideas for further research.

## LITERATURE REVIEW AND THEORY

### General information on biodiversity

Biodiversity is not a simple thing to define. It is short for biological diversity, which biologists have classified into four different levels. The levels are, in increasing order of scale, the genetic level, the population/species level, the community/ecosystem level and finally the landscape/regional level of biodiversity (Noss and Cooperrider). At the current state of knowledge, however, species offer the most pragmatic unit of measurement and management for the conservation of biodiversity. In effect, "one common thread running through discussions of biological diversity is that it is something that is reduced by the extinction of species" (Solow, Polasky and Broadus).

Many species are known and have been named at present (about 1.5 millions), but even more remain undiscovered. The total number of species is uncertain to an order of magnitude: probably between five million and thirty million, but possibly as many as one hundred million species exist (Wilson 1988, 1992). One species predominates the landscape however - *Homo sapiens*. Since the beginning of the agrarian revolution some ten thousand years ago, through the recent industrial and green revolutions, humans have been modifying the environment for their own needs, at the expense of the other species. Non-steady-state harvesting, environmental degradation and natural habitat destruction are bound to continue as the human population is still growing (Brown, Pearce, Perrings and Swanson).

More than half of the species on Earth inhabit only six percent of its land area, that is the area covered by tropical rainforests (Wilson, 1988). But tropical forests are being destroyed at unprecedented rates for human demographic, economic and political reasons (Hecht). Other forests, wetlands and other natural areas are also being irreversibly converted to other land uses all over the world, at least in human time scale. In the next century, "A twenty percent extinction in total global diversity, with all habitats incorporated, is a strong possibility if the present rate of environmental destruction continues" (Wilson 1992). It has been estimated that 27,000 species go extinct each year under rather optimistic assumptions (Wilson 1992). According to fossil records, the background extinction rate, *i.e.*, without human interference, was around one species a year per one million existing species. The rise of the human population has thus brought this rate 270 to 5400 times higher depending on whether we assume that five million or one hundred million species exist today (Wilson, 1992). These estimates are of course not precise, and others exist. The main point here is that there is a sense of rapid increase in the rate of extinction of species.

Economic development, education, higher standards of living that make people value the environment more, and continuing environmental destruction all have led scientists and others to recognize the value of environmental assets, including biodiversity. There exists a paradox in this: economic development generally requires some environmental destruction, and as a country develops economically, its citizens place a higher value on the environment. The development path is a matter of choice, constrained

by the possible tradeoffs between economic welfare and the conservation of the environment.

### **The value and the measure of biodiversity**

Many types of values exist. The total value of a good is obtained by the aggregation of all its values of different types. This section is inspired by Pearce and Turner's treatment of economic value, although I do not embrace it completely. It is also inspired by Polasky's *Valuing Biodiversity and Ecosystems*, and by Brown, Pearce, Perrings and Swanson. The viewpoint proposed here is consistent with neoclassical utilitarianism, although others exist.

This research will deal with the anthropocentric value of biodiversity uniquely. The main classification of anthropocentric value is use *versus* non-use value. Use value includes direct use value such as resource value (*i.e.*, input to production or consumption good) and amenity value. The resource value of biodiversity comprises harvest values and what I will refer to as genetic blueprint values. Harvest values exist for timber, fish and ivory, for example. Blueprint value is related to pharmaceutical, agricultural and industrial research that uses genetic "leads" in order to develop and eventually synthesize new products. Such biodiversity prospecting is used more extensively than before, especially in the pharmaceutical industry, due to the development of biotechnologies (Sedjo). The amenity value of biodiversity is observed through landscape appreciation, enhanced aesthetic quality of one's surroundings, eco-tourism or photography. Indirect use value

includes ecological regulation functions and services like pollution assimilative capacity, nutrient cycling and carbon storage, for example.

Non-use value includes existence value, bequest value and option value. The existence value of a species is the value assigned by individuals to the simple fact of knowing that a species exists. Bequest value is the value assigned to what is wished to be left to one's descendants or to future generations in general. Option value is assigned to species and ecosystems conserved as an investment for future use. Here, I use the financial economics definition of option value that assumes risk neutrality. Option value is thus a current non-use value that represents an expected future use value. The option value of biodiversity can be very large because of the irreversible character of the extinction of species. The lost option value of an extinct species is an opportunity cost which should be included as a cost of investment in land use conversion (Dixit and Pindyck). Option values are very sensitive to uncertainty. As such, there is value to gaining information prior to making irreversible decisions concerning environmental assets. Since there exists a lot of uncertainty with regards to biodiversity (economic value, probability of survival, *etc.*), irreversible land use conversions ought to be delayed accordingly. The same idea gives rise to the safe minimum standard (SMS) approach. A SMS policy attempts to conserve species unless the cost of doing so is intolerably large (Bishop). The SMS basically places a very large option value on biodiversity, and does not call for marginal economic analysis. In political science, the Precautionary Principle (Myers) also addresses the irreversibility issue in a way analogous to the SMS.



Figure 1 summarizes the different types of economic value of biodiversity described above.

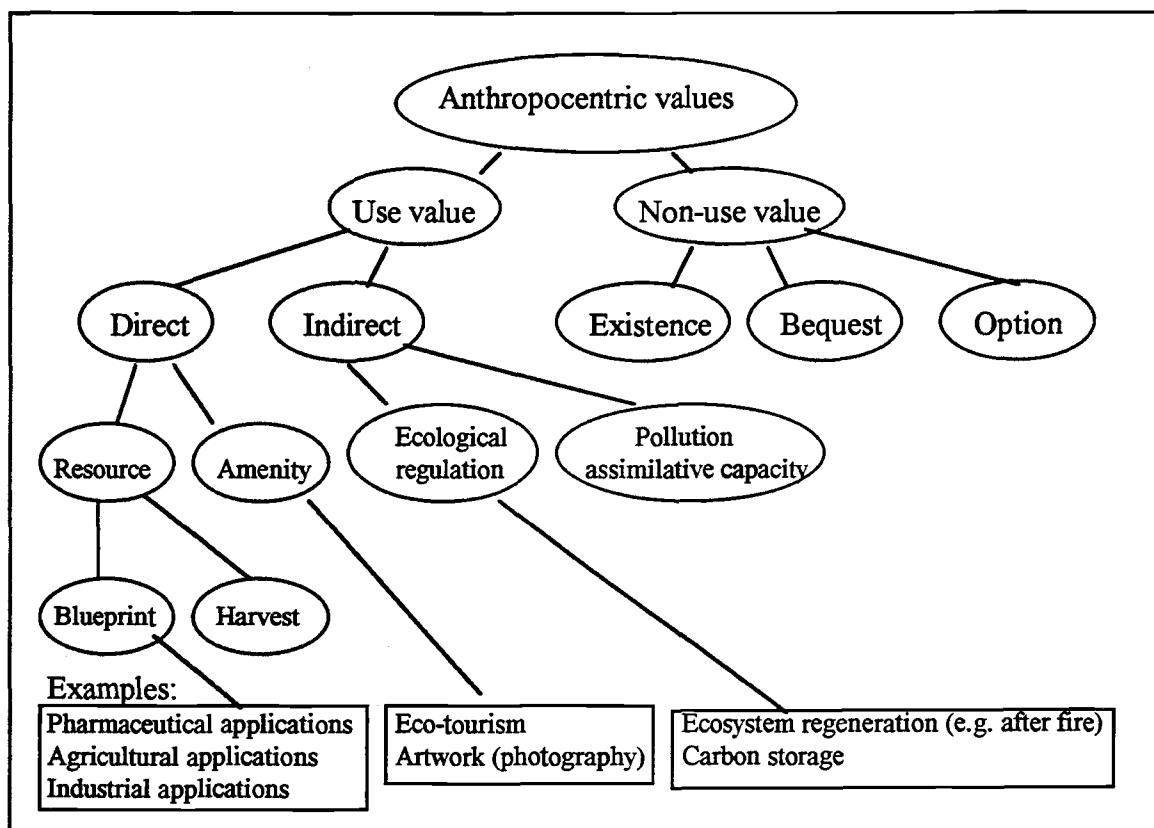


Figure 1: Economic values of biodiversity

Values can be estimated in many ways, depending on their type. Market transactions of resources can be observed and their values or demand can be estimated empirically. Indirect market prices can be elicited for amenity values through hedonic pricing methods and travel-cost methods of valuation. Non-use values are the hardest to estimate, if and when it is possible at all. Contingent valuation methods (CVM) are used

in such cases. Surveys are conducted that ask people their willingness to pay for the conservation of a species or their willingness to accept compensation for the extinction of it. The economic profession is, however, split as to the validity and applicability of CVM methods. Guidelines for surveys and recommendations for future research on CVM have been elaborated by the NOAA panel whose eminent members believe that contingent valuation studies provide useful information but that they must be conducted very carefully (Arrow, Solow, Portney, Leamer, Radner and Schuman). It is unlikely that CVM will reveal precise valuation of species. Rather, it might suggest some ranking among species and it might indicate what people prioritize in conservation.

Biodiversity at the species level can be measured by simply adding up the number of species in a given area; this has been termed *species richness*. However, *diversity* also implies some dissimilarity between the members of a set (Polasky, 1993). A better measure of the value of biodiversity could involve some weighing of species according to their genetic distances or phenotypic dissimilarities (Polasky, 1993; Solow, Polasky and Broadus). An "effective number of species" (Polasky, 1993) could be calculated that would be less than the simple species richness indicator, much less if the species considered are close relatives. The option value of a unique species is likely to be much higher than the option value of a species that has many close relatives possessing similar qualities and thus satisfying similar demands. Some species, being more unique, have more value than others, and therefore should be prioritized for conservation. Measurements of dissimilarities are difficult to make at a large scale, but as will be shown

in the next chapter, such knowledge would increase the possibility of efficient conservation of biodiversity.

### Economic explanation for the loss of biodiversity

The loss of biodiversity can be considered to be a negative externality of different economic activities, that is, an unwanted consequence of them. Randall defines an economic externality as:

$$U_j = [X_{1j}, X_{2j}, \dots, X_{nj}, f(X_{mk})], \quad j \neq k;$$

where  $X_i$  ( $i=1, 2, \dots, n, m$ ) refers to activities, and  $j$  and  $k$  refer to individuals. This means that the utility of an individual ( $j$ ) is influenced by the actions of another ( $k$ , through  $f(X_{mk})$ ).

An externality is *relevant* when the affected individual ( $j$ ) wishes that the other one change his or her activity  $X_{mk}$ . Furthermore, a *Pareto-relevant externality* exists only if it is possible to change  $X_{mk}$  in such a way that  $j$ 's utility is improved without making  $k$  worse off. A Pareto-improvement is then possible (Randall). Nicholson offers a more prosaic definition of externality; it is "the effect of one party's economic activity on another party that is not taken into account by the price system."

In the case of biodiversity loss, decision-makers act in a way that increases their own utility (and society's by the same token) while decreasing society's utility with respect to the portion of social utility derived from biodiversity. One of the reasons evoked for the loss of biodiversity is the open-access character of unit of biodiversity (Pearce and Turner). In effect, we have the standard result that if a species has some

resource value and it is accessible by all, it is going to be overharvested compared to society's optimal rate of harvest (or compared to the monopolist's optimal rate of harvest which would internalize the costs of overharvesting). This could lead to extinction. Other types of values are not directly, if at all, elicited by market transactions, and as such, are not bound to stimulate the conservation of biodiversity. Even though society as a whole might attribute a very high existence value to a given ecosystem, for example, individual decision-makers will tend to act as though they do not personally value it much, attempting to be free-riders. Since there is no monetary value to, nor any rent derived from, the ecosystem, no individual wants to assume its conservation. This is a problem of a public good, in the sense that there are no exclusive property rights on species. Government intervention is thus warranted through the definition of new property rights, through investments in the public good, through law and coercion or through policies building new economic incentives. Such intervention should occur if it leads to Pareto improvements.

Some resources are non-rival in consumption, that is, their use by one individual does not prevent others from using them. An example is given in "genetic prospecting" for agricultural, industrial and especially pharmaceutical purposes (Sedjo). Since genetic information inputs are non-rival in consumption, they do not generate any rent to the landowner whose land was the habitat of the species prospected. As such, it is clear that there are no incentives for the landowner to conserve biodiversity, even though it would benefit prospectors, and through research and development, society in the long run.

In many externality cases, well defined, non-attenuated property rights are warranted. In this way, individuals have incentives to work out the best solution for all when a *relevant* externality exists. "Property rights develop to internalize externalities when the gains of internalization become larger than the cost of internalization" (Demsetz). In the genetic prospecting case, scientific and technical developments in biotechnology have lowered the costs of prospecting and increased the possible applications due to natural chemical "leads" (Sedjo). If the gains of internalization are large enough with respect to its costs, we can expect to see property rights on genetic material emerge, according to the argument made by Demsetz (Sedjo). These property rights have in fact started to emerge since the 1992 UN Convention on Biological Diversity.

As far as other, non-resource values of biodiversity are concerned, as people tend to enjoy higher standards of living and to become more aware of environmental issues, they value things like biodiversity more highly. Also, the fact that remaining habitat where biodiversity is found are disappearing at an accelerated rate tends to increase the value attributed to biodiversity. In effect, increasing scarcity generally increases the value of each unit of a good. Again, following Demsetz, we might expect to see property rights emerge, even for values other than resource value.

### **Potential policy for the conservation of biodiversity**

The usual policies to remedy negative externalities are direct regulation, and taxes/subsidies. Regulation can be applied to the conservation of biodiversity by requiring

natural habitat conservation. For example, the ESA approach requires the conservation of the critical habitat of endangered and threatened species on public and on private land. It is estimated that the entire habitat of half of the species listed as endangered or threatened under the ESA occurs on private land (Defenders of Wildlife). Conservation on private land hence seems to be as important as on public land in this country. There exists a lot of uncertainty, however, about the occurrence and distribution of species, and such an approach as prohibitive as the ESA does not encourage cooperation of decision-makers with regulating agencies. Information is likely to be distributed asymmetrically, and private landowners have strong incentives not to share information about species of interest being on their land if no compensation is made for lost economic opportunities (Polasky, Doremus and Rettig).

Taxes could be used nationally to limit the economic activities that put species in danger. However, a large number of economic activities can affect one single species (e.g. Pacific salmon) and determining the efficient tax for each owner would be complex if not impossible. Equity issues would also arise since not all decision-makers of a given industry or sector would have to pay such a tax, only those whose activities affect the species of concern. In this case, as for the strict regulation approach, decision-makers have no incentives to share information about the species with regulators.

If a compensation scheme exists, however, decision-makers might be willing to collaborate. Marginal analysis could be conducted so that the land use would maximize profits. Rather than preserving the entire habitat, land should be converted until the marginal benefit from compensation (which should represent the value attributed to the

conservation of the species by society) equals the marginal benefit of converting the land. Such a policy is likely to induce a higher level of cooperation from the decision-makers and to appease tensions that arise with the current ESA.

In the global context, strict regulations are not enforceable and, if suggested, would likely be considered an assault to nation-states sovereignty. However, compensation is applicable, and the amount paid to a given country should at least be equal to the “incremental cost” of conservation (UNCED; Brown, Pearce, Perrings and Swanson). The incremental cost of conservation of natural areas for biodiversity is defined as the difference between the domestic cost and the domestic benefit. If the global benefit is larger than the incremental cost, then further conservation and compensation should occur (Brown, Pearce, Perrings and Swanson).

Assuming zero transactions costs, the compensation policy is a straightforward application of the Coase Theorem with the decision-makers being awarded the property rights on their land.

### **Current policies, conventions and agreements**

Policies, conventions and agreements on biodiversity exist, and some were mentioned already. In this section I will describe them more substantially in order to later highlight the similarities between reality and the mathematical models developed in this thesis, as well as to derive some implications for future policy.

## **Biodiversity policy in the U.S.A.: The Endangered Species Act**

The Endangered Species Act was enacted in 1973 in the United States. It has been amended since, but is still considered to be enormously powerful because of its absolute requirement for conservation. It is seen as the most powerful environmental law in this country, and even worldwide (Stroup).

The original version of section 7 of the ESA required the protection of threatened and endangered species at all costs by government agencies. In 1978, it was amended to include exceptions at the discretion of the Endangered Species Committee, nicknamed the God Squad. The mandate of the Committee is to weigh the benefits and costs of an action planned by a government agency, and to allow such an action if, among other things, "the benefits of such action clearly outweigh the benefits of alternative courses of action consistent with conserving the species or its critical habitat, and such action is in the public interest" (ESA§7(h)(A)(ii)). The Committee has only been called on three times since, and its usefulness was overshadowed by the fact that Congress had to pass reauthorization Act amendments to simplify the procedures and order the Committee to convene (Endangered Species Act Roundtable). This approach has been said to reflect the SMS approach, or the Precautionary Principle with extreme risk aversion with respect to species extinction (Bishop; Myers). It does not allow for marginal economic analysis, however. Rather, it allows for a benefit-cost analysis of a given lump project, and only under exceptional circumstances.

The ESA also restricts private owners' action through section 9 by making it illegal to "take any such species within the United States or the territorial sea of the United



States” (ESA§9(a)(B)). It is further specified that “The term ‘take’ means to harass, *harm*, pursue, hunt, shoot, wound, trap, capture, or collect, or to attempt to engage in any such conduct” (ESA§3(18)) (*italics added*). Also, in *Babitt v. Sweet Home Chapter of Communities for a Greater Oregon*, No. 94-859, the Supreme Court has recently confirmed previous rulings that the “ordinary definition” of the word *harm* “naturally encompasses habitat modification that results in actual injury or death to members of an endangered or threatened species” (Cushman Jr.). This restricts private property rights even more by requiring the conservation of the whole critical habitat of a listed species. Since the 1982 amendment of the Act, section 10 allows the Fish and Wildlife Service to issue a permit that authorizes some incidental take if the private owner submits an acceptable habitat conservation plan (ESA§10). However, only a few permits have been granted so far, they have been very costly to the private landowners, and in most cases they have taken years to negotiate (Endangered Species Act Roundtable). This process is hardly accessible for most landowners. The current ESA is thus as powerful on private land as it is on public land for the protection of threatened and endangered species.

Stroup reports that Michael Bean, an Environmental Defense Fund attorney, stated that there is “increasing evidence that at least some private landowners are actively managing their land so as to avoid potential endangered species problems.” Effectively, if a decision-maker knows that a listed species inhabits her land, but she thinks that government agencies do not have that information, then she has the incentive to “shoot, shovel and shut up” (Polasky, 1994). The problem of incomplete and asymmetric information places government agencies at a disadvantage for the conservation of species

on private land. The strict regulation of the ESA on private land without any compensation scheme for lost economic opportunity gives decision-makers incentives not to cooperate with government agencies (Polasky, Doremus and Rettig; Stroup).

Coerced conservation on private land can, however, be interpreted as a "taking" in the context of property rights, for which government should compensate the private landowners (Innes; Blume, Rubinfeld and Shapiro; Micelli and Segerson; Stroup; Polasky, Doremus and Rettig). In effect, the Fifth Amendment to the U.S. Constitution prohibits government takings of private land without just compensation to the owners. Government regulations for the purpose of nuisance prevention or for the protection of public or private resources do not, however, represent a taking (*Mugler v. Kansas* 1887) (Innes). But when government actions aim at providing a public good (road, dam, park), compensation is sometimes required, although "the distinction between harm-preventing and public-good-providing government actions is not always clear in practice" (Innes). There are also issues of fairness and equal protection that arise. If one landowner is penalized, against reasonable expectations, by a government regulation while others with similar property are not, then the regulation can be interpreted as a taking. If this is the case, compensation is warranted. However, if government has to pay compensation and if it is averse to budgetary outlays, as it is likely to be, then a compensation requirement will lead to more development and less conservation, although it might allow conservation to be better targeted (Innes; Polasky, 1994). Compensation is regarded as a necessary complement to the current regulation in order to remove the incentives that private

decision-makers have for hiding information and doing away with listed species that occur on their lands (Stroup; Polasky, 1994).

### **Global biodiversity policy: The UN Convention on Biological Diversity**

The Earth Summit of the United Nations Conference on Environment and Development (UNCED) in 1992 was an important event for the promotion of biodiversity conservation at the global scale.

Pre-conference negotiations created much debate that revealed the confrontation between developed and developing nation-states regarding many aspects of the Convention. Nevertheless, more than 150 countries signed the Convention on Biological Diversity during the Conference, but the U.S.A. was not one of them. Article 1 of the Convention summarizes its three objectives:

The objectives of this Convention, to be pursued in accordance with its relevant provisions, are the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer for relevant technologies, taking into account all rights over those resources and to technologies, and by appropriate funding (UNCED).

The U.S.A. was particularly concerned about the consequences of article 15 which gives nation-states the possibility to patent their genetic resources, and article 16 which calls for preferential access to biotechnologies for developing countries (UNCED). The pharmaceutical industry, which had previously acquired tropical genetic resources for free, might see its profit margins decrease because they would likely have to pay for samples in

the future. Also, the preferential access to biotechnologies for developing countries could increase the vertical integration in these countries and create more competition with the existing firms. Articles 20, 21 and 39 were also contentious as they refer to financial issues. Developing countries wanted the Conference of the Parties (COP), where they would constitute the majority, to bear the sole authority on the Convention. Developed nations, however, preferred to see the Global Environment Facility (GEF) as the Convention's funding institution. The GEF is operated by the World Bank, the UN Development Programme and the UN Environment Programme. The final text of the Convention is rather unclear and somewhat contradictory with respect to the most hotly debated issues (Articles 16, 20, 21, 39). It also remains vague about the procedures to be adopted in the implementation of the Convention and its institutions. However, article 15 seems to be better accepted than it was in 1992 by developed nations and the U.S.A. particularly; the property rights of genetic resources are now generally perceived to be necessary to generate rent and provide economic incentives for their conservation. The COP will provide the field of discussion and negotiations for the more detailed application of the Convention (U.S. Senate Report together with Minority Views on the Convention on Biological Diversity, Exec. Rept. 103-30).

The new Clinton administration reviewed the Convention and developed a series of understandings concerning its treatment of intellectual property rights and finances especially. The U.S.A. finally signed the Convention in June 1993, with the support of American environmental organizations as well as that of the pharmaceutical and

biotechnology industries (Senate Report together with Minority Views on the Convention on Biological Diversity, Exec. Rept. 103-30).

The GEF is the interim funding instrument to achieve the goals of the convention, as well as those of the Framework Convention on Climate Change. Biodiversity conservation in tropical forests offers an important joint service - carbon storage - that affects the world climate (Brown, Pearce, Perrings and Swanson). It thus seems convenient that the GEF be concerned both with the conservation of biological diversity and with climate change issues. A GEF working paper briefly suggests way of conserving biological diversity (Brown, Pearce, Perrings and Swanson). For example, regulation of oceanic resources with nation-state quotas is recommended. Also, the Convention on International Trade in Endangered Species of Flora and Fauna, with its system of bans on the ivory trade, for example, is criticized for reducing the profitability of resources and thus taking away the economic incentives for conservation. In addition, this Convention cannot be used to protect biodiversity at large. The GEF paper suggests investing in the internalization of the global stock effect, through three different approaches: i) international subsidy agreements; ii) market regulation agreements; and iii) tradable development permits (Brown, Pearce, Perrings and Swanson).

International subsidy agreements need to be conditional on specific applications, and there has to be assurance of the continuity of the future flow of payments for conservation. The economic incentives need to remain present for conservation to continue over time. Subsidies can be in the form of debt-for-nature swaps, franchise agreements or GEF-subsidized projects. Debt-for-nature swaps allow a country to pay

part of its external debt by investing in environmental conservation on its territory. Franchise agreements restrict the land use of an area in exchange for subsidies from some international fund. GEF-subsidized projects are specifically designed to increase the rate of return to conservation in order to reflect the global benefits they generate (Brown, Pearce, Perrings and Swanson).

Market regulation agreements include rent appropriation due to the creation and enforcement of legal and beneficial property rights on diverse resources, ivory and genetic information, for example. Such markets could be exclusively allocated to nation-states that invest in their resource (Brown, Pearce, Perrings and Swanson).

Tradable development permits (TDR) would create an artificial market for the development of zoned land. In exchange for payments, land users in conservation zones agree to develop the land in a manner that is consistent with biodiversity conservation. The price of the TDR's represent the opportunity cost of conservation. Purchasers of the permits can be domestic or international, private or public, and interestingly, they can be environmental organizations (Brown, Pearce, Perrings and Swanson).

In tropical countries, deforestation often occurs because of subsidization that sends the wrong market signals and creates more deforestation incentives than warranted by real markets (Hecht). In order to slow down the deforestation of tropical rainforests, governments should be encouraged to remove these perverse distortions (Hecht; Brown, Pearce, Perrings and Swanson).

The UN Convention on Biological Diversity and the GEF are in their infancy, however, and much remains to be accomplished in terms of research on policy and experimentation at the global level.

### **Private agreements**

While most of the genetic resources for pharmaceutical applications are found in developing nations, most of the required scientific expertise for their exploitation is found in developed nations. Following the UN Convention on Biological Diversity, agreements and contracts are being created that facilitate the transfer of genetic resources to the pharmaceutical industry (Simpson and Sedjo). At the same time, a number of countries are trying to enforce property rights on their genetic resources and to improve their domestic research capacity.

In the U.S.A., the National Cancer Institute has made agreements for the provision of samples with organizations of Madagascar, Tanzania, Zimbabwe and the Philippines. In Britain, Biotics Limited does business with organizations in Ghana and Malaysia. The best known of such agreements, however, is that of Merck and Company which is the world's largest pharmaceutical firm, and INBio, the Costa Rican national institute of biodiversity. INBio has received a one million dollar up-front payment and a right to royalties in the event of profitable discoveries in exchange for the supply of samples and some related services. INBio possesses rather advanced facilities in comparison with other tropical countries (Simpson and Sedjo).

Such agreements are in harmony with the objectives of the UN Convention on Biological Diversity. The property rights of nation-states on their genetic resources are emerging through these agreements. Transactions of samples rarely include the unique access to genetic resources, however. They often include collection, classification, extraction of components and even testing by the supplying nation, making the value of the genetic resource unclear. Investment in vertical integration with source-country, as was done in the Merck-INBio agreement, can be a useful conservation strategy for the pharmaceutical industry. It increases the potential rents to be captured by source-countries and thus diminishes the incentives towards deforestation and the loss of option value (Simpson and Sedjo).



## MODELS, RESULTS AND POLICY IMPLICATIONS

In this section I analyze two partial equilibrium models: (1) a model in which the demand for biodiversity is downward-sloping so that its marginal value is positive but decreasing; (2) a model in which species have a genetic "blueprint" value.

Decision-makers can be thought of as private landowners in the context of the U.S. Endangered Species Act (ESA), or as tropical nation-states where rainforests are found, in the global context. In either case, there are not enough decision-makers to insure perfect competition in the "biodiversity market", if it exists. This is why they will be modeled as oligopolists in the production of biodiversity conservation. If a biodiversity market exists, some payment will be made for biodiversity conservation. The decision-makers, being biodiversity oligopolists, will exhibit strategic behavior. Valued species are bound to be scarce or in the process of becoming scarce, so we cannot expect to find them everywhere, in which case they would be supplied in something similar to a competitive market structure and would have very little value per unit. *Landowner* and *decision-maker* will be used interchangeably.

I assume in my models that there are only two choices of land use for the parcels considered: economic activity or conservation. Perfect competition is assumed for the economic activity and therefore, decision-makers are price-takers in those markets. The economic activity can differ from one decision-maker to the other. It could be timber harvesting, mineral mining, agricultural crops, cattle raising, or urban/suburban development. Conservation, on the other hand, means that the land is left in its current state. I assume that economic activities are incompatible with the conservation of species;

economic activity and conservation are mutually exclusive in a given geographical area. Conservation and the economic activity are thus opportunity costs of each other. For simplicity, I will identify the *economic activity* as *harvesting*, as in the harvesting of a forests that destroys the habitat of a species, at least temporarily, perhaps permanently. *Conservation* will be used interchangeably with *biodiversity conservation*.

The profit curve of the economic activity is modeled as a concave quadratic function. In model 1, the profit function of biodiversity conservation is also concave quadratic, and it is left undetermined for model 2, but is certainly not strictly convex. Profit maximization will then occur according to the first order condition, the necessary second order condition always holding true, except for the general form models where the necessary conditions will be made explicit (models 1.G and 2.G). The profit function of the harvest is modeled as:

$$\pi = \alpha_i a_i - (a_i^2/2), \quad \pi \geq 0, \quad 0 \leq \alpha_i \leq 1, \quad 0 \leq a_i \leq 1;$$

where  $\pi$  denotes the profit,  $\alpha_i$  is the price on the competitive market where decision-maker  $i$  is producing ( $i$  and  $j$  may not produce the same good), “ $a$ ” is a variable that represents the area owned that is available for harvest, and  $a_i^2/2$  is the cost function faced by decision-maker  $i$ . Most models are solved for duopolistic situations,  $i = 1, 2$ . Oligopolistic markets will consist of  $n$  decision-makers that will be identified as  $i = 1, 2, \dots, n$ . Since harvesting and conservation are modeled as mutually exclusive activities, the profit due to biodiversity conservation is a function of  $(1-a_i)$ , the area *not* harvested. The different profit functions of biodiversity conservation will be determined as the two main models are introduced. Optimization will be performed with respect to “ $a_i$ ”, the

geographic area harvested. The private equilibrium and the socially optimal amount of  $a_i$  are defined as  $a_i^*$ , but private and social  $a_i^*$  are not necessarily equal.

All the models assume common knowledge, or perfect information. Models 1, 2.A, 2.B, 2.C, and 2.G, are static games of perfect knowledge and, as such, are solved for Nash equilibrium. Model 2.D is dynamic and is thus solved for subgame-perfect Nash equilibrium. Letters in the numbering of the models correspond to the same types of models for the two different types of demand considered; 2.A is the blueprint version of 1.A for example. Model 2 has more extensions than model 1, however. As a general rule, I will solve for the private (*i.e.* decision-makers') equilibrium first. Models will be symmetric for all players, so that only one private equilibrium will be solved for (player  $i$ 's), keeping in mind that the solutions for the other decision-makers will be symmetric. Then social optimum will be solved for, and finally the two will be compared. Social optimum in the ESA context can be thought of as the national optimum, or as the global optimum for species in the United States if other countries value them as well. The social optimum in the context of tropical nations is the global optimum since it is widely recognized that tropical forests carry most of the world biodiversity and as such are of considerable global value.

### **MODEL 1: Downward-sloping demand curve for biodiversity**

In this simple model, species,  $S$ , have a linear downward-sloping demand curve. This means that marginal species or marginal individuals of a given species have positive but decreasing value (or utility) to society. A decreasing marginal value of individuals of a

given species can be found in most harvested species, like tuna and timber for example, which have a downward-sloping market demand curve. Other use and non-use types of demands for individuals can also be downward-sloping, especially when the population of interest is already viable. The marginal demand for species (marginal species richness) is likely to be downward-sloping also, since a collection of species usually includes imperfect substitutes and redundancy (Polasky and Solow). Here, I do not specify which type of economic value this demand curve represents; it can be use or non-use value, partial or total economic value. The inverse demand curve is as follows:

$$P(S(1-a)) = \beta - (S(1-a)/2), \quad 0 \leq (S(1-a)/2) \leq \beta, \text{ so that } P \geq 0, \text{ and } 0 \leq a \leq 1.$$

The value of the species is then:

$$v(S) = S \times P(S) = \beta S - (S^2/2), \quad \text{where } S = S(1-a).$$

$S(1-a)$  is equal to the sum of  $S_i(1-a_i)$  over all the land parcels ( $i=1,2,\dots,n$ ) where species  $S$  is found.  $S_i(1-a_i)$  represents the quantity of individuals of the species considered, or the quantity of species in the collection considered.  $S_i'$  is the marginal production of  $S_i$  on one more percentage unit of land preserved, so that  $S_i' \geq 0$ . The derivative of  $S_i$  with respect to  $(1-a_i)$ , the area harvested will then be equal to  $-S_i'(1-a_i)$ .

This value can be only part of the economic value or it can be the total economic value. Either way, it is what is to be considered for the social optimum decision on land use of the area  $a_i$ . I assume no tangible cost of conservation; in this model, conservation occurs by simply leaving the area untouched.

### **MODEL 1.A: No biodiversity rent**

This model assumes that the decision-makers  $i$  and  $j$  have no way of capturing any rent from the species. In addition, species considered on both areas are the same. This model is analogous to the ESA regulation where there are no economic incentives for conservation. It is also similar to the case of tropical deforestation where no rent is obtained from a standing forest, although it might have some value to society as a whole. Hence, the profit maximization of the decision-makers will only take the harvesting activity into account.

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2)$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i = 0.$$

Therefore

$$a_i^* = \alpha_i.$$

#### Social optimum:

To solve for the social optimum, the sum of producer and consumer surpluses due to biodiversity conservation has to be maximized. From a social standpoint,  $S = S_i + S_j$ .

$$\begin{aligned}
\text{Max}_{a_i, a_j} \pi &= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \int_0^{S_i+S_j} P(S) d(S) \\
&= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \int_0^{S_i+S_j} [\beta - ((S)/2)] d(S) \\
&= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \beta(S_i+S_j) - ((S_i+S_j)^2/4) \\
&= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \beta S_i + \beta S_j - S_i^2/4 - S_j^2/4 - S_i S_j/2.
\end{aligned}$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \beta S_i'(1-a_i) + [S_i(1-a_i) S_i'(1-a_i)/2] + [S_i'(1-a_i) S_j(1-a_j)/2] = 0.$$

Therefore,

$$a_i^* = \alpha_i - S_i'(1-a_i) [\beta - S_i(1-a_i)/2 - S_j(1-a_j)/2] = \alpha_i - S_i'(1-a_i) P(S(1-a)).$$

A symmetric result exists for  $a_j^*$ .

Let us compare the private equilibrium and the social optimum.

**Table 1:** Private equilibrium and social optimum of Model 1.A: No biodiversity rent

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i$	$\alpha_i - S_i'(1-a_i) P(S(1-a))$
$a_j^*$	$\alpha_j$	$\alpha_j - S_j'(1-a_j) P(S(1-a))$

The equilibrium for decision-maker  $i$  occurs when the marginal cost of harvesting,  $a_i$ , equals the market price of harvesting,  $\alpha_i$ . The social optimum for decision-maker  $i$

occurs when the marginal profit of the harvest,  $\alpha_i - a_i$ , equals the marginal profit to society from biodiversity,  $S_i'(1-a_i) P(S(1-a))$ . Since  $S_i'$ ,  $S_j'$  and  $P(S)$  are all positive, the private equilibrium is greater than the social optimum. Hence, private owners overharvest from society's point of view. Overharvesting of  $\{S_i'(1-a_i) [\beta + S_i(1-a_i)/2 + S_j(1-a_j)/2]\}$  occurs in  $a_i^*$ .

This is what is observed in general all over the world. Diverse species values are not revealed in transactions markets and private decisions tend to ignore their value. Policies are therefore needed for the conservation of biodiversity in order to counteract this market failure. Regulations, taxes and subsidies are potential tools for policy. The ESA makes use of a powerful regulation. It might have to be amended in order to compensate landowners for the loss of economy opportunity and earn the cooperation and respect of private decision-makers. Strict regulation and taxes cannot be used in the international context, so compensation or rent appropriation schemes need to be invented that will encourage the conservation of tropical forests.

### **MODEL 1.B: Biodiversity rent**

This model assumes that decision-makers  $i$  and  $j$  have a way to capture a rent from the species. In this case, their profit maximization will take into account the harvesting activity as well as the biodiversity conservation of the area.

Private equilibrium:

$$\begin{aligned}
\text{Max}_{a_i} \pi &= \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + S(1-a_i) P(S(1-a_i) + S(1-a_j)) \\
&= \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + S(1-a_i) [\beta - (S(1-a_i)/2) - (S(1-a_j)/2)] \\
&= \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \beta S(1-a_i) - [S(1-a_i)]^2/2 - [S(1-a_i) S(1-a_j)]/2.
\end{aligned}$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \beta S'(1-a_i) + [S(1-a_i) S'(1-a_i)] + [S'(1-a_i) S(1-a_j)]/2 = 0.$$

Therefore,

$$a_i^* = \alpha_i - S_i'(1-a_i) [\beta - S_i(1-a_i) - S_j(1-a_j)/2].$$

Social optimum:

This maximization problem is the same as the one for social optimum in model

1.A. Therefore,

$$a_i^* = \alpha_i - S_i'(1-a_i) [\beta - S_i(1-a_i)/2 - S_j(1-a_j)/2].$$

Let us compare the private equilibrium and the social optimum.



**Table 2: Private equilibrium and social optimum of Model 1.B: Biodiversity rent**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - S_i'(1-a_i) [\beta - S_i(1-a_i) - S_j(1-a_j)/2]$	$\alpha_i - S_i'(1-a_i) [\beta - S_i(1-a_i) /2 - S_j(1-a_j)/2]$
$a_j^*$	$\alpha_j - S_j'(1-a_j) [\beta - S_j(1-a_j) - S_i(1-a_i)/2]$	$\alpha_j - S_j'(1-a_j) [\beta - S_j(1-a_j) /2 - S_i(1-a_i)/2]$

It is clear that in this model, the private equilibrium is equal to the social one augmented by  $\{S_i'(1-a_i) [S_i(1-a_i) /2]\}$  for land  $a_i$ , symmetrically for land  $a_j$ . Since  $S_i'$  and  $S_i$  are both positive, the conclusion is that the private equilibrium is greater than the social optimum. Hence, private owners overharvest from society's point of view. Overharvesting of  $\{S_i'(1-a_i) [S_i(1-a_i) /2]\}$  occurs in  $a_i^*$ .

This is the typical oligopolistic result where decision-makers strategically limit their production of a good in order to increase its price and capture the highest rent possible. Therefore, even if the conservation of biodiversity was paid for, the quantity of species (or the quantity of individuals of a given species, depending on how we define  $S$ ) provided would be less than the socially optimal amount of it. Since this is an oligopoly result, the market equilibrium and social optimum should converge as the number of decision-makers increases. If the number of decision-makers is high enough, a perfectly competitive market structure will lead to the efficient market outcome.

### MODEL 1.C: Biodiversity rent with imperfect substitute species

This model is the same as the first two models, only more refined. The one species or the collection of species considered on each decision-maker's land are not the same this time. Rather, they are imperfect substitutes. This is closer to what might be expected in reality. We therefore have  $S_i$  and  $S_j$ , rather than just  $S$ . As suggested in Solow, Polasky and Broadus,  $S_i$  and  $S_j$  might very well have different values, depending on how much of them are preserved on the areas considered and on what exists elsewhere. The values of species are thus modeled as being dependent on one another.

The demand functions for the species need to be redefined taking the imperfect substitutability into account. The demand functions are defined as:

$$S_i = \gamma_i - \eta_i P_i + \psi_i P_j, \text{ and}$$

$$S_j = \gamma_j - \eta_j P_j + \psi_j P_i,$$

where  $\gamma \geq 0$ ;  $\eta, \psi > 0$  (if  $\psi = 0$ , this corner solution would bring us back to the preceding model);  $\eta_i > \psi_i$  and  $\eta_j > \psi_j$ ;  $\eta_i > \psi_j$  and  $\eta_j > \psi_i$ .

I need to solve for the inverse demand curves. In matrix notation, the demand functions become:

$$\begin{pmatrix} -\eta_i & \psi_i \\ \psi_j & -\eta_j \end{pmatrix} \begin{pmatrix} P_i \\ P_j \end{pmatrix} = \begin{pmatrix} S_i - \gamma_i \\ S_j - \gamma_j \end{pmatrix}.$$

Using Cramer's rule, I solve for  $P_i$ :

$$P_i = \frac{\begin{vmatrix} S_i - \gamma_i & \psi_i \\ S_j - \gamma_j & \eta_j \end{vmatrix}}{\eta_i \eta_j - \psi_i \psi_j} = \frac{(S_i - \gamma_i)(-\eta_j) - (S_j - \gamma_j)(\psi_i)}{\eta_i \eta_j - \psi_i \psi_j}.$$

$$\text{Therefore, } P_i = \frac{-\left(\eta_j S_i\right) + \left(\eta_j \gamma_i\right) - \left(\psi_i S_j\right) + \left(\psi_i \gamma_j\right)}{\eta_i \eta_j - \psi_i \psi_j}.$$

Note that  $P_j$  is symmetric to  $P_i$ .

Defining

$$\beta_0 = \frac{\left(\eta_j \gamma_i\right) + \left(\psi_i \gamma_j\right)}{\eta_i \eta_j - \psi_i \psi_j}, \quad \beta_1 = \frac{\eta_j}{\eta_i \eta_j - \psi_i \psi_j} \quad \text{and} \quad \beta_2 = \frac{\psi_j}{\eta_i \eta_j - \psi_i \psi_j},$$

we get:

$$P_i(S_i, S_j) = \beta_0 - \beta_1 S_i - \beta_2 S_j, \quad \text{where } \beta_0, \beta_1, \beta_2 > 0, \text{ and } \beta_1 > \beta_2.$$

Symmetrically, defining

$$\phi_0 = \frac{\left(\eta_i \gamma_j\right) + \left(\psi_j \gamma_i\right)}{\eta_i \eta_j - \psi_i \psi_j}, \quad \phi_1 = \frac{\eta_i}{\eta_i \eta_j - \psi_i \psi_j} \quad \text{and} \quad \phi_2 = \frac{\psi_i}{\eta_i \eta_j - \psi_i \psi_j},$$

we get:

$$P_j(S_j, S_i) = \phi_0 - \phi_1 S_j - \phi_2 S_i, \quad \text{where } \phi_0, \phi_1, \phi_2 > 0, \text{ and } \phi_1 > \phi_2.$$

These are the inverse-demand curves to be used in the maximization problems below. For simplicity, I define  $S_i = S_i(1-a_i)$  and  $S_j = S_j(1-a_j)$ .

Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \beta_0 S_i - \beta_1 S_i^2 - \beta_2 S_i S_j.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \beta_0 S_i' + 2\beta_1 S_i S_i' + \beta_2 S_j S_i' = 0.$$

Therefore,

$$a_i^* = \alpha_i - S_i' [\beta_0 - 2\beta_1 S_i - \beta_2 S_j] = \alpha_i - S_i' (P_i - \beta_1 S_i).$$

### Social optimum:

To solve for the social optimum, as in model 1.A, the sum of producer and consumer surpluses due to biodiversity conservation has to be maximized. In this case, however,  $S_i$  and  $S_j$  cannot be added together since they do not represent the same species.

$$\begin{aligned} \text{Max}_{a_i, a_j} \pi &= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \int_0^{S_i^*} (\beta_0 - \beta_1 S_i - \beta_2 S_j) dS_i \\ &\quad + \int_0^{S_j^*} (\phi_0 - \phi_1 S_j - \phi_2 S_i) dS_j \\ &= \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \beta_0 S_i^* - \beta_1 (S_i^{*2}/2) \\ &\quad + \phi_0 S_j^* - \phi_1 (S_j^{*2}/2) - (\beta_2 + \phi_2) S_i^* S_j^*. \end{aligned}$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - S_i' [\beta_0 - \beta_1 S_i - (\beta_2 + \phi_2) S_j] = 0.$$

Therefore,

$$a_i^* = \alpha_i - S_i' [\beta_0 - \beta_1 S_i - (\beta_2 + \phi_2) S_j] = \alpha_i - S_i' (P_i - \phi_2 S_j).$$

Let us compare the private equilibrium and the social optimum.

**Table 3: Private equilibrium and social optimum of Model 1.C:  
Biodiversity rent with imperfect substitute species**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - S_i'(P_i - \beta_1 S_i)$	$\alpha_i - S_i'(P_i - \phi_2 S_j)$
$a_j^*$	$\alpha_j - S_j'(P_j - \phi_1 S_j)$	$\alpha_j - S_j'(P_j - \beta_2 S_i)$

The comparison is somewhat difficult to make here. For  $a_i^*$ , we know that by definition,  $\beta_1 > \phi_2$ . However, we have to compare  $\beta_1 S_i$  and  $\phi_2 S_j$ . There can be different cases here.

If we have a case where the demands of the two species are alike ( $\beta_1 \approx \phi_1$  and  $\beta_2 \approx \phi_2$ ), then  $S_i(1-a_i^*) \approx S_j(1-a_j^*)$ . Thus,  $\beta_1 S_i > \phi_2 S_j$ . For  $a_j^*$ , we have that  $\phi_1 > \beta_2$ , so that  $\phi_1 S_j > \beta_2 S_i$ . In this case, the private equilibrium is clearly greater than the social optimum. That is to say that the decision-makers overharvest from society's point of view.

However, if we have an asymmetric case with respect to the demand functions of  $S_j$  and  $S_i$ , the result might be that one of the decision-makers is harvesting too much while the other one is not harvesting enough from society's point of view. This last possible outcome is still a conjecture, however. Thus, the comparison of private equilibrium with optimal harvest is somewhat ambiguous.

### MODEL 1.G: General form with biodiversity rent

The necessary and sufficient conditions are derived here for the general model with downward-sloping demand curve for biodiversity conservation. For simplicity, I assume that  $S_i$  and  $S_j$  are perfect substitutes, that is  $S = S_i + S_j$ , as in model 1.B.

Here the species considered is  $S_i = S_i(1-a_i)$ , its revenue per unit is  $R_i[S_i(1-a_i)]$  and  $i$  is the decision-maker considered. There are again no tangible costs of conservation. The revenue per unit of economic activity is  $P_i$  (perfect competition), and the related cost is  $C_i(a_i)$ . The first and second derivatives of these variables are assumed to be as follows. For the species conservation,  $S_i' > 0$ ,  $S_i'' < 0$ , and  $R' < 0$ ,  $R'' > 0$ . The derivatives of  $S_i$  and  $R$  are taken with respect to the area preserved. For the economic activity,  $P_i' = P_i'' = 0$ , and  $C_i' > 0$ ,  $C_i'' > 0$ . The derivatives are taken with respect to the area harvested in this case.

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} P_i a_i - C_i(a_i) + R[S_i(1-a_i) + S_j(1-a_j)] S_i(1-a_i).$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = P_i - C_i' + \left[ \frac{\partial R(S_i + S_j)}{\partial (S_i + S_j)} \times \frac{\partial (S_i + S_j)}{\partial a_i} \times S_i(1-a_i) \right] + \left[ R(S_i + S_j) \times \frac{\partial S_i(1-a_i)}{\partial a_i} \right] = 0.$$

Therefore,

$$P_i - C_i' = \left[ R'(S_i + S_j) \times (S_i'(1-a_i)) \times S_i(1-a_i) \right] + \left[ R(S_i + S_j)(S_i'(1-a_i)) \right].$$

The equilibrium occurs when the marginal profit from harvesting,  $P_i - C'_i$ , is equal to the marginal profit (or revenue in this case since I assumed no tangible costs) from the conservation of the area by the decision-maker.

The second order condition is:

$$\begin{aligned} \frac{\partial^2 \pi}{(\partial a_i)^2} = & -C''_i - \left[ \frac{\partial R'(S_i + S_j)}{\partial (S_i + S_j)} \times \frac{\partial (S_i + S_j)}{\partial a_i} \times S'_i(1 - a_i) \times S_i(1 - a_i) \right] \\ & - \left[ R'(S_i + S_j) \times \frac{\partial S'_i(1 - a_i)}{\partial a_i} \times S_i(1 - a_i) \right] \\ & - \left[ R'(S_i + S_j) \times S'_i(1 - a_i) \times \frac{\partial S_i(1 - a_i)}{\partial a_i} \right] \\ & - \left[ \frac{\partial R(S_i + S_j)}{\partial (S_i + S_j)} \times \frac{\partial (S_i + S_j)}{\partial a_i} \times S'_i(1 - a_i) \right] \\ & - \left[ R(S_i + S_j) \times \frac{\partial S'_i(1 - a_i)}{\partial a_i} \right] \\ & < 0. \end{aligned}$$

Therefore,

$$\begin{aligned} C''_i > & \left[ R''(S_i + S_j) \times (S'_i(1 - a_i))^2 \times S_i(1 - a_i) \right] \\ & - \left[ R'(S_i + S_j)(S''_i(1 - a_i))(S_i(1 - a_i)) \right] \\ & + 2 \left[ R'(S_i + S_j) \times (S'_i(1 - a_i))^2 \right] \\ & - \left[ R(S_i + S_j)(S''_i(1 - a_i)) \right]. \end{aligned}$$

The second order condition tells us that the first order condition leads to a maximum when the slope of the marginal cost of harvesting is greater than the slope of the marginal revenue from conservation,  $\partial^2(R \times S_i) / \partial a_i$ .

Social optimum:

Again, the sum of producer and consumer surpluses due to biodiversity conservation has to be maximized.

$$\text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} P_{a_i} - C_i(a_i) + P_{a_j} - C_j(a_j) + \int_0^{S_i(1-a_i)+S_j(1-a_j)} R[S(1-a_i, 1-a_j)] dS.$$

By Liebnitz's Rule, the first order condition is:

$$\frac{\partial \pi}{\partial a_i} = P_i - C'_i - \left[ R(S_i + S_j)(S'_i(1-a_i)) \right] - \int_0^{S_i(1-a_i)+S_j(1-a_j)} \left[ R'(S_i + S_j)(S'_i(1-a_i)) \right] dS.$$

Therefore, for decision-maker i, this implies:

$$P_i - C'_i = \left[ R(S_i + S_j)(S'_i(1-a_i)) \right] + \int_0^{S_i(1-a_i)+S_j(1-a_j)} \left[ R'(S_i + S_j)(S'_i(1-a_i)) \right] dS.$$

From theory, we know that the optimum occurs when the marginal profit from harvesting,  $P_i - C'_i$ , is equal to the marginal economic surplus,  $R'$ , derived from the marginal species  $S'_i$ . The algebraic expression above is however ambiguous and therefore difficult to interpret in detail.

Again, using Liebnitz's Rule, the second order condition is:

$$\begin{aligned} \frac{\partial^2 \pi}{(\partial a_i)^2} = & -C''_i - \left[ \frac{\partial R(S_i + S_j)}{\partial (S_i + S_j)} \times \frac{\partial (S_i + S_j)}{\partial a_i} \times S'_i(1-a_i) \right] \\ & - \left[ R(S_i + S_j) \times \frac{\partial S'_i(1-a_i)}{\partial a_i} \right] \\ & + \left[ R(S_i + S_j) \times [S'_i(1-a_i)]^2 \right] \end{aligned}$$



$$+ \int_0^{S_i(1-a_i)+S_j(1-a_j)} \left\{ \begin{array}{l} \left[ R''(S_i + S_j) \times [S'_i(1-a_i)]^2 \right] \\ \left[ -R'(S_i + S_j) \times S''_i(1-a_i) \right] \end{array} \right\} dS < 0.$$

Therefore,

$$C''_i > \left[ \frac{\partial R(S_i + S_j)}{\partial (S_i + S_j)} \times \frac{\partial (S_i + S_j)}{\partial a_i} \times S'_i(1-a_i) \right] \\ - \left[ R(S_i + S_j) \times \frac{\partial S'_i(1-a_i)}{\partial a_i} \right] \\ + \left[ R(S_i + S_j) \times [S'_i(1-a_i)]^2 \right] \\ + \int_0^{S_i(1-a_i)+S_j(1-a_j)} \left\{ \begin{array}{l} \left[ R''(S_i + S_j) \times [S'_i(1-a_i)]^2 \right] \\ \left[ -R'(S_i + S_j) \times S''_i(1-a_i) \right] \end{array} \right\} dS.$$

From theory, we know that this represents the fact that the slope of the marginal cost of harvest at the optimum needs to be greater than the slope of the marginal economic surplus attributed to the conservation of species. Again, it is not obvious to interpret the algebraic expression above.

Let us compare the private equilibrium and the social optimum for  $a_i^*$ .

**Table 4:** Private equilibrium and social optimum of Model 1.G: General form with biodiversity rent

Private equilibrium	Social optimum
$P_i - C'_i = \left[ R(S_i + S_j)(S'_i(1-a_i)) \right] \\ + \left[ R'(S_i + S_j) \times (S'_i(1-a_i)) \times S_i(1-a_i) \right]$	$P_i - C'_i = \left[ R(S_i + S_j)(S'_i(1-a_i)) \right] \\ + \int_0^{S_i(1-a_i)+S_j(1-a_j)} \left[ R'(S_i + S_j)(S'_i(1-a_i)) \right] dS$

The result for the general model with downward-sloping demand curve is still ambiguous from the expressions above. However, theory tells us that the private equilibrium should be greater than the social optimum, so that decision-makers overharvest from a social standpoint.

### **MODEL 2: Blueprint demand for biodiversity**

The “blueprint” or “genetic prospecting” demand for biodiversity is the demand for knowledge contained in the genes and the chemicals produced by different species. Such a demand can originate from the industrial, agricultural or pharmaceutical sectors. The knowledge is beneficial to society through research and development of new products.

Samples are needed for research, and in that sense, the specific abundance of a species does not have any value. As long as the population considered is viable, so that enough samples can be tested and studied before a new product is developed, a population qualifies for this type of demand. It is thought that the production process can be done synthetically, that the valued chemical can be reproduced in a laboratory or that the species can easily be produced more intensively than in the wild. In the case of agricultural genetic manipulations, it is assumed that vegetative plant reproduction can be done in a laboratory, and frozen animal zygotes can be used. In any case, an extensive *in situ* population is not needed. This represents a resource use of biodiversity, but not a harvest type of value. From society’s point of view, the species of interest needs to be

found in one place only to be useful. Its multiple occurrence only brings redundancy and does not lead to a higher societal utility level.

The harvesting profit function is the same as previously, but the biodiversity utility function differs. It is assumed in the following models that there is a density function for the occurrence of a species on a land area. The probability of survival of a useful species, given its occurrence of course, is represented by  $\lambda$ . This value can vary for different areas considered. It is assumed that  $\lambda = \lambda(1-a)$  and  $d\lambda/da = -\lambda'$ , where  $0 \leq \lambda \leq 1$  and  $\lambda' > 0$ ;  $\lambda'$  is the marginal probability of survival of the species due to one more unit of land preserved.

#### **MODEL 2.A: No biodiversity rent**

In this model,  $S$  is the expected value placed by society on a species. However, as in model 1.A, the decision-makers do not capture any of that value. The social optimum is derived here for an oligopoly of  $n$  landowners. This case is similar to the situation in all tropical forests before the UN Convention on Biodiversity was signed. It is still the case in countries that have not yet decided to invest in their genetic resources.

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2).$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i = 0.$$

Therefore,

$$a_i^* = \alpha_i.$$

Social optimum:

$$\text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} \sum_{i=1}^n \{ \alpha_i a_i - (a_i^2/2) \} + [1 - (1 - \lambda_i (1 - a_i)) \prod_{j=1}^{n-1} (1 - \lambda_j (1 - a_j))] S; \quad i \neq j.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1 - a_i) \prod_{j=1}^{n-1} (1 - \lambda_j (1 - a_j)) S = 0; \quad i \neq j.$$

Therefore

$$a_i^* = \alpha_i - \lambda_i' (1 - a_i) \prod_{j=1}^{n-1} (1 - \lambda_j (1 - a_j)) S; \quad i \neq j.$$

Let us compare the private equilibrium and the social optimum.

**Table 5: Private equilibrium and social optimum of Model 2.A: No biodiversity rent**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i$	$\alpha_i - \lambda_i' (1 - a_i) \prod_{j=1}^{n-1} (1 - \lambda_j (1 - a_j)) S; \quad i \neq j$
$a_j^*$	$\alpha_j$	$\alpha_j - \lambda_j' (1 - a_j) \prod_{i=1}^{n-1} (1 - \lambda_i (1 - a_i)) S; \quad j \neq i$

The private equilibrium is therefore greater than the social optimum. This means that the landowners overharvest from society's point of view. This was expected since they do not capture any rent from the value that is attributed to biodiversity by society. The conclusion here is the same as in model 1.A. Compensation or rent appropriation schemes need to be invented that will encourage the conservation of tropical forests.

### **MODELS 2.B: Biodiversity rent**

In the following models, I assume that the decision-makers can capture some rent for the value of useful species on their land. These models are the blueprint version of model 1.B, with some extensions.

#### **MODEL 2.B: Monopolistic rent in a duopoly**

In this model I will solve for the Cournot duopoly equilibrium as well as for society's optimum. It is assumed here that only a monopoly rent can be captured by the decision-makers. That is, if a species of value is found on the land of both owners, prices get bid down by the buyers until all rent is dissipated; this situation is analogous to a Bertrand duopoly game. Decision-makers are therefore trying to preserve according to the probability of the species being on their land and surviving until the end of the game, but not on others'. Hence, the expected payoff from the species is:

$$E_i(\pi_s) = \begin{cases} S & \text{monopoly;} \\ 0 & \text{else.} \end{cases}$$

Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \lambda_i (1-a_i) (1-\lambda_j (1-a_j)) S.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S = 0.$$

Therefore,

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S.$$

Social optimum:

$$\text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + [1 - (1-\lambda_i (1-a_i)) (1-\lambda_j (1-a_j))] S.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S = 0.$$

Therefore,

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S.$$

Let us compare the private equilibrium and the social optimum.

**Table 6: Private equilibrium and social optimum of  
Model 2.B: Monopolistic rent in a duopoly**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S$	$\alpha_i - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S$
$a_j^*$	$\alpha_j - \lambda_j' (1-a_j) (1-\lambda_i (1-a_i)) S$	$\alpha_j - \lambda_j' (1-a_j) (1-\lambda_i (1-a_i)) S$

In this model, the private and social optima coincide. The best of situations occurs naturally. This is a surprising result since decision-makers usually do not have the right incentives to conserve a resource optimally when there exists a market failure. If this situation prevails, policies are not needed to improve the social benefits from the species.

Although the first order conditions are equal in the private equilibrium and the social optimum, it is interesting to note that the respective profits are not the same. In effect, the sum of the private expected profits is:

$$\begin{aligned} \pi_i + \pi_j &= \alpha_i a_i - (a_i^2/2) + \lambda_i (1-a_i) (1-\lambda_j (1-a_j)) S \\ &\quad + \alpha_j a_j - (a_j^2/2) + \lambda_j (1-a_j) (1-\lambda_i (1-a_i)) S \\ &= \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) \\ &\quad + [\lambda_i (1-a_i) (1-\lambda_j (1-a_j)) + \lambda_j (1-a_j) (1-\lambda_i (1-a_i))] S. \end{aligned}$$

However, the social expected profit is equal to:

$$\begin{aligned} \pi_{\text{social}} &= \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + [1-(1-\lambda_i (1-a_i)) (1-\lambda_j (1-a_j))] S \\ &= \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) \\ &\quad + [1-(1-\lambda_i (1-a_i)) -\lambda_j (1-a_j) + [\lambda_i (1-a_i) \times \lambda_j (1-a_j)]] S \end{aligned}$$

$$\begin{aligned}
&= \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + [\lambda_i (1-a_i) + \lambda_j (1-a_j) - [\lambda_i (1-a_i) \times \lambda_j (1-a_j)]] S \\
&= \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + [\lambda_i (1-a_i) (1-\lambda_j (1-a_j)) + \lambda_j (1-a_j)] S.
\end{aligned}$$

Since  $[\lambda_j (1-a_j) (1-\lambda_i (1-a_i))] < [\lambda_j (1-a_j)]$ , it is clear that the sum of the private profits is smaller than the social profit. It can be explained intuitively by the fact that the decision-makers benefit from the species conservation only if they have a monopoly over it. In the duopoly case, this represents two separate possible rent-capturing outcomes: the species of concern exists either on land  $i$  or on land  $j$ , *but not on both* lands. Society, however, captures some rent from three possible outcomes: the species of concern exists either on land  $i$ , or on land  $j$ , *or on both* lands. Therefore, even though the first order conditions are the same for the decision-makers and for society, it is logical that the social expected profits will be greater than the sum of the individual private expected profits.

### MODEL 2.B: Monopolistic rent generalized

This model is essentially the same as the last one, but it is extended to the oligopoly case, with  $n$  decision-makers identified as  $i = 1, 2, \dots, n$ .

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \lambda_i (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S; \quad i \neq j.$$

The first order condition is:



$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S = 0; \quad i \neq j.$$

Therefore,

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S; \quad i \neq j.$$

Social optimum:

$$\text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} \sum_{i=1}^n \{ \alpha_i a_i - (a_i^2/2) \} + [1 - (1-\lambda_i (1-a_i)) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j))] S; \quad i \neq j.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S = 0; \quad i \neq j.$$

Therefore,

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S; \quad i \neq j.$$

Let us compare the private equilibrium and the social optimum.

**Table 7: Private equilibrium and social optimum of Model 2.B: Monopolistic rent generalized**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S; i \neq j$	$\alpha_i - \lambda_i' (1-a_i) \prod_{j=1}^{n-1} (1-\lambda_j (1-a_j)) S; i \neq j$
$a_j^*$	$\alpha_j - \lambda_j' (1-a_j) \prod_{i=1}^{n-1} (1-\lambda_i (1-a_i)) S; j \neq i$	$\alpha_j - \lambda_j' (1-a_j) \prod_{i=1}^{n-1} (1-\lambda_i (1-a_i)) S; j \neq i$

Again, both equilibria coincide. The previous result is not valid in the case of duopolistic biodiversity conservation only, it is applicable to  $n$  countries where the valuable species exist. This reinforces the importance of the previous result by making it hold in any oligopolistic situation.

### MODEL 2.B: Monopolistic and duopolistic rents

This model is a variant of the previous duopoly model. Here, however, it is made possible for landowners to collect duopoly rents ( $D$ ) as well as a monopoly rent ( $S$ ), where  $0 < D < S$ . In this model then,

$$E_i(\pi_S) = \begin{cases} S & \text{monopoly;} \\ D & \text{duopoly;} \\ 0 & \text{else.} \end{cases}$$

Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \lambda_i (1-a_i) \lambda_j (1-a_j) D + \lambda_i (1-a_i) (1-\lambda_j (1-a_j)) S.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S = 0.$$

Therefore

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S.$$

Social optimum:

$$\begin{aligned} \text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} & \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \lambda_i (1-a_i) \lambda_j (1-a_j) D \\ & + [\lambda_i (1-a_i) (1-\lambda_j (1-a_j)) + \lambda_j (1-a_j) (1-\lambda_i (1-a_i))] S. \end{aligned}$$

First order conditions:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D - [\lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) - \lambda_i' (1-a_i) \lambda_j (1-a_j)] S = 0.$$

Therefore,

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D - [\lambda_i' (1-a_i) (1-2\lambda_j (1-a_j))] S.$$

Let us compare the private equilibrium and the social optimum.

**Table 8: Private equilibrium and social optimum of Model 2.B: Monopolistic and duopolistic rents**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D$ $- \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S$	$\alpha_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) D$ $- [\lambda_i' (1-a_i) (1-2\lambda_j (1-a_j))] S$
$a_j^*$	$\alpha_j - \lambda_j' (1-a_j) \lambda_i (1-a_i) D$ $- \lambda_j' (1-a_j) (1-\lambda_i (1-a_i)) S$	$\alpha_j - \lambda_j' (1-a_j) \lambda_i (1-a_i) D$ $- [\lambda_j' (1-a_j) (1-2\lambda_i (1-a_i))] S$

The private equilibrium solution is smaller than the social optimum here. This means that the private owners *underharvest* from society's point of view. In other words, when only the blueprint value of the species is considered, this case offers too much incentive for conservation. It makes intuitive sense since we had previously found that a unique monopoly rent would induce the private equilibrium and the social optimum to coincide. This conclusion can be extended to any oligopolistic rent-paying scheme. The model reveals that as the probability of obtaining some rent increases, the private incentives for conservation increase. However, the value of the species to society remains the same. Since the case with a unique possible monopolistic rent resulted in the private equilibrium being optimal, any rent-sharing scheme will lead to too much conservation.

This result reinforces the fact that the result of the preceding model is an important one. There could have been many optimal rent-capturing schemes, but this suggests that the monopolistic rent model is better than any model that makes rent-sharing possible. It has been suggested that rent sharing would promote the conservation of pristine areas (Mendelsohn and Balick). We realize here that it is true, but that it would not lead to an efficient outcome. This offers one more reason to extend the monopolistic rent model in

order to model real transactions better and to investigate whether in reality rent-sharing by tropical nations is better than monopolistic rent.

### **MODEL 2.C: Monopolistic rent with imperfect substitute species**

This model is simply the blueprint version of model 1.C where species  $S_i$  and  $S_j$  are imperfect substitutes. Define  $j=0$  if  $S_j$  is extinct and  $j=1$  if  $S_j$  still exists (a symmetric situation exists for  $S_i$ ). Then, we have that  $S_{iH}=S_i$  ( $j=0$ ) and  $S_{iL}=S_i$  ( $j=1$ ), with  $S_{iH} > S_{iL}$ .

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} \alpha_i a_i - (a_i^2/2) + \lambda_i (1-a_i) \lambda_j (1-a_j) S_{iL} + \lambda_i (1-a_i) (1-\lambda_j (1-a_j)) S_{iH}.$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) S_{iL} - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S_{iH} = 0.$$

Therefore

$$a_i^* = \alpha_i - \lambda_i' (1-a_i) \lambda_j (1-a_j) S_{iL} - \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S_{iH}.$$

#### Social optimum:

$$\begin{aligned} \text{Max}_{a_i, a_j} \pi = \text{Max}_{a_i, a_j} & \alpha_i a_i - (a_i^2/2) + \alpha_j a_j - (a_j^2/2) + \lambda_i (1-a_i) \lambda_j (1-a_j) [S_{iL} + S_{jL}] \\ & + [\lambda_i (1-a_i) (1-\lambda_j (1-a_j))] S_{iH} + [(1-\lambda_i (1-a_i)) \lambda_j (1-a_j)] S_{jH} \end{aligned}$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = \alpha_i - a_i - \lambda_i'(1-a_i) \lambda_j(1-a_j) [S_{iL} + S_{jL}]$$

$$- [\lambda_i'(1-a_i)(1-\lambda_j(1-a_j))] S_{iH} + [\lambda_i'(1-a_i) \lambda_j(1-a_j)] S_{jH} = 0.$$

Therefore

$$a_i^* = \alpha_i - [\lambda_i'(1-a_i) \lambda_j(1-a_j)] S_{iL} - [\lambda_i'(1-a_i)(1-\lambda_j(1-a_j))] S_{iH}$$

$$- [\lambda_i'(1-a_i) \lambda_j(1-a_j)] [S_{jL} - S_{jH}].$$

Let us compare the private equilibrium and the social optimum.

**Table 9: Private equilibrium and social optimum of Model 2.C:  
Monopolistic rent with imperfect substitute species**

	Private equilibrium	Social optimum
$a_i^*$	$\alpha_i - \lambda_i'(1-a_i) \lambda_j(1-a_j) S_{iL}$ $- \lambda_i'(1-a_i)(1-\lambda_j(1-a_j)) S_{iH}$	$\alpha_i - [\lambda_i'(1-a_i) \lambda_j(1-a_j)] S_{iL}$ $- [\lambda_i'(1-a_i)(1-\lambda_j(1-a_j))] S_{iH}$ $- [\lambda_i'(1-a_i) \lambda_j(1-a_j)] [S_{iL} - S_{iH}]$
$a_j^*$	$\alpha_j - \lambda_j'(1-a_j) \lambda_i(1-a_i) S_{jL}$ $- \lambda_j'(1-a_j)(1-\lambda_i(1-a_i)) S_{jH}$	$\alpha_j - [\lambda_j'(1-a_j) \lambda_i(1-a_i)] S_{iL}$ $- [\lambda_j'(1-a_j)(1-\lambda_i(1-a_i))] S_{jH}$ $- [\lambda_j'(1-a_j) \lambda_i(1-a_i)] [S_{iL} - S_{iH}]$

The private equilibrium solution is smaller than the social optimum here. This means that the private owners *underharvest* from society's point of view. Unlike model 1.C, where substitute species faced downward-sloping demand curves, the result here is unequivocal.

The implication here is that it is suboptimal for decision-makers to receive rents for substitute species. Intuitively, this is equivalent to society paying for some redundancy between species. Redundancy between species and subspecies might be a valuable quality

in certain circumstances, like for the assurance for the survival of a species against environmental or human caused catastrophes, but it is clearly not valuable for genetic prospecting.

### **MODEL 2.D: Three stage model**

This model makes use of the blueprint demand for biodiversity in a dynamic context. The reason for solving this model is to reveal whether or not there exists a dynamic externality when model 2.B with monopolistic rent is extended to multiple stages. Remember that the static game revealed the important result that the private equilibrium and the social optimum coincide. If there exists a dynamic externality, this coincidence will not hold over time, however. I will derive the private subgame perfect equilibria for three stages in model 2.D.1 as well as the social optimum, and I will give a numerical example in order to get more intuition from the model.

Intertemporal optimization is used here, and  $\delta_i$  is the discount rate which is assumed to be constant over time for each decision-maker. Decision-makers can have different discount rates, however, and subscripts will be used to specify whose discount rate is being used. Let  $a_{in}^*$  be the optimal area to be harvested by decision-maker  $i$  in period  $n$ . The probability of survival of a species to the next stage, given its occurrence in the current stage, will be noted as  $\lambda_{in}$ , where  $i$  is the decision-maker, as before, and  $n$  is the period. For shortness, I will sometimes use  $\lambda_{in}$  only, keeping in mind that  $\lambda_{in} = \lambda_{in} (1 - a_{in})$  in the optimization process.

The subgame perfect Nash equilibria is solved for by backward induction. The social optima is solved for in the same way, although the open-loop solution would give the same results in this case. In order to solve by backward induction, the probability function  $\lambda_{in}$  needs to be specified. The specification of the function is necessary in order to obtain an expected profit at every stage that will be used in the optimization calculation for the preceding stages. A simple linear function will be used :  $\lambda_{in} = \lambda_{in} (1-a_{in}) = p_{in} (1-a_{in}) = p_{in} - p_{in} a_{in}$ . It is furthermore assumed that  $p_{in} = p_i$  for all stages,  $0 \leq p_i \leq 1$ . Here,  $\partial \lambda_{in} / \partial a_{in} = -\lambda'_{in} = -p_i$ . The probability of survival to stage (n+1) thus depends on what proportion of the land was harvested in stage n. Each stage will first be solved in the more general form, then the linear probability function will be substituted for the general one.

Figure 2 shows a representation of the three stage duopolistic game. In the first stage, the species exists on both decision-makers' lands, in the second stage, it might exist or not, giving four possible cases. The third stage offers four possible cases also, although, there are nine different time paths to get to them. The four possible initial states will be denoted as in the diagram, with  $S_{in}$  and  $S_{jn}$  meaning that the species exists on i and j's land at the beginning of stage n, while  $S_i$  and  $S_j$  means it disappeared before stage n. The probabilities of ending up in all different possible states in the next stage are also given on the diagram, with  $\lambda_{i1} = p_i - p_i a_{in}$  and  $\lambda_{j1} = p_j - p_j a_{jn}$ .

The irreversibility of extinction is seen in the asymmetry of the diagram when fewer initial states are possible as the species disappears from one land area or both. The left branch of the diagram is a repetition of the first stage over time, where at each stage the initial state is that the species exists on both land area. The other branches where  $S_i$  or



$S_j$  disappeared in the second and third stages do not present any strategic games. The solutions to those situations are thus expected to be the same for the social optima and the private equilibria.

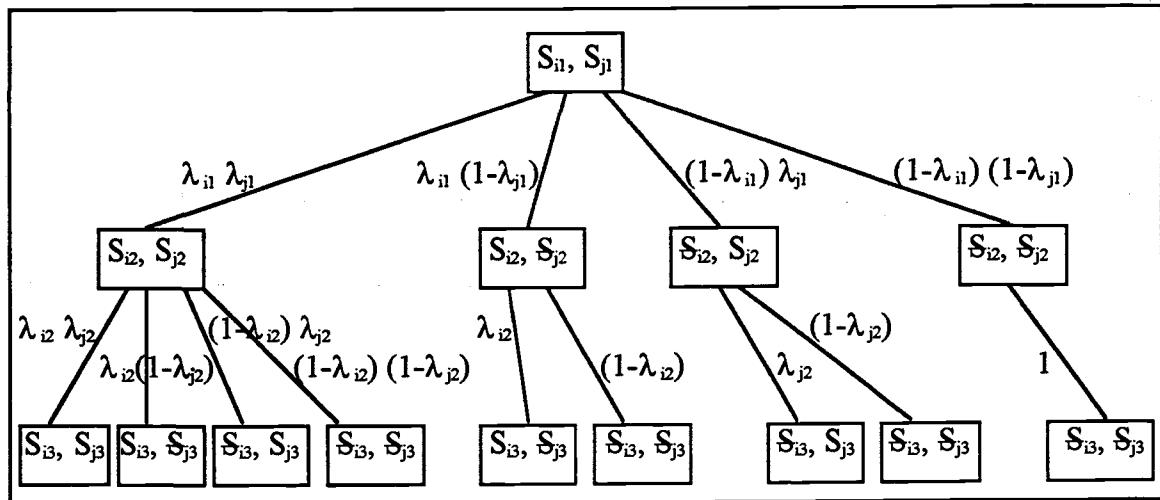


Figure 2: A diagrammatic representation of Model 2.D

### Subgame Perfect Nash Equilibria

#### Third stage

Four different initial states can exist in this stage. Since this is the last stage of the game, all similar states will have the same solution. Let us solve for them.

Case 1:  $S_{i3}, S_{j3}$

This is the same case as in the static model 2.B with monopolistic rent since there is no following stage. We already the result to be  $a_{i3}^* = \alpha_i - \lambda_{i3}' (1-\lambda_{j3}) S$ .

Also, by symmetry, we have that  $a_{j3}^* = \alpha_j - \lambda_{j3}' (1-\lambda_{i3}) S$ . Substituting the specified probability function and using Cramer's rule to solve for  $a_{i3}^*$ , we get:

$$a_{i3}^* = \frac{\alpha_i + (p_i p_j - p_j) S - \alpha_j p_i p_j S - (p_i p_j - p_j) p_i p_j S^2}{1 - p_i^2 p_j^2 S^2}$$

Of course, the solution for  $a_{j3}^*$  is symmetric. The corresponding expected profit for  $a_{i3}^*$  is then  $\pi_{i3}^* = \alpha_i a_{i3}^* - ((a_{i3}^*)^2/2) + (p_i - p_j a_{i3}^*) (1 - p_j + p_j a_{j3}^*) S$ . I will define this as  $\pi_{i3}^* = \pi_{i3}^*(S_{i3}, S_{j3})$  in order to simplify the objective functions of the precedent stages to be solved later.

Case 2:  $S_{i3}, S_{j2}$

$$\text{Max}_{a_{i3}} \pi_{i3} = \text{Max}_{a_{i3}} \alpha_i a_{i3} - (a_{i3}^2/2) + \lambda_{i3} S.$$

The first order condition is:

$$\frac{\partial \pi_i}{\partial a_{i3}} = \alpha_i - a_{i3} - \lambda_{i3}' S = 0.$$

Therefore, specifying the probability function,

$$a_{i3}^* = \alpha_i - \lambda_{i3}' S = \alpha_i - p_i S.$$

The corresponding expected profit for  $a_{i3}^*$  is:

$$\pi_{i3}^* = \frac{\alpha_i^2}{2} - 2\alpha_i p_i S + 2 p_i S + \frac{p_i^2 S^2}{2}.$$

I will define this as  $\pi_{i3}^* = \pi_{i3}^*(S_{i3}, S_{j3})$ .

Case 3:  $S_{i3}, S_{j3}$

$$\text{Max}_{a_{i3}} \pi_{i3} = \text{Max}_{a_{i3}} \alpha_i a_{i3} - (a_{i3}^2/2).$$

The first order condition is:

$$\frac{\partial \pi_i}{\partial a_{i3}} = \alpha_i - a_{i3} = 0.$$

Therefore,

$a_{i3}^* = \alpha_i$ , and  $\pi_{i3}^* = \alpha_i^2/2$ . Let us define the expected profit as  $\pi_{i3}^* = \pi_{i3}^*(S_{i3}, S_{j3})$ .

Case 4:  $S_{i3}, S_{j3}$

The objective function here is the same as in Case 3 for decision-maker i.

Therefore,  $a_{i3}^* = \alpha_i$ , and  $\pi_{i3}^* = \alpha_i^2/2$ . Let us define the expected profit as  $\pi_{i3}^* = \pi_{i3}^*(S_{i3}, S_{j3})$ .

### Second stage

Four different initial states can exist in this stage as well. Let us solve for them, using the expected profits of the third stage for each of the four possible initial state.

#### Case 1: $S_{i2}, S_{j2}$

$$\begin{aligned} \text{Max}_{a_{i2}} \pi_{i2} = \text{Max}_{a_{i2}} & \alpha_i a_{i2} - (a_{i2}^2/2) + \lambda_{i2} (1-\lambda_{j2}) S + \delta_i \{ \lambda_{i2} \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] \\ & + \lambda_{i2} (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] + (1-\lambda_{i2}) \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] \\ & + (1-\lambda_{i2}) (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] \}. \end{aligned}$$

The first order condition is:

$$\begin{aligned} \frac{\partial \pi_i}{\partial a_{i2}} = \alpha_i - a_{i2} - \lambda_{i2}' (1-\lambda_{j2}) S + \delta_i \{ -\lambda_{i2}' \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] - \lambda_{i2}' (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] \\ + \lambda_{i2}' \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] + \lambda_{i2}' (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] \} = 0. \end{aligned}$$

Therefore,

$$\begin{aligned} a_{i2}^* = \alpha_i - \lambda_{i2}' (1-\lambda_{j2}) S + \delta_i \{ -\lambda_{i2}' \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] - \lambda_{i2}' (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] \\ + \lambda_{i2}' \lambda_{j2} [\pi_{i3}^*(S_{i3}, S_{j3})] + \lambda_{i2}' (1-\lambda_{j2}) [\pi_{i3}^*(S_{i3}, S_{j3})] \}. \end{aligned}$$

As usual, we get a symmetric solution for  $a_{j2}^*$ .

Substituting the specified linear probability function and using Cramer's rule, one can solve algebraically for  $a_{i2}^*$ . Again, the solution for  $a_{j2}^*$  is symmetric. Substituting  $a_{i2}^*$  in the objective function, we get the corresponding expected profit, defined as  $\pi_{i2}^* =$

$\pi_{i2}^*(S_{i2}, S_{j2})$ . In the next section,  $a_{i2}^*$  and  $\pi_{i2}^*(S_{i2}, S_{j2})$  are solved for in a numerical example. The algebraic solution is cumbersome and little intuition can be gotten from it.

Case 2:  $S_{i2}, S_{j2}$

$$\text{Max}_{a_{i2}} \pi_{i2} = \text{Max}_{a_{i2}} \alpha_i a_{i2} - (a_{i2}^2/2) + \lambda_{i2} S + \delta_i \{ \lambda_{i2} [\pi_{i3}^*(S_{i3}, S_{j3})] + (1-\lambda_{i2}) \pi_{i3}^*(S_{i3}, S_{j3}) \}.$$

The first order condition is:

$$\frac{\partial \pi_i}{\partial a_{i2}} = \alpha_i - a_{i2} - \lambda_{i2}' S + \delta_i \{ -\lambda_{i2}' [\pi_{i3}^*(S_{i3}, S_{j3})] + \lambda_{i2}' [\pi_{i3}^*(S_{i3}, S_{j3})] \} = 0.$$

Therefore, specifying the probability function,

$$\begin{aligned} a_{i2}^* &= \alpha_i - \lambda_{i2}' S + \delta_i \{ -\lambda_{i2}' [\pi_{i3}^*(S_{i3}, S_{j3})] + \lambda_{i2}' [\pi_{i3}^*(S_{i3}, S_{j3})] \} \\ &= \alpha_i - p_i S + \delta_i p_i \times \{ (\pi_{i3}^*(S_{i3}, S_{j3})) - [\pi_{i3}^*(S_{i3}, S_{j3})] \}. \end{aligned}$$

I will define the corresponding expected profit as  $\pi_{i2}^* = \pi_{i2}^*(S_{i2}, S_{j2})$ .

Case 3:  $S_{i2}, S_{j2}$

$$\text{Max}_{a_{i2}} \pi_{i2} = \text{Max}_{a_{i2}} \alpha_i a_{i2} - (a_{i2}^2/2) + \delta_i (\alpha_i^2/2).$$

The first order condition is:

$$\frac{\partial \pi_i}{\partial a_{i2}} = \alpha_i - a_{i2} = 0.$$

Therefore,

$$a_{i2}^* = \alpha_i, \text{ and } \pi_{i2}^* = \alpha_i^2/2.$$

The corresponding expected profit is:

$$\pi_{i2}^* = \alpha_i^2/2 + \delta_i (\alpha_i^2/2) = (1+\delta_i) \alpha_i^2/2.$$

Let us define it as  $\pi_{i2}^* = \pi_{i2}^*(S_{i2}, S_{j2})$ .

#### Case 4: $S_{i2}, S_{j2}$

The objective function here is the same as in Case 3 for decision-maker i.

Therefore,  $a_{i2}^* = \alpha_i$ , and  $\pi_{i2}^* = \alpha_i^2/2 (1+\delta_i)$  defined as  $\pi_{i2}^* = \pi_{i2}^*(S_{i2}, S_{j2})$ .

#### First stage

There is a unique case here, since it is the starting point of the game:  $S_{i1}, S_{j1}$ .

$$\begin{aligned} \text{Max}_{a_{i1}} \pi_{i1} = \text{Max}_{a_{i1}} & \alpha_i a_{i1} - (a_{i1}^2/2) + \lambda_{i1} (1-\lambda_{j1}) S + \delta_i \{ \lambda_{i1} \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] \\ & + \lambda_{i1} (1-\lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})] + (1-\lambda_{i1}) \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] \\ & + (1-\lambda_{i1}) (1-\lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})] \}. \end{aligned}$$

The first order condition is:

$$\begin{aligned} \frac{\partial \pi_i}{\partial a_{i1}} = \alpha_i - a_{i1} - \lambda_{i1} (1-\lambda_{j1}) S + \delta_i \{ -\lambda_{i1} \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] - \lambda_{i1} (1-\lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})] \\ + \lambda_{i1} \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] + \lambda_{i1} (1-\lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})] \} = 0. \end{aligned}$$

Therefore,

$$a_{i1}^* = \alpha_i - \lambda_{i1} (1-\lambda_{j1}) S + \delta_i \{ -\lambda_{i1} \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] - \lambda_{i1} (1-\lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})] \}$$

$$+ \lambda_{i1}' \lambda_{j1} [\pi_{i2}^*(S_{i2}, S_{j2})] + \lambda_{i1}' (1 - \lambda_{j1}) [\pi_{i2}^*(S_{i2}, S_{j2})]}.$$

Again, we get a symmetric solution for  $a_{j1}^*$ .

As in case 1 of the second stage, substituting the specified linear probability function and using Cramer's rule, one can solve algebraically for  $a_{i1}^*$ . Again, the solution for  $a_{j1}^*$  is symmetric. Substituting  $a_{i1}^*$  in the objective function, we get the corresponding expected profit, defined as  $\pi_{i1}^* = \pi_{i1}^*(S_{i1}, S_{j1})$ . In the next section,  $a_{i1}^*$  and  $\pi_{i1}^*(S_{i1}, S_{j1})$  are solved for in a numerical example.

### Social Optima

The method used to solve for the social optima is the same as that used for the above subgame perfect Nash equilibria. The objective functions will differ, however, since here the social optima depend on expected social profits from both land  $i$  and land  $j$ . I will explain how to solve for the social optima, without reproducing all the steps equivalent to the ones from the subgame perfect Nash equilibria above. A numerical example of the three stage social optima has been solved that will be compared to the decision-makers' strategy in the following section.

### Third stage

As before, four different initial states can exist in this stage. Since this is the last stage of the game, all similar states will have the same solution. Moreover, the  $a_{i3}^*$  are all

the same as the subgame perfect Nash equilibria here since this stage alone is equivalent to a static game, that is, a game without any following stage.

In effect, it has been found in model 2.B with monopolistic rent that in the static game, the social optimum and private equilibrium coincide when the initial state is  $S_{i3}$ ,  $S_{j3}$ . The expected social profit here will be greater than the sum of the decision-maker's profits, since there are three cases that increase society's profit while there are only two for each decision-makers. The three cases that serve society are when S survives on land i only, when it survives on land j only, and finally when it survives on both. However, the only states that serve the decision-maker's purposes are when S survives on land i only, or on land j only. As before, if it survives on both lands, they will not collect any rent from conservation. The difference is translated in the different objective functions. The objective function of decision-maker i and j are:

$$\text{Max}_{a_{i3}} \pi_{i3} = \text{Max}_{a_{i3}} \alpha_i a_{i3} - (a_{i3}^2/2) + \lambda_{i3} (1-\lambda_{j3}) S, \text{ and}$$

$$\text{Max}_{a_{j3}} \pi_{j3} = \text{Max}_{a_{j3}} \alpha_j a_{j3} - (a_{j3}^2/2) + \lambda_{j3} (1-\lambda_{i3}) S.$$

In contrast, the social objective function is:

$$\text{Max}_{a_{i3}, a_{j3}} \pi_{G3} = \text{Max}_{a_{i3}, a_{j3}} \alpha_i a_{i3} - (a_{i3}^2/2) + \alpha_j a_{j3} - (a_{j3}^2/2) + [1-(1-\lambda_{i3})(1-\lambda_{j3})] S.$$

Hence, the expected social profits will be greater than the sum of the private ones, even though the optimal harvested areas, the  $a_{i3}^*$ 's and  $a_{j3}^*$ 's, are the same. This is bound to create a dynamic externality in the optimization process of the second and first stages.

The social  $a_{i3}^*$  and  $a_{j3}^*$  for the three other possible initial states ( $(S_{i3}, S_{j3})$ ,  $(S_{i3}, S_{j3})$  and  $(S_{i3}, S_{j3})$ ) are the same as the decision-makers' since there is no strategic behavior



occurring. Social and private optimization thus lead the same solution and the social expected profits are simply the sum of the private ones.

### Second stage

Four different initial states can exist in this stage as well. The optimal areas harvested by decision-makers  $i$  and  $j$  are the same as the ones from the subgame Nash equilibria for the non-strategic initial states  $(S_{i2}, S_{j2})$ ,  $(S_{i2}, S_{j2})$  and  $(S_{i2}, S_{j2})$ . As noted above, the initial state where the species exists on both lands gives rise to a dynamic externality. Hence the socially optimal areas harvested,  $a_{i2}^*$  and  $a_{j2}^*$ , are not the same as the ones the decision-makers would like to harvest.

### First stage

There is a unique case here, since it is the starting point of the game. The species exists on both lands, and therefore this game is a strategic one. As before, a dynamic externality exists, and the socially optimal  $a_{i2}^*$  and  $a_{j2}^*$ , are expected not to be the same as the ones the decision-makers would like to harvest

### MODEL 2.D: Numerical example

The three stage dynamic game above has been solved along with the dynamic social optima. Parameters have been specified symmetrically in order to simplify the calculations.

The total area for harvest available is  $a_i = a_j = 1$ , with  $0 \leq a_i^* \leq 1$  and  $0 \leq a_j^* \leq 1$  as before. The revenue per unit of land harvested is  $\alpha_i = \alpha_j = 0.9$ . The species probability of survival to the next stage on each land unit, given its occurrence, is  $p_i = p_j = 0.5$ . The per stage expected value to society of the species is  $S = 0.4$ . The discount rates are all equal:  $\delta_i = \delta_j = \delta_G = 0.9$ ;  $\delta_G$  is the social, or global discount rate. The results are produced in Table 10.

As expected, the harvested areas are equal in the private equilibrium and the social optimum for all cases in the third stage, as well as for any other case where the species has disappeared on at least one of the land areas ( $(S_i, S_j)$ ,  $(S_i, S_j)$  and  $(S_i, S_j)$ ). The first and second stages show differences, however, where the species is found on both lands as an initial state,  $(S_i, S_j)$ , and a dynamic externality appears (results in bold and italicized in the table). Somewhat surprisingly, the decision-makers have the incentives to preserve too much, or not harvest enough, since the private equilibria are smaller than the social optima. It is interesting to see that the difference increases between the private equilibria and social optima as the stage observed gets farther from the last stage.

This can be explained intuitively, as in model 2.B with monopolistic rent, by the fact that in the duopoly case, decision-makers face only two separate possible rent-capturing outcomes: the species of concern exists either on land  $i$  or on land  $j$ , *but not on*

*both* lands. Society, however, captures some rent from three possible outcomes: the species of concern exists either on land  $i$ , or on land  $j$ , or on *both* lands. In the static case, it was concluded that, even if the first order conditions are the same for the decision-makers and for society, as is the case in the last stage here, it is logical that the social expected profits will be greater than the sum of the individual private expected profits. Therefore, when the expected profits are used in the backward induction method of optimization, the socially optimal area gets smaller and smaller than the private equilibria because of higher future expected profits for an identical land area preserved in the social case.

The differences shown below are very small, and it is not obvious that they would be significant in reality. Empirical estimates should be used in order to investigate this question for real cases. It would also be interesting to derive the equilibrium and optimum results of any stage with initial state  $(S_i, S_j)$  where the number of stages approaches infinity in order to appreciate the importance of the dynamic externality with an infinite planning horizon.

**Table 10: Results of the numerical example for Model 2.D**

Initial state	Subgame Perfect Nash Equilibria				Social Optima		
	$a_{i1}^*$	$\pi_{i1}^*$	$a_{j1}^*$	$\pi_{j1}^*$	$a_{i1}^*$	$a_{j1}^*$	$\pi_{G1}^*$
<i>Stage 1</i>							
$S_{i1}, S_{j1}$	<b>0.709163682</b>	1.134842882	<b>0.709163682</b>	1.134842882	<b>0.709189705</b>	<b>0.709189705</b>	2.278305544
<i>Stage 2</i>							
$S_{i2}, S_{j2}$	<b>0.711370172</b>	0.806153589	<b>0.711370172</b>	0.806153589	<b>0.711392092</b>	<b>0.711392092</b>	1.62077731
$S_{i2}, S_{j2}$	0.682	0.815062	0.9	0.7695	0.682	0.9	1.584562
$S_{i2}, S_{j2}$	0.9	0.7695	0.682	0.815062	0.9	0.682	1.584562
$S_{i2}, S_{j2}$	0.9	0.7695	0.9	0.7695	0.9	0.9	1.539
<i>Stage 3</i>							
$S_{i3}, S_{j3}$	<b>0.72727272</b>	0.437190083	<b>0.72727272</b>	0.437190083	<b>0.72727272</b>	<b>0.72727272</b>	0.88181818
$S_{i3}, S_{j3}$	0.7	0.445	0.9	0.405	0.7	0.9	0.85
$S_{i3}, S_{j3}$	0.9	0.405	0.7	0.445	0.9	0.7	0.85
$S_{i3}, S_{j3}$	0.9	0.405	0.9	0.405	0.9	0.9	0.81

### MODEL 2.G: Static general form with monopolistic rent

The necessary and sufficient conditions are derived here for the general model with the blueprint demand curve for biodiversity conservation. The harvest profit function is generalized in the same way as was done in model 1.G, while the expected profit function of biodiversity conservation is the same as in model 2.B with monopolistic rent, since it was already written in general form. As in model 1.G, the first and second derivatives of  $P$  and  $C$  are  $P' = P'' = 0$ , and  $C' > 0$ ,  $C'' > 0$ . The derivatives are taken with respect to the area harvested in this case. The first and second derivatives of  $\lambda$  with respect to the area preserved are assumed to be  $\lambda' > 0$  and  $\lambda'' < 0$ . This is in agreement with the well-known species-area relationship which states that the number of species,  $N$ , present is a function of the area preserved:  $N = \alpha(1-a_i)^z$ , where  $0.15 \leq z \leq 0.35$ , and  $\alpha$  is a coefficient (MacArthur and Wilson).

#### Private equilibrium:

$$\text{Max}_{a_i} \pi = \text{Max}_{a_i} P a_i - C_i(a_i) + \lambda_i(1-a_i) [1 - \lambda_j(1-a_i)] S$$

The first order condition is:

$$\frac{\partial \pi}{\partial a_i} = P - C_i'(a_i) - \lambda_i'(1-a_i) (1 - \lambda_j(1-a_i)) S = 0$$

$$\frac{\partial a_i}{\partial a_i}$$

Therefore,

$$P - C_i'(a_i) = \lambda_i' (1-a_i) (1-\lambda_j (1-a_j)) S$$

As in model 1.G, the equilibrium occurs when the marginal profit from harvesting,  $P_i - C_i'$ , is equal to the expected marginal (or revenue in this case since I assumed no tangible costs) conservation of the area by the decision-maker.

The second order condition is:

$$\frac{\partial^2 \pi}{\partial a_i^2} = -C_i''(a_i) - \lambda_i'' (1-a_i) (1-\lambda_j (1-a_j)) S < 0.$$

Therefore,

$$C_i''(a_i) > \lambda_i'' (1-a_i) (1-\lambda_j (1-a_j)) S.$$

The second order condition tells us that the first order condition leads to a maximum when the slope of the marginal cost of harvesting is greater than the slope of the expected marginal revenue from conservation.

#### Social optimum:

The social optimum for the general form blueprint demand model is the same as the general form private equilibrium. The social harvest profit function will give the same first and second derivatives as in the private case since we are assuming perfect competition. The expected profit function of biodiversity conservation is the same as in model 2.B with monopolistic rent, that is  $[1-(1-\lambda_i)(1-\lambda_j)]S$ . We had found that the first derivative was the same as that of the private expected profit function. The second derivative is thus the same as the one found above for the private equilibrium. Hence the first and second order conditions are the same ones as for the private equilibrium.

## DISCUSSION

The preceding models answered some questions regarding the incentives to conserve biodiversity but have raised other questions. The most obvious result is that some scheme for rent capture is needed in order for the decision-makers to have any economic incentive for conservation. The models reveal how, when property rights are well-defined, as in models 1.B, 1.C, 2.B, 2.C and 2.D, there exist economic incentives to conserve biodiversity.

Model 1 showed that when faced with a downward-sloping demand curve on non-substitutable species, decision-makers will conserve less than the optimal amount even when they receive the market value for it. This result occurs because of the oligopolistic structure of the supply side of the biodiversity market. This case is applicable to any harvest type of demand for species, as in the ivory trade. The criticisms of Brown, Pearce, Perrings and Swanson towards The Convention on International Trade in Endangered Species of Flora and Fauna, with its system of bans, are better understood in light of model 1. Why should any country invest in species conservation when they have some market value that cannot be captured? Regulated markets could exist for countries that invest in management of their resources and their conservation.

Model 1 applies also to any other type of value that can be elicited by indirect pricing methods when some services are paid to a decision-maker for the species found on her land (e.g., eco-tourism). Contingent valuation methods can also be used to reveal the importance of species to society, although a specific demand curve is unlikely to be revealed this way.

Model 1.C leads to an ambiguous result. In effect, depending on the demand for the substitute species from areas  $i$  and  $j$ , both areas would be *overharvested* in a symmetric demand functions case. In the case of an asymmetric demand functions, it may be possible that one land area is *overharvested* while the other land area is *underharvested*. This indicates the importance of obtaining more knowledge about species, in order to aim at the socially optimal outcome.

If we abstract from the imperfect substitute case, model 1 tells us that landowners have some economic incentives to conserve species if they can capture some rent from them. This points to the usefulness of creating well-defined property rights and payment transfers for biodiversity. It also indicates that in order to approach the socially optimal amount of a species supplied, some policy will be needed in order to increase the oligopolistic equilibrium quantity. Further models should be developed in order to observe the effects of such policies. Potential policies could be a mixture of regulation and payment for the value of biodiversity, or regulation combined with some compensation scheme for the loss of economic opportunity.

At the global scale, tropical forest endowed countries could form a "biodiversity cartel" in order to capture more rent from the conservation of biodiversity. The simple monopolistic outcome would of course provide less conservation than the oligopolistic one, but the cartel members could practice price discrimination in order to capture an even greater rent and at the same time provide more biodiversity. Different nations may have different willingnesses to pay for the biological diversity conservation, and tropical nations could take advantage of it. Demanding nations could also be modeled as oligopsonistic



demanders in a strategic game. They could also be modeled as a cartel. Many further extensions of model 1 can thus be thought of and solved for in order to get some further insights for policy making.

Model 2 provided a very interesting result when a monopolistic rent can be captured for a given valuable species. The private equilibrium and social optimum then coincide. This is a surprising result, especially given that the supply side is constituted of oligopolists providing a non-rival good. This model, however, assumes perfect knowledge of the existing species and its expected value. In reality, there exists a lot of uncertainty and possibly even asymmetric information. Also, the demand side of the pharmaceutical genetic prospecting market consists of an oligopsony - the pharmaceutical industry. More complex models could include multiple demanders of different species. Imperfect information could also be modeled with a sequential search function, where a pharmaceutical firm stops searching as soon as it has found the lead it was looking for. Still, the result found here is interesting enough that it should be kept in mind in future modeling. It basically tells us that if a decision-maker knows that a valuable species is on her land, she has the socially optimal incentives to conserve it. Future research could extend this model in order to investigate if this optimal result is likely to occur in reality. This model and its potential extensions could lead to interesting conclusions for the pharmaceutical industry and tropical countries where many species are believed to have option value in medicine. As was said, the assumption of perfect information does not make this model realistic, but the result is important enough to warrant extensions of the model to cases with incomplete information and interactions between decision-makers and

the pharmaceutical industries. A market structure could possibly be invented for genetic resources that would make the private and social incentives coincide, as in this simple model. The UN Convention on Biological Diversity offers some incentives for conservation of tropical genetic resources by allowing property rights to be recognized on genetic material. Otherwise, nation-states would not, and did not in the past, take the global value of their genetic resources into account in their decision-making process, as in model 2.A. Model 2.C reveals that imperfect substitutability will trigger too much conservation from society's point of view. This can be taken into account in further modeling by allowing a minimum of redundancy in the material screened by pharmaceutical firms. In effect, the high costs of screening is likely to prevent these firms from redundant screening. However, these considerations go beyond model 2 and will need to be modeled separately in order to derive any conclusion from these ideas. The dynamic model 2.D revealed a slight dynamic externality, and comparison with real world data will be needed in order to appreciate its importance. Also, the discount rates used in the numerical example are all equal, but this is unlikely to happen in reality. The model ought to be computerized in order to conduct sensitivity analyses with respect to the discount rates as well as other parameters. Further modeling should try to elicit the equilibrium and optimal solutions as the number of stages tends to infinity. A different model could also be developed in order to understand the dynamics of irreversible land conversion. In model 2.D, it is assumed that the forest grows back at every stage, while tropical forests are known to go through irreversible conversion to other land uses due to

the mediocre regeneration capacity of their soils. It is more difficult to model but could result in interesting insights for the case of tropical rainforests.

For all the models above, more advanced game theoretic modeling can also be done in order to take into account the possibility and likely occurrence of incomplete and asymmetrically distributed information, as well as learning games.

It is important to add, however, that conservation issues are also influenced by general equilibrium consequences that have not been modeled here. Economic activities have multiplier effects in society, and the substitution of conservation for economic activities is likely to have substantial effects, at least locally, where communities are asked to adjust. These effects need to be taken into consideration when elaborating policies in order to approach Pareto improvements and avoid social tensions. The models developed in this thesis suggest the proper welfare comparisons when there are no income effects and no price effects across markets. If income effects or price effects across markets occur, there could be a path dependency problem making welfare comparisons more involved than in the cases presented here. One also needs to be careful in aggregating welfare measures across harvesting and conservation markets. It is necessary to use the same level of quantities and values for both activities: primary, intermediate or final good. The same caution needs to be taken with aggregation across producer and consumer surplus.

The partial equilibrium models developed in this thesis thus revealed interesting information about the economic incentives for the conservation of biodiversity with multiple decision-makers, but further modeling is needed to derive specific policies that will insure that the optimal outcome occurs.

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