THREE ESSAYS ON ENVIRONMENTAL AND NATURAL RESOURCE MANAGEMENT AND POLICY

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Abstract

The theory of games can be applied to many resource and environmental problems. Cooperative games are relevant to situations such as fishery agreements, whereby parties can increase both individual and total welfare and resource stock levels. However, in other cases, illegal activity as a result of imperfect monitoring may prevent cooperation from taking place, and thus a non-cooperative modelling is necessary. While maintaining the common element of game theory throughout, this thesis covers both of these situations, as well as the case where a government is strategically regulating a resource-using industry (the pharmaceutical or biotechnology industry) to satisfy its own conservation objectives. In the fishery contract chapter, cooperation regarding a shared (or transboundary) fish stock is modelled, accounting for both differences in breakdown (or non-cooperative) payoffs between the two players and the possibility that one (or both) players may be faced with incentives to conserve the stock independently of the present and future profits earned from direct harvesting. The former may be the consequence of a cost, accessibility, or geographic advantage, whereby the breakdown payoff (or "threat-point") becomes the starting point of negotiations for a cooperative agreement. The latter, often termed a "non-use" value, may result from some traditional, cultural, political, ideological or moral obligation, or may be linked to other factors such as the reliance of the population of a region on the stock in question, and potentially removes extinction from the optimal extrac-

tion set without relying on very low discount rates (which simply convey a player's willingness to trade-off present profits for future profits). Under the assumption that the parties negotiate a subgame perfect, or dynamically consistent, contract (as opposed to a binding contract), so that there is no incentive for either player to deviate from its negotiated harvest and share, outcomes which differ substantially from those previously found are possible.

Illegal activity (or poaching) is particularly relevant to endangered species protection and management, which is the concern of the following chapter. A sequential game is presented, whereby the government sets its own legal harvest quota and chooses its enforcement expenditure prior to the decisions of individual poachers so that incentives to poach are influenced by the conditions of the market (especially the output price) and the probability of being caught. In equilibrium, the manager manipulates these incentives, knowing the reaction of individual and total poaching, to maximize the legal return from harvesting net of enforcement costs or to maximize a combination of net legal returns and the stock level (to incorporate non-use values as in the fishery agreement chapter). Further, this specification permits the examination of the impact of a ban on legal harvesting on total poaching harvests, stock levels, and enforcement. Under the assumption of limited entry of poachers, the first move of the government makes it possible to completely deter poaching in equilibrium if there is a cost advantage on the part of legal harvesters or enforcement is sufficiently effective and the punishment very high. Trade bans increase stock levels at the expense of reduced profits, and further, reduce the value of the government objective function, suggesting that trade bans may be imposed externally on harvesting countries by foreign nations which contain individuals who hold non-use values for the resource in organizations such as the Convention on International Trade in

Endangered Species of Flora and Fauna (*CITES*).

The final chapter examines the interaction between the government, which has to finance its own endangered species or biodiversity conservation costs, and a firm, which uses species (in a non-destructive way) to find products which can be sold to consumers. The firm is said to be "bioprospecting," that is, searching for successful pharmaceuticals or biotechnology, maximizing expected profits given the costs of sampling species and the incentives (or disincentives) provided by the government. As in the endangered species chapter, the government choices are given prior to the decisions of the firm. The sampling of natural species is assumed to provide information to the firm which increases the probability of finding a commercially valuable product, although the firm can also observe part of the information set of other firms (and vice versa) and some information becomes obsolete over time. This specification permits the examination of the accumulation of information (or knowledge) derived from the sampling of natural species over time in an infinite-horizon model. As the information of other firms cannot be observed at each point in time and consequently less information is gathered and fewer species sampled than under perfect information, there is the potential for the government to correct this informational externality by subsidizing species sampling. At the same time, the government desires to extract the surplus generated by firms, and the choice of lump-sum fees each period are shown to be superior instruments to shares of the profits from successful products (royalties), which tend to reduce sampling below the socially optimal rate. Employing the results of the theoretical model and data from the literature, it is concluded that biodiversity prospecting may not be as poor of a conservation financing tool as suggested in previous studies.

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Contents

List of Tables

List of Figures

Chapter 1

Overview

Within the scope of emphasis in natural resource and environmental economics are two broad problems common to most, if not all, economics in general: how to manage a particular scarce resource (or set of resources) and how agents interact to achieve a particular outcome. Natural and environmental resources are fraught with externalities and public goods, making these issues even more vital in the examination of market equilibria and public choice. Nonetheless, the two problems are highly interrelated, as proper management of resources requires an understanding of how users will react to management policies. The theory of games has often been used to illuminate these issues throughout economics. This thesis concerns the application of game theory to resource and environmental problems, including both cooperative and non-cooperative situations. Cooperation has previously been shown, in many different circumstances, to be superior to non-cooperation in both total welfare and resource stock levels, which is of particular relevance to cases where agreements are being contemplated such as the renewable resource (for example, fishery) management game detailed in Chapter 2. However, in other situations, it is not wise to consider cooperation as the likely outcome of a management conflict. One of the most obvious cases is examined in Chapter 3, where a resource manager (such as the government) is faced with illegal supply (from poachers of endangered or other valuable species). If it was possible to identify specific agents which illegally harvest, a properly chosen punishment would be sufficient to achieve the first-best social optimum. In reality, monitoring costs and ineffectiveness eliminate the possibility of identifying potential cooperators and consequently remove the potential of welfare enhancing cooperative efforts. Chapter 4 can best be described as a hybrid of cooperation and non-cooperation, where a government attempts to induce firms searching for successful products among natural substances or species to choose the socially optimal level of sampling (and thus expected successful products) by manipulating incentives to search, but at the same time chooses across policy instruments to extract as much surplus as possible to finance its own conservation costs.

In Chapter 2, cooperation regarding a shared (or transboundary) fish stock is modelled, accounting for both differences in breakdown (or non-cooperative) payoffs between the two players (denoted the Home and Foreign) and the possibility that one (or both) players may be faced with incentives to conserve the stock independently of the present and future profits earned from direct harvesting. The former may be the consequence of a cost, accessibility, or geographic advantage, whereby the breakdown payoff (or "threat-point") becomes the starting point of negotiations for a cooperative agreement. The latter, often termed a "non-use" value, may result from some traditional, cultural, political, ideological or moral obligation, or may be linked to other factors such as the reliance of the population of a region on the stock in question, and potentially removes extinction from the optimal extraction set without relying on very low discount rates (which simply convey a player's willingness to trade-off present profits for future profits). Under the assumption that the parties negotiate a subgame perfect, or dynamically consistent, contract (as opposed to a binding contract), so that there is no incentive for either player to deviate from its negotiated harvest and share, outcomes which differ substantially from those previously examined (Munro, Vislie, etc.) are possible, and in some cases, probable. For example, a greater emphasis placed on conservation by one player results in that player foregoing a larger share of the total harvest to induce its rival to accept a lower total harvest (and thus a higher stock level), a result which holds independently of threat-point positions and of whether one or both players hold non-use values.

The situation of concern in Chapter 3 contains some elements similar to the fishery game of Chapter 2, but deals with the case where one party is unable to negotiate a cooperative agreement with other(s), as the latter is engaged in an illegal activity. To demonstrate the interactions between the regulator or resource manager (the government) and the group of illegal harvesters (the poachers), the dynamics are ignored for the most part, until introduced in later sections. A sequential game is presented, whereby the government sets its own legal harvest quota and chooses its enforcement expenditure prior to the decisions of individual poachers so that incentives to poach are influenced by the conditions of the market (especially the output price) and the probability of being caught. In equilibrium, the manager manipulates these incentives, knowing the reaction of individual and total poaching, to maximize the legal return from harvesting net of enforcement costs or to maximize a combination of net legal returns and the stock level (to incorporate non-use values as in Chapter 2). Further, this specification permits the examination of the impact of a ban on legal harvesting on total poaching harvests, stock levels, and enforcement. Under the assumption of limited entry of poachers, the first move of the government makes it possible to completely deter poaching in equilibrium if there is a cost advantage on the part of legal harvesters or enforcement is sufficiently effective and the punishment very high. Trade bans increase stock levels at the expense of reduced profits, and further, reduce the value of the government objective function (if the legal pre-ban quota was positive), suggesting that trade bans may be imposed externally on harvesting countries by foreign nations which contain individuals who hold non-use values for the resource in organizations such as the Convention on International Trade in Endangered Species of Flora and Fauna (*CITES*).

Chapter 4 examines the interaction between the government, which has to finance its own species or biodiversity conservation costs, and a firm, which uses species (in a non-destructive way) to find products which can be sold to consumers. The firm is said to be "bioprospecting," that is, searching for successful pharmaceuticals or biotechnology, maximizing expected profits given the costs of sampling species and the incentives (or disincentives) provided by the government. As in Chapter 3, the government choices are given prior to the decisions of the firm. The sampling of natural species is assumed to provide information to the firm which increases the probability of finding a commercially valuable product, although some information becomes obsolete over time. This specification permits the examination of the accumulation of information (or knowledge) derived from the sampling of natural species over time in an infinite-horizon model. As the information of other firms cannot be observed at each point in time and consequently less information is gathered and fewer species sampled than under perfect information, there is the potential for the government to correct this informational externality by subsidizing species sampling. At the same time, the government desires to extract the surplus generated by firms, and the choice of lump-sum fees each period are shown to be superior instruments to shares of the profits from successful products (royalties), which tend to reduce sampling below the socially optimal rate. Employing the results of the theoretical model and data from the literature, it is concluded that biodiversity prospecting may not be as poor of a conservation financing tool as suggested in previous studies.

All three chapters have the common element of dynamics, at least to some extent. Both Chapter 2 and Chapter 4 have multiple periods, each with a single stage in each period (that is, both are simultaneous dynamic games). Chapter 3 primarily deals with a single period, multi-stage game (that is, a sequential game), although multiple periods are introduced at one point. Multiple periods are relevant in each case to incorporate intertemporal stock effects and accumulation dynamics which generally have a profound effect on appropriate management policy. Each model attempts to rely on simplicity and reasonable, justifiable assumptions of payoffs and strategies, following *Occam's Razor*, where "entities should not multiply beyond necessity." The objective in each case is to model behaviour related to natural resource management in a straightforward and realistic way in order to suggest feasible solutions to important questions, without obscuring the underlying assumptions. In summary, the Chapter 2 concerns cooperative modelling of a renewable resource (such as a fish stock), allowing for the possibility that agents (here countries) will deviate from a negotiated outcome if it is in their best interests to do so, and considering non-linear objectives of at least one agent. Chapter 3 examines an alternate case, applied to endangered species management, where a resource manager (government) can preempt some (or all) illegal poaching through its own choice of legal harvest (or quota) and expenditure on enforcement. The last chapter deals with two simultaneous objectives of a biological diversity managing government: to provide incentives to induce firms to select the socially optimal rate of sampling over time while extracting surplus of firms to finance its own conservation costs.

Chapter 2

A Dynamic Cooperative Game of Transboundary Renewable Resource Management with Non-Use Values

2.1 Introduction and Literature

Open or free access to scarce natural resources undoubtedly leads to economic inefficiency from two sources. The first arises from the sheer numbers of users, as profit-maximizing total harvests increase as the number of users grows, to a maximum in a perfectly competitive industry. Further, individuals or firms lack incentives to conserve the resource stock, given that it is then impossible to preclude other from its use (and destruction). Without the assignment of specific property rights over a private good resource, any stock left unexploited by one user for future use will not necessarily be in that user's best interest due to the possibility the unexploited stock may be removed by other users. Thus, the lack of distinct ownership not only has negative consequences for the resource stock level at each point in time, but also provides incentives to deplete the stock in the present as opposed to leaving part of the stock for future use (Plourde, 1999). Many resources have been open access at some point in the past, and the consequent inefficiencies have typically lead to the creation of international property rights, usually given to countries containing or nearby the resource stock. One common example is the 200-mile Exclusive Economic Zone around nations established by the United Nations Law of the Sea in 1977. When a resource stock, such as a fishery, is not entirely contained within the jurisdiction of a single owner, there is potential for conflict (whether passive or active), which can be modelled as a non-cooperative game as in Plourde and Yeung (1989) or Levhari and Mirman (1980), or can be cooperatively managed. Plourde and Yeung show that the joint exploitation of a fish stock will result in lower total fishing effort and a higher steady-state stock level relative to the non-cooperative solution, suggesting that the "players" should prefer cooperation as long as transaction costs are not prohibitively high. Cooperation can take many forms, but it is most realistic to assume that each party is self-interested and negotiates an agreement which makes them better off than without a contract, and so that some form of conflict remains in terms of bargaining among the players of the "cooperative game." One example of such as situation is a transboundary resource stock, where either straddles the boundary between one jurisdiction and another (including across the boundary of the Exclusive Economic Zone of one country into that of another or across the EEZ of one country and the adjacent open sea), or concerns a stock which is highly migratory and resides in more than one jurisdiction over the course of a year. As examples from world fisheries, the original United Nations Law of the Sea of 1982 failed to address transboundary fisheries, but since the later UN Law of the Sea of 1995, "straddling stocks" and highly migratory fish stocks have been recognized as issues managed by international organizations and frequent agreements have been made within organizations such as the UN, North Atlantic Fishery Organization (NAFO), and International Commission for the Northwest Atlantic Fishery (ICNAF).

This section will outline the cooperative renewable resource game literature to date, focussing primarily on a seminal article by Munro (1979) and its extensions Vislie (1987), Ferrara and Missios (1996), and Missios and Plourde (1997), relative to the non-cooperative resource game literature, and will identify the situation of this chapter within this literature. As noted by Plourde (1999), there are two distinct branches of the cooperative fishery literature, the first being that parties (or nations) negotiate binding contracts, and the second that this is not possible and contracts must be dynamically consistent through subgame perfection (or backward-induction). Munro and Missios and Plourde both fall into the first category, while Vislie, Ferrara and Missios and this chapter fall into the second. Within these two branches, there are also two treatments of risk aversion: Munro, Vislie, and Ferrara and Missios maximize discounted profits, and so utilize a linear objective if unit harvesting costs are constant (risk neutrality), while Missios and Plourde and this chapter suggest non-linear objectives. Risk arises in these models as a result of the threat of a breakdown of the cooperative solution.

Munro was one of the first to model cooperative fishery management agreements, covering several aspects and assumptions of the issue, with two players/nations and an infinite time horizon. As mentioned above, contracts are assumed to be binding, so that parties will not deviate from their negotiated share, although there may exist incentives to do so (this can be achieved by perfect monitoring and a sufficiently high punishment).[1] In the event of a breakdown of the contract, the game is presumed to revert to a bionomic equilibrium (that is, a perfectly competitive long-run market

[1] Kaitala and Pohjola (1988) explicitly extend Munro's model to allow for monitoring, but instead of a monetary punishment for a violation, the game reverts to the non-cooperative outcome. Instead of one-time (side-payment) transfers, the authors also suggest harvest shares.

equilibrium with the resource stock at its steady-state level), but is more realistically assumed by later authors to be the outcome of a non-cooperative game between the two players. For part of the paper, the harvest shares of the two countries are given and time invariant, and the agreement maximizes an objective incorporating the present value of profits for each country, weighted by a bargaining parameter. This bargaining parameter is given by the solution of the (symmetric) Nash product of the countries' gains from cooperation (that is, the payoff under cooperation less the payoff under non-cooperation, or default payoff). Plourde notes that this specification is controversial in the sense that differing bargaining abilities should result in a *non-symmetric* Nash solution, whereby the gains from cooperation are skewed toward the nation with the bargaining advantage. As long as the bargaining abilities of the two nations are the same, Munro's specification is appropriate, and the result that the less future-oriented (high discount rate) country will harvest in the present while the more future-oriented country will harvest later follows. In later sections of the paper, the harvest shares are permitted to vary between zero and unity, and for particular ranges of the bargaining parameter, will lead to one extreme value or the other (corner solutions), implying that one country (the 'better' bargainer) will perform all of the harvesting and the other will never harvest. This necessitates a side-payment from the sole harvester to the other in order to induce the non-harvester to select the agreement over the default (non-cooperative) payoff. These so-called "bang-bang" solutions of this type are a result of linearity assumptions in the model, and later papers have proposed other objectives to remove this over-simplifying restriction, including Missios and Plourde and the model of this chapter.

In studies such as Munro and others, discount rates have typically been employed to compare differences in countries' views on conservation, as low discount rates imply a greater emphasis on future returns, so that countries with such rates would prefer to harvest more in the future than higher discount rate countries and would therefore be more "conservationist." While this view may in part describe this motivation, clearly other social, political and moral reasons for conservation exist. Observation suggests that some countries are interested in conservation of fish stocks for reasons other than future profit, and frequently, the countries which are more conservative have some vested interest in conservation of a particular fish stock itself (as in the case where a country has a significant domestic industry which is dependent on that fish stock). Often, the more conservationist country borders on the resource and may have a fishing fleet suitable for fishing close to home but unsuitable for global harvesting, so that the survival of the fish stock is vital to the industry. A foreign country fishing fleet usually has alternative fishing possibilities so that depletion of a particular stock is of less consequence, and therefore may have an incentive to ignore the conservation of the resource and move on to other areas. Accordingly, Missios and Plourde extend the specification of Munro to the case where one country has a "conservation motive," preferring a higher stock independently of the level of the harvest, and another country, the foreign country, which has no such motive, and thus is simply concerned with a discounted flow of profits derived from the harvest. The paper is concerned about the negotiated total harvest and consequent steady-state stock levels, and ignores the division between the two countries. The presence of a conservation motive serves to increase the steady state fish stock level, as do increases in the negotiated share of the country holding such a motive, which is taken as given from a previous stage of bargaining.

Vislie relaxes the restrictive requirement that countries are bound to their negotiated shares, using a two-period variation of Munro's model and solving the model by backward induction for subgame perfection (that is, the Nash bargaining solution holds in each period). When countries differ only by discount rates, the total harvest will be shared equally in the second (and final) period and the low discount rate country (which is more forward looking) will receive a share less than fifty percent in the first period in order to induce a larger second period stock and harvest. However, Vislie assumes that the payoffs to each player in the event of a breakdown of the cooperative agreement are identical, essentially providing each side with equal bargaining power as the default or threat-point is the same for each, even if there are differences between the two players such as a harvesting cost advantage for one. Since it is normally assumed that the parties revert to a non-cooperative situation in the event of a breakdown, this cannot be the case, since Levhari and Mirman, Plourde and Yeung and others show that the non-cooperative outcome will depend on several factors, and should be equivalent only if the two parties are identical. For example, Plourde and Yeung examine closed-loop feedback Nash equilibria over a finite time horizon,[2] finding a feedback strategy solution which depends on the agent's discount rate and the net natural mortality rate of the stock. Joint maximization is shown to result in lower total fishing effort and a higher steady-state stock size, and countries with higher discount rates will select larger harvests. Levhari and Mirman use a infinite-horizon dynamic Cournot-Nash model, employing discrete time dynamic programming.[3] Each of the two players acts as a Cournot duopolist, maximizing a non-linear objective (utility) taking the choice of its rival as given. An extension is also provided with a leader-follower structure, where one country is "sophisticated"

[2]Closed-loop strategies depend not only on time but on the remaining stock, as opposed to open-loop strategies which vary only over time.

[3]It should be noted that the resulting closed-form Cournot-Nash solution of Levhari and Mirman may not be a steady-state, implying that the solution presented could represent a fish population which is out of equilibrium in a dynamic sense.

(accounts for the ability to manipulate its rivals' harvest) and the other is "naive" (takes its rivals' harvest as given, as in Cournot). Extinction is a distinct possibility under non-cooperation but is shown to be impossible in their framework for a cooperative regime, and differences in various factors will result in different harvest levels for the rivals, at the same point in time.

As a consequence of the previous findings of varying harvests under non-cooperation, the issue of differing breakdown positions was originally addressed in my previous work (Ferrara and Missios) by allowing for differences in the threat-points or default positions of the two parties, within a modified framework of Munro and Vislie. The treatment in this chapter considers and compares the two possibilities, although it should be kept in mind that the identical threat-point solution is simply a special case of the (potentially) differing threat-point solution. Conservation motives are also incorporated in this analysis, providing a unification of the various theories within the subgame perfect renewable resource (fishery) literature.

2.2 Example: The Canada-European Union Turbot Dispute

In early 1995, a "fish war," which gained considerable public attention, erupted between Canada and the European Union (EU) over turbot, also known as the Greenland halibut. The conflict arose from Spanish and Portuguese alleged overfishing in the area off the coast of Canada but outside the two hundred nautical mile limit on the Grand Banks of Newfoundland. To justify its overfishing above the quota set by the fifteen-country North Atlantic Fishery Organization (NAFO), the European Union cited the persistent low Canadian share of the turbot caught as an indication of excessively high quotas set for Canada. In contrast, Canada claimed that its low catch share was the immediate consequence of the continued overfishing by the European Union and other NAFO members.

The dispute has only recently come to an end, with Canada and the European Union agreeing on a total allowable catch for 1996 of 20,000 tonnes, approximately 26% lower than that set by NAFO for 1995, and on their respective catch shares of 15% and 55%. While the total allowable catch limits have followed a downward trend in previous years, from over 100,000 tonnes in 1989 to just 20,000 tonnes in 1996, the catch shares have undergone a drastic change, as in the past Canada would typically be granted more than fifty percent of the total allowable catch, and the European Union would consequently receive less than fifty percent. The steady decline of the total allowable catch is likely a consequence of the significant decrease of turbot stocks in recent years to dangerous levels. In fact, even though estimates of the stock size of turbot vary substantially, most conform to the view that turbot could face extinction if the overfishing of the 1980s and early 1990s were to continue.

That greater emphasis on the conservation of turbot has induced NAFO to set a lower total allowable catch for 1996 is consistent with the prediction of the infinite-horizon model developed by Missios and Plourde, in which the steady state total allowable harvest is chosen as to maximize the sum of the two countries objective functionals subject to the relevant constraints. The driving force of their model is the assumption that one of the two countries, denoted the Home country and identified with Canada in the turbot war, has a non-pecuniary incentive to conserve the fish stock in addition to being profit-maximizing, and thus receives benefits from both the harvest and the level of the fish stock. From the continuous time specification of the model, though, a detailed analysis of the sharing rule becomes impossible. Prior to this study, the extent of countries conservation attitudes has been measured by the magnitude of discount factors; specifically, higher discount factors, implying greater emphasis on the future, have been taken to be equivalent to more conservationist positions. However, discount factors merely represent countries' willingness to trade present profit for future profit, so their relatively high levels are necessary but not sufficient to prevent optimal extinction in a finite-horizon setup. On the other hand, if countries derive a non-use value (that is, a value derived neither from direct nor indirect use of the resource stock) from the resource, then reasons of a social, political, ideological, or moral nature exist to conserve the fish stock and extinction is no longer possible as an optimal outcome, given that countries are now utility-maximizing and their utility is not independent of the level of the fish stock. The prime examples of these non-use values are known in the literature as existence value, which refers to preservation for its own sake, and bequest value, which refers to conservation for future generations' use (see Krutilla, 1967). Bishop and Welsh (1992) find evidence that existence values likely exist for species which are obscure or even unknown. Non-use values provide an additional incentive to leave part of the resource stock unharvested (beyond the inter-temporal profit-maximization and cost-savings incentives), applying even in the final period in a finite horizon when other profit-based incentives disappear. The existence of a non-use value for at least one country is important not only in the determination of optimal harvests, as Missios and Plourde show, but also in that of catch shares.[4]

In the following sections of this chapter, we address the harvest division issue in a two-period model of the type proposed by Vislie and extended by Ferrara and Missios, and derive a subgame perfect contract between two countries, at least one

[4] By assuming that the catch shares are determined prior to the negotiation of the total allowable catch, Missios and Plourde do not need to consider the question of how the harvest is divided between the two countries.

of which is assumed to receive a non-use benefit from the stock. Like Missios and Plourde, we find that the harvest or total allowable catch is smaller compared to that of the benchmark case in which neither of the countries receives a non-use value; furthermore, we show that the harvest share of the country with such a motive is less than fifty percent in both periods, a result which is consistent with NAFO's decision to assign Canada only 15% of the total allowable catch for 1996.

2.3 The Model

We consider two countries, denoted the Home country and the Foreign country, which are engaged in a two-period exploitation of a transboundary renewable natural resource, such as fish, and which (in the absence of reliable enforcement mechanisms) need to design a contract specifying both the total allowable catches and the sharing rules that neither party has any incentive to breach. For the sake of exposition, we assume that the two countries face a world demand for harvested fish that is infinitely elastic, implying a parametric price, p,[5] and an identical constant unit cost of extraction, c.[6] In a bargaining situation where the agreement is negotiated at the beginning of the first period, the two countries maximize the product of their individual gains from cooperation, subject to the relevant constraints, and obtain dynamic consistency (or subgame-perfection) by incorporating into the two-period Nash-product the op-

[5]This assumption, made by both Munro (1979) and Vislie, removes the "market" externality associated with the impact of management decisions on the price, leaving only the dynamic or stock externality associated with the effects of the same decisions on the fish biomass.

[6]The assumption of a constant extraction cost, as opposed to a cost decreasing in the level of the fish stock, will have no impact on the sharing rule in either period. Although a stock-dependent cost would lower the harvest in the first period because of the "marginal stock effect" developed by Clark (1976), by which additional fish are left unharvested in order to decrease the future harvesting cost, our conclusions regarding the impact of non-use values under both equal and differing no-agreement payoffs will remain unchanged.

timal second-period catch shares.[7] This yields a solution which is Pareto-optimal so that making one country better off must be done so at the expense of the other country[8] and is subgame perfect if the decisions made in the second-period are recognized in the first, implying that there is no incentive for either country to deviate from its negotiated harvest quota in either period.

Here we will initially consider the general case in which the payoffs without cooperation are not necessarily equal as a result of one country's proximity to the resource, presumably the case of the Canada-European Union turbot dispute.[9]. We define B_t^H, and B_t^F as the no-agreement payoffs in period t, and B^H and B^F as the two-period discounted no-agreement payoffs, of the Home country and Foreign country.

The Home country is assumed to hold a non-use value and thus benefits from both the harvest and the fish left unharvested, so that its objective functional is

$$W^H = V(x_1) + \alpha_1(p-c)h_1 + \delta_H[V(x_2) + \alpha_2(p-c)h_2], \qquad (2.1)$$

where x_t , α_t , and h_t are the fish biomass, the Home country's share, and the total harvest in period t, respectively, and $\delta_H = \frac{1}{1+r^H}$ is the Home country's discount factor,[10] and where $V'(x_t) > 0$ and $V''(x_t) \leq 0$. On the other hand, the Foreign country does not receive utility from the level of the fish stock and therefore remains

[7]The Nash-product is the product of the net benefits from cooperation to each country, and the two-period Nash-product is simply the product of present values of the net benefits from cooperation.

[8]Nash (1953) demonstrated that the maximization of the Nash-product yields the only solution that satisfies the axioms of feasibility, independence of irrelevant alternatives, rationality, and symmetry, in addition to Pareto-optimality.

[9]For example, the European Union can only employ "offshore" technologies that must incorporate both the harvesting and the processing (e.g., canning and freezing) of the fish caught.

[10]It is possible for the Home country to discount profits and utility at different rates. In particular, utility is sometimes discounted at the rate of "impatience" and profits at the appropriate rate of interest. While the former refers to preferences, the latter refers to opportunities. See Silberberg (1990), 419-426. Here, we assume that these two rates coincide.

purely profit-oriented, so that its objective functional is

$$W^F = (1-\alpha_1)(p-c)h_1 + \delta_F(1-\alpha_2)(p-c)h_2, \tag{2.2}$$

where δ_F is the Foreign country's discount factor. The two countries therefore choose the total harvest and sharing rule for both periods by maximizing the two-period Nash-product,

$$\{V(x_1) + \alpha_1(p-c)h_1 + \delta_H[V(x_2) + \alpha_2(p-c)h_2] \tag{2.3}$$

$$-B^H\}\{(1-\alpha_1)(p-c)h_1 + +\delta_F(1-\alpha_2)(p-c)h_2 - B^F\}, \tag{2.4}$$

such that

$$0 \leq \alpha_t \leq 1, \tag{2.5}$$

$$0 \leq h_t \leq h_{MAX}, \tag{2.6}$$

and

$$x_t = x_{t-1} + F(x_{t-1}) - h_t \geq 0. \tag{2.7}$$

where h_{MAX} is determined by economic catch constraints, and $F(x_{t-1})$ is the biomass growth function. Since the countries seek a dynamically-consistent contract, they need to take into account the second-period harvest and sharing rule which maximize the second-period Nash-product,

$$[V(x_2) + \alpha_2(p-c)h_2 - B_2^H][(1-\alpha_2)(p-c)h_2 - B_2^F], \tag{2.8}$$

subject to the above constraints for $t = 2$, when choosing the first-period harvest and catch shares.

The constrained maximization of (2.8) with respect to α_2 yields

$$\alpha_2 = \frac{1}{2} + \frac{(B_2^H - B_2^F) - V(x_2)}{2(p-c)h_2}, \tag{2.9}$$

and with respect to h_2 upon substitution for α_2 from (2.9) yields

$$p - c = V'(x_2), \tag{2.10}$$

which states that the marginal benefit from harvesting, i.e., the constant average profit from the harvest, must be equated to the second-period marginal benefit the Home country receives from leaving the fish unharvested. Only if the agreed-upon first-period harvest and catch shares are such that this condition is satisfied in the second period will the two-period contract be subgame perfect.

For the first period, the sharing rule and total harvest must satisfy

$$W^H - B^H = W^F - B^F, \tag{2.11}$$

or

$$V(x_1) + (2\alpha_1 - 1)(p-c)h_1 + \frac{\delta_H - \delta_F}{2}[V(x_2) + (p-c)h_2] - (B^H - B^F) = 0, \tag{2.12}$$

and

$$\{-V'(x_1) + \alpha_1(p-c) + \frac{\delta_H}{2}[V'(x_2)\frac{\partial x_2}{\partial h_1} + (p-c)\frac{\partial h_2}{\partial h_1}]\}[W^F - B^F]$$
$$+\{(1-\alpha_1)(p-c) + \frac{\delta_F}{2}[V'(x_2)\frac{\partial x_2}{\partial h_1} + (p-c)\frac{\partial h_2}{\partial h_1}]\}[W^H - W^H] = 0. \tag{2.13}$$

Rearranging (2.12), we obtain that

$$\alpha_1 = \frac{1}{2} - \frac{V(x_1)}{2(p-c)h_1} - \frac{(\delta_H - \delta_F)[h_2(p-c) + V(x_2)]}{4(p-c)h_1} \tag{2.14}$$
$$+\frac{[(B^H - B^F) - \frac{(\delta_H+\delta_F)}{2}(B_2^H - B_2^F)]}{2(p-c)h_1}. \tag{2.15}$$

Manipulating (2.13) and using (2.10), (2.11), and $\partial x_2/\partial h_1 + \partial h_2/\partial h_1 = -[1+F'(x_1)]$, we have that

$$V'(x_1) - (p-c) + \frac{(\delta_H + \delta_F)}{2}[1 + F'(x_1)](p-c) = 0. \tag{2.16}$$

By (2.10) and (2.16) we confirm the result obtained by Ferrara and Missios that the assumption of differing default payoffs has no impact on the choices of the optimal first- and second-period harvests; in other words, the second-period harvest maximizing the second-period Nash-product and the first-period harvest maximizing the two-period Nash-product are independent of the corresponding no-agreement payoffs. However, the assumption does have an effect on the choices of the optimal first- and second-period sharing rule; as indicated by (2.9) and (2.15), α_2 is positively related to the difference between the Home country's second-period breakdown payoff and that of the Foreign country, and α_1 is positively related to the average "perceived value" of the first-period no-agreement payoff differential.[11] On the other hand, a non-use value on the part of the Home country affects not only the sharing rule but also the harvest choice. In particular, it reduces α_2, may increase or decrease α_1, depending on the difference between the two countries' discount factors,[12] and serves to increase the fish stock levels, and thus decrease the harvests, in both periods by the concavity of the growth function.

If the Foreign country receives a higher payoff under non-cooperation than the Home country in each period, that is, $B_i^H < B_i^F$, for $i = 1, 2$, α_2 is unambiguously less than one half, given that both the differential and the benefit to the Home country from the second-period fish stock left unharvested work in the same direction to increase the bargaining power of the Foreign country. In other words, the Home country is willing to accept a lower second-period catch share in return for a lower

[11] The numerator of the fourth term on the right-hand-side of (13) is one-half of the sum of the first-period non-cooperative payoff differential discounted by δ_H and the same differential but discounted by δ_F.

[12] The derivative of α_1 with respect to the difference between δ_H and δ_F is negative; in fact, if the Home country is more future-oriented and thus willing to accept a lower harvest today for a larger one tomorrow, then it has to compensate the Foreign country with a higher current catch share.

harvest, and thus a higher fish stock; further, for an agreed upon harvest, the Home country has to accept an even lower share because of the Foreign country's better default position.[13] In the first period, the Home country is to receive a share less than one half, again provided that the Foreign country is not significantly more future-oriented, or that $\delta_F \gg \delta_H$, for the same reasons as discussed above. The result that α_2 and α_1 are both less than one half holds as well for the identical breakdown payoff case, or $B_i^H = B_i^F$, for $i = 1, 2$.

For $B_H > B_F$, whether the former agrees to a catch of less than fifty percent of the total harvest in the second period depends on the magnitude of the second-period default payoff differential relative to the benefit the Home country receives from the fish left unharvested. As intuition suggests and (2.9) confirms, the larger the differential is relative to the benefit, a benefit which in turn depends on the strength of the conservation commitment, the more likely the Home country must receive more than fifty percent of the second-period harvest to conform to the agreement. Similarly, under the assumption that the two countries have identical discount factors, the Home country agrees to a first-period catch share less than one-half if the first-period average breakdown payoff differential is less than the benefit from the fish stock at the end of the same period. On the other hand, if the discount factors differ, and, in particular, if $\delta_H > \delta_F$, implying that the Home country places more emphasis on the future, a dynamically consistent settlement between the two countries has to assign the more future- and conservation-oriented country more than fifty percent of the first-period total catch if

$$\frac{(\delta_H - \delta_F)}{2}[(p-c)h_2 + V(x_2)] + V(x_1) < B^H - B^F - \frac{(\delta_H + \delta_F)}{2}(B_2^H - B_2^F), \quad (2.17)$$

[13] In Munro (1979), compensation is made through explicit "side-payments," although the need for such compensation arises from differences in discount factors, fishing effort costs, and/or consumer preferences.

that is, if the sum of the average social net benefit from the Home country's higher discount factor and the benefit from the first-period fish biomass is smaller than the average perceived value of the first-period no-agreement payoff differential. The result is again intuitive, as the Home country bargaining power is positively related to its relative non-cooperative advantage over the Foreign country, but negatively to the benefit from the fish stock and the discount factor differential. Clearly, the more favorable default position the Home country enjoys serves to increase its catch shares in both periods. However, while in the absence of the non-use value the Home country must receive a harvest share greater than fifty percent in the second period and, under the assumption of identical discount factors, in the first period,[14] here it is still possible for the country to agree upon a share smaller than fifty percent if its utility from the fish biomass is greater than the non-cooperative payoff differential. In summary then, there is a fish stock remaining after the second period whenever one country places an existence value on the biomass stock level.

Returning to the previously mentioned example, the results that the first-period harvest is smaller and that the Home country's share is less than fifty percent are consistent with the terms of the September 1995 agreement with NAFO ending the dispute between Canada and the European Union over turbot, whereby Canada is entitled to catch only 3,000 tonnes of turbot for 1996, or 15% of the total allowable catch. The decision by NAFO seems to have been dictated by the need of a settlement that

[14]In such a case, both the first- and second-period shares are greater than one-half by the average ratio of the default payoff differential to the harvesting profits for the corresponding period, that is,

$$\alpha_2 = \frac{1}{2} + \frac{(B_2^H - B_2^F)}{2(p-c)h_2},$$

and

$$\alpha_1 = \frac{1}{2} + \frac{[(B^H - B^F) - \delta(B_2^H - B_2^F)]}{2(p-c)h_1}.$$

would accommodate the two parties' conflicting positions and prevent future losses associated with the reoccurrence of fish wars (non-cooperation).[15] Specifically, NAFO seems to have taken into account Canada's apparent greater future orientation[16] and ideological commitment to conservation, and the increased risk of turbot extinction resulting from the continued overfishing by the European Union. That Canada has a more conservation-oriented attitude is also in concert with the observation over recent years of its low share of the turbot caught, around 20%, in spite of its high allowable catch share, over 60%, and the visible signs of non-cooperative behavior of the European Union. Obviously, if Canada's sole objective had been maximization of harvesting profits, then it would have responded to the overfishing of some NAFO members by fishing itself above the set quota. Instead, in light of the declining stock of turbot, apparently the last commercially viable fish stock in the North Atlantic, it chose to fish below its allowable quota, and this clearly identifies conservation as one of the key determinants of Canada's policies regarding fisheries.

For Canada, the decision by NAFO to set the total allowable catch for 1996 at a level lower than that of 1995 may signify an increase in the benefit received from the fish stock at the end of the year, a benefit which is only partially offset by the loss in the harvesting profits resulting from the lower 1996 total harvest. For the European Union, on the other hand, the smaller total allowable catch amounts exclusively to a loss in the profits from its share of the total harvest. Therefore, had NAFO limited itself to a reduction in the 1996 total allowable catch by about 26% relative to the

[15] Levhari and Mirman (1980) and Plourde and Yeung (1989) show that cooperation Pareto-dominates non-cooperation with two countries and n countries, respectively.

[16] European interest rates, which can be regarded as a rough proxy for discount rates, have been traditionally higher than Canadian interest rates, implying a lower discount factor for the European Union, consequently a greater future-orientation for Canada. This claim is supported by the notorious reputation of the main European Union fleets (Spain and Portugal) as exploitive. Notwithstanding, Canada has also been involved in similar incidents, but not to the same extent.

1995 harvest, and had Canada and the European Union accepted the decision, the latter would have not delayed to deviate from the negotiated sharing rule, as it would have not been willing to pay for the increase in the welfare of the former without adequate compensation. In the context of the dispute over turbot, given the absence of a legally binding agreement which requires not only monitoring[17] but also a system able to severely punish the parties deviating from the agreed-upon terms, Canada, which gains from NAFO decision to allow a smaller total turbot catch for 1996 at expense of the European Union, has to somehow compensate the latter in order to prevent it from overfishing.

NAFO, which is likely to also aim at minimizing the costs associated with the continued switching from cooperation to non-cooperation and vice versa, seems to have given due attention to the need of a dynamically consistent agreement, and thus to the requirement that the European Union must be compensated for the loss in the net profits from its share of the harvest. This would explain the other NAFO decision, which won the support of both Canada and the European Union, to assign the former only 15% and the latter 55% of the total harvest, 75% lower and 337% higher, respectively, than the 1995 catch shares, or, in terms of the allowable quantity of turbot, a maximum of 3,000 tonnes for Canada, 81% lower than the 1995 quota, and a maximum of 11,000 tonnes for the European Union, 223% higher than the 1995 quota.

[17] One of the terms of the September 1995 agreement is that vessels be monitored by satellite. Monitoring, however, may be necessary but certainly not sufficient to bind parties to their commitments regarding future actions.

2.4 A Subgame Perfect Agreement When Both Countries Receive Non-use Values

Until now we have been concerned with situations in which only one country benefits from the fish stock and made no mention that both countries may pursue conservation for non-lucrative reasons, even if to different extents. This possibility arises in the context of the salmon dispute between Canada and the United States, as they are both known to contemplate policies aiming at preserving the natural status quo.[18] Paradoxically, the century-old conflict has been recently exacerbated by the decision of the American President Bill Clinton to ban salmon fishing in the area from California to the Canadian border in order to avoid the complete depletion of the US-spawned salmon, a resolution that carries the name of conservation but does not exclude the strategic attempt of the United States to expropriate some of the profits from the harvesting of the Canadian-spawned salmon. In fact, US fishermen responded by moving to Alaska, thereby adding to the pressure on the salmon originating in British Columbia. In turn, Canadian fishermen, on instruction of the Canadian Department of Fisheries and Oceans, began to fish the Fraser river aggressively in order to deny the catch to Americans, contributing to devastate the west coast salmon fishery.

In view of the dangers of competition in common-access fisheries in the absence of an international system that provides safeguards against the actions of self-interested entities, dynamic consistency or subgame perfection becomes a vital requirement in any cooperative attempt to address the total allowable catch and harvest division issues. For completeness, we find it necessary to adapt the above model to encompass

[18]Munro and Stokes (1989) point out that the salmon dispute is not simply between Canada and the United States, as there is considerable antagonism between Washington, Oregon and Alaska. However, if we assume that the United States can solve their internal conflicts by a self-enforcing division of their national quota, then Canada will have to negotiate only with the United States as a whole.

the case in which both countries have some incentive to conserve the fish stock. Given that the analysis is of most relevance in the evaluation of the positions of Canada and the United States in potential resolutions of the salmon dispute, and that neither of the two countries seems to have a relative better position in the harvesting of salmon under non-cooperation, we assume identical and equal to zero breakdown payoffs and introduce $U(x_t)$, to represent the benefit the Foreign country receives from the fish biomass, with $U'(x_t) > 0$ and $U''(x_t) \leq 0$, so that its objective functional is now

$$W^F = U(x_1) + (1-\alpha_1)(p-c)h_1 + \delta_F[U(x_2) + (1-\alpha_2)(p-c)h_2]. \tag{2.18}$$

Under the same constraints and assumptions about the price and cost structures as before, the two countries stipulate a contract in which the sharing rule and total allowable catch maximizing the second-period Nash-product are given by

$$\alpha_2 = \frac{1}{2} + \frac{[U(x_2) - V(x_2)]}{2(p-c)h_2}, \tag{2.19}$$

and

$$p - c = [V'(x_2) + U'(x_2)], \tag{2.20}$$

respectively, and the first-period terms maximizing the product of the objective functionals of the two countries, or two-period Nash-product, subject to (among the other relevant restrictions) the second-period conditions that (2.19) and (2.20) are satisfied (so that subgame perfection is ensured), are given by

$$\alpha_1 = \frac{1}{2} + \frac{[(U(x_1) - V(x_1)]}{2(p-c)h_1} + \frac{(\delta_F - \delta_H)[U(x_2) + V(x_2) + (p-c)h_2]}{4(p-c)h_1}, \tag{2.21}$$

and

$$V'(x_1) - (p-c) + U'(x_1) + \frac{(\delta_H + \delta_F)}{2}[1 + F'(x_1)](p-c) = 0. \tag{2.22}$$

Although we cannot determine whether the Home country is to receive a higher harvest share in either period or both periods unless we have a proxy for the benefit derived from the fish stock or at least some kind of relative measure of the extent of the two countries commitment to conservation, we are able to conclude that the Home country's marginal cost of not harvesting in terms of its catch share is lower here than in the case where the Foreign country does not hold a non-use value, as in the present framework both countries benefit from the level of the fish stock, and therefore there is no longer the need for the Home country to fully compensate the Foreign country with a higher share in exchange for a larger fish biomass. On the other hand, we are able to assert without a shadow of a doubt that the total allowable catch satisfying (2.20), which says that the constant average harvesting profit has to be equal to the sum of the two countries respective marginal benefits from the fish stock, is smaller than that from (2.16), and, similarly, the fish stock satisfying (2.22) is larger than that from (2.16), by the concavity of the utility functions. In conclusion, the assumption that even the Foreign country has some non-economic interest in the conservation of the fish stock results in a lower total harvest and higher catch share of the Home country in both periods.

2.5 A Numerical Example

To demonstrate the results of the above model, a numerical example is provided in this section using particular functional forms and parameters. Specifically, assuming a price level, cost level, constant growth rate (g), discount factors for each country, non-cooperative payoffs for each country, given by

Parameter	Value
p	10
c	7.5
g	0.02
δ_F	0.95
δ_H	0.95
d	1
B_2^F	10
B_2^H	10

for the benchmark case (to be modified later) and assuming a strictly concave conservation motive function

$$V(x_i) = d[x_i^{0.5}] \tag{2.23}$$

Under this benchmark case of identical discount factors and identical non-cooperative payoffs, the positive conservation motive implies that the harvest share of the Home country would be 49.9057 percent in the second period and 47.8629 percent in the first period.[19] When the Home country enjoys a non-cooperative payoff that is twice that of the Foreign country, the harvest share of the Home country increases in both periods, to over fifty percent in the second period (52.2633) percent and to 49.5191 percent in the first period. If the non-cooperative payoff of the Home country was ten times that of the Foreign country, the harvest share of Home would be greater than fifty percent in each period (54.1494 and 50.8442). This confirms the results stated around the condition (2.21), in which the conservation motive and non-cooperative advantage work in opposite directions so that whether the Home country receives more or less than one-half of the total harvest depends on their relative magnitudes. For each of the above cases, the total harvest in each period is independent of the relative non-cooperative payoffs, at 60.3767 in the initial period and 42.4158 in the

[19] These results are independent of the magnitude of the non-cooperative payoffs as long as the Home and Foreign payoffs are the same.

second period. However, if the conservation motive of the Home country decreases to half of its former level (that is, the parameter d falls to 0.5 from its initial value of 1), not only does the first period harvest share of the Home country increase, but also the first period harvest increases to 91.5942 and the second period harvest decreases to 10.60394 and the stock remaining after the second period falls to zero. Finally, a five percent decrease in the discount factor of one country serves to increase the share of that country in the first period (to 49.1414 percent if Home's discount factor falls, for example) and, as the two countries are now collectively more present-oriented, the harvest increases in the first period to 89.4697 and consequently decreases in the second period to 12.7410.

2.6 Concluding Remarks

In this paper we have examined the impact of non-use values on the optimal choice of dynamically consistent total harvest and catch shares in a two-period, two-country setting. Notwithstanding the simplicity of the model, we have been able to show the very intuitive result that the more a country benefits from the fish stock, or the more committed to conservation it is, the larger the portion of the harvest it has to forego in order to induce the other country to accept a reduction in the total allowable catch. This trade-off holds independently of whether the two countries share the non-use value, and of their respective threat-point positions. In other words, if both countries gain from the fish stock and for reasons completely unrelated to its potential of enhancing future harvesting profits, in any subgame perfect contract it is the party benefitting the most from leaving the fish unharvested that has to receive a lower share of a lower second-period or future harvest, as the second period can be roughly thought of as representing the future, and of a lower first-period, or present, harvest.

Differing discount factors, with the more conservation-oriented country also placing more emphasis on the future, have a negative effect on the catch share of the less present-oriented country but only in the first-period, contributing therefore to reduce its already less than one-half harvest portion. On the other hand, differing breakdown positions, with the conservation-committed country enjoying a better payoff under non-cooperation, have a positive impact on the same share, thus making it possible for the country with the higher default payoff to receive more of the harvest in both periods if the negative effect of its non-economic incentive to conserve the fish stock, which also result in a lower total allowable catch, is more than offset by the positive effect of its better default position.

Even though the conclusions of the models above presented are seemingly applicable to the current conflicts in fishery management, our analysis is also intended to stress the importance of clearly identifying all the variables relevant to the decision-making of the various parties involved in any such dispute. In fact, far from aiming at criticizing the often assumed profit-maximizing objective, we have shown how a simple variation in the behavior of at least one of the parties influences not only the optimal level of the fish stock, but also the subgame perfect sharing rule. Understanding the determinants of the behavior of the countries exploiting a transboundary fishery then becomes essential in the formulation of lasting cooperative policies.

Chapter 3

A Non-Cooperative Game of Wildlife Trade and Endangered Species Protection

3.1 Introduction and Background

While habitat destruction and transformation has been considered the leading factor in endangering species, several high-profile extinctions in North America have been the direct result of over-harvesting and many other currently endangered species are subject to harvesting for international trade. As noted by Kahn (1998), the American bison was harvested for generations by the native peoples of North America, but was hunted from millions to extinction in the wild upon colonization (current herds are apparently descendants derived from former zoo populations). CITES, the Convention on International Trade in Endangered Species of Wild Fauna and Flora, was enacted in an attempt to ensure that endangered species do not become extinct as a result of harvesting of this type for international trade. Initially signed by 21 countries in March 1973, there are now 144 member countries (all members also of the United Nations), and more than 30,000 species covered under the Convention. While instituting bans and other regulatory measures on trade for certain species or the products derived from them among member countries, CITES is also concerned with other species that are currently not endangered but could become so if international trade were left unchecked.

Under the Convention, species listed in Appendix I are subject to complete bans on international trade, while those in Appendix II tend to have less severe restrictions on trade, including quotas on harvests and customs requirements such as permits. Finally, Appendix III lists species which may become endangered in the future due to trade, and are subject to sanctions applied at each party's own discretion. High profile examples in Appendix I are the black rhinoceros (*Diceros bicornis*), tiger (*Panthera tigris*), American crocodile (*Crocodylus acutus*), Orang-utan (*Pongo pygmaeus*), whooping crane (*Grus americana*), blue whale (*Balaenoptera musculus*), and giant panda (*Ailuropoda melanoleuca*); in Appendix II are the American alligator (*Alligator mississippiensis*), common wolf (*Canis lupus*), bottle-nosed dolphin (*Tursiops truncatus*), ring-tailed lemur (*Lemur catta*), black spider monkey (*Ateles paniscus*), and hippopotamus (*Hippopotamus amphibius*, moved from Appendix III in 1995).

While the actual hunting or gathering of species may be simple and subject to open-access, the poaching of endangered species for sale in foreign markets is likely to be a situation where access is limited to those who can transport and sell plants or, more commonly, animals, without being easily caught. In order to deter such activities, two distinct methods are available to concerned governments of countries containing harvested endangered species. The first is to use physical resources or spend money on guards, protected areas, special customs officers, and the like, in order to increase the probability of catching illegal harvesters, thereby increasing the expected fine/punishment received from poaching. The second deterrence method is to provide species to the market, driving down the price and therefore the return to poaching. In this way, the government choice of harvest (or domestic legal quota if direct control is not possible) and enforcement can be thought of as a "first move" in a non-cooperative game with poachers.[1] While certain species may be better suited to an open-access characterization (such as most commonly consumed fish), many endangered species or their parts cannot simply be taken across a nearby border and sold to an end-user, but instead must be transported over long distances to countries with strict import regulations. Examples, to be considered in more detail later, would be several large mammals, including the elephant (ivory), rhinoceros (horn), tiger (skin and bones), and bear (gallbladder), derived in countries with little or no end-use consumption but exported and sold in North America and Asia.

In the literature, limited entry with illegal activity has previously been examined in Sutinen and Andersen (1985) and Crabbé and Long (1993). Sutinen and Andersen endogenize the enforcement level and poaching but the price, legal harvest and punishment are all exogenous. Crabbé and Long solve for the legal harvest within their model, but hold the enforcement level, price and punishment level constant. In the open-access literature with illegal activity, Anderson and Lee (1986) desire to endogenize enforcement, legal harvest and penalty level initially, but eventually are required to fix the fine (at its upper bound), with the price exogenous, and Milliman (1986) has endogenous enforcement and legal harvest and an exogenous price and punishment. Finally, in a related paper on rhinoceros horn cropping, Brown and Layton (1997) ignore poaching (under the premise of a strict cartel) and enforcement and only look at the legal harvest and price.

[1]The international oil market can be thought of in the same way, with the OPEC cartel setting its own oil production for a period and other small producing countries then choosing their own production levels. The key difference here is that both the first and second movers select species from the same stock.

In this paper, enforcement, the price level, legal harvesting and poaching are all endogenous, and harvest costs are stock dependent. As in Sutinen and Anderson, Milliman, Crabbé and Long, Bergeron (1998), and Brown and Layton, however, the punishment (fine) for being caught poaching is exogenous.[2] As mentioned above, poaching activity is characterized by limited entry, where poachers act according to Cournot conjectures (take the legal harvest and poaching by others as given), and choose their illegal harvests after the government has set (or taken but not sold) the legal harvest quantity or quota. Unlike other related papers, the cases in which the government maximizes profits and stock-oriented national welfare that depends on the endangered species stock level are considered, as well as the explicit evaluation of the impact of the CITES policies on welfare, poaching, enforcement and endangered species stocks.[3] Further, the analysis presented does not require constant unit costs or linear punishment functions, as employed in the optimal control open-access model of Bergeron. Other questions addressed here include: how is poaching affected by imperfect, costly enforcement with limited entry? Is deterrence completely or partially successful? And what variables or parameters affect the extent of successful deterrence?

[2] In this paper, the punishment can be thought of as a monetary fine paid by poachers, but it is more correct to think of the government combining this with the proceeds from sale of the confiscated goods (as the illegal supply is unaffected by the amount of poaching caught).

[3] Despite the alternatives examined, total surplus maximization is one government objective not covered here. As noted by Milliman, it is difficult to believe that a government would value illegal activity as much as legal activity, despite the fact that both supply socially valued goods to the market. Further, redistribution becomes a problem when the activities and income of some parties are not observable, so the standard argument promoting efficiency and ignoring distribution does not apply, not to mention that in many cases organized poaching is performed by foreigners (for example, organized elephant poaching is allegedly typically carried out by Zambians in Zimbabwe and by Somalis in Kenya). Resource managers have a tendency to maximize only legal gains from a stock, as they are typically only rewarded on such grounds, and policy-makers promote legal gain maximization as these activities generate revenues from licensing fees, greater social recognition and general funding (Milliman), as well as income taxes.

3.2 Recent Examples of CITES Actions

Two species which have gained a great deal of public attention have recently switched Appendices, at least to a limited extent. At the tenth meeting of CITES in Zimbabwe in 1997, the African elephant (*Loxodonta africana*) populations of Botswana, Namibia and Zimbabwe were moved from Appendix I to Appendix II, allowing international commercial trade under a permit system and the export of sport hunting trophies for non-commercial purposes (Zimbabwe can export elephant hides and ivory carvings as well). Also established was a procedure for registration and non-commercial disposal of government ivory stocks in all African range states (those countries which have elephants). However, for trade in raw ivory to occur, deficiencies in enforcement and control measures identified in all three African countries and in Japan would have to be remedied, international co-operation in law enforcement would have to be supported and committed to, and an international reporting and monitoring system to track illegal hunting of elephants and illegal trade in elephant products would have to be established.[4] Ivory continues to accumulate in most range states: it is estimated that more than 470 tonnes of legal ivory is held by government or private individuals in Africa. First begun at the ninth meeting of CITES members in 1994, CITES member countries also accepted a proposal in 1997 from these three range states to allow for a one-time purchase of government stocks of ivory, again for non-commercial purposes.

It is an accepted fact that elephant populations have decreased dramatically in the last thirty years. In the early 1970s, there were estimated to be well over one million elephants in Africa, and more recent estimates in 1995 suggest there are now only

[4]The three countries also had to withdraw their reservations to the 1989 Appendix I listing of the African Elephant.

some 581,175 (Said et al., 1995), which can be broken down by likelihood probability: 285,246 were classified definite, another 101,285 probable, 171,892 possible, and 22,752 speculative. It was this precipitous decline which prompted the 1989 CITES ban on trade in elephants and their derivatives (especially ivory). African range states have shown mixed results after the ban, as illustrated for selected states in Table 3.1, although the majority have seen increases in elephant populations. This is despite population pressures, civil wars and habitat destruction in several nations, and one must keep in mind that elephants do not respect political borders and some changes in populations are simply due to cross-border migration.

Elephant Population	Cameroon	Kenya	Malawi	Tanzania	Zimbabwe
Pre-ban (1989)	22,000	16,000	2,800	61,000	52,000
Post-ban (1995: definite, probable or possible)	16,613	25,554	2,087	98,209	81,855
Change (1989-1995)	-5,387	+9,554	-713	+37,209	+29,855
% Change	-24.5%	+59.7%	-25.5%	+61.0%	+57.4%

Table 3.1. Estimates of pre- and post-ban elephant populations, selected range states. Source: 1989 estimates from Barbier et al. (1990); 1995 estimates from Said et al. (1995). For definitions of definite, probable and possible, see the latter (speculative estimates are ignored here).

Thus, for the most part, harvesting of elephants (including poaching) appears to have decreased since the institution of the CITES ban, possibly dramatically. This suggests that any increases in poaching caused by bans does not completely offset the reduction of legal harvesting to zero. Of course, the extent to which total poaching differs from the no-ban total harvesting depends on the level of enforcement after implementation relative to that with the free legal market. Table 3.2 provides poaching estimates, again from selected range states, and Table 3.3 shows enforcement expenditures per square kilometer and enforcement staff employed for the same nations. It is interesting to note that expenditures on enforcement have generally decreased and that poaching in many countries has decreased nonetheless. These observations will be discussed in the context of the model later.

Poaching	Cameroon	Kenya	Malawi	Tanzania	Zimbabwe
Pre-ban	77	45	89	55	48
Post-ban (1992/1993)	42	208	77	12	175
Change	-35	+163	-12	-43	+127
% Change	-45.5%	+362.2%	-13.5%	-78.2%	+264.5%

Table 3.2. Estimates of pre- and post-ban elephant poaching (illegal harvesting), selected range states. Source: Dublin, Milliken and Barnes (1995).

	Cameroon	Kenya	Malawi	Tanzania	Zimbabwe
pre-ban enforcement budget*	1.58	6.60	14.80	12.60	24.00
post-ban enforcement budget*	1.23	4.00	11.40	0.38	2.63
pre-ban enforcement staff	1,130	270	65	87	118
post-ban enforcement staff	654	137	65	146	105

Table 3.3. Estimates of pre- and post-ban elephant-related enforcement levels, selected range states. Source: Dublin, Milliken and Barnes. * denotes $\frac{\$US}{km^2}$.

Also transferred from Appendix I to Appendix II in 1995, but with an annotation which restricted trade to live animals and hunting trophies, was Zambia's population of southern white rhinoceroses (*Ceratotherium simum simum*). At the 1997 meeting, South Africa introduced a proposal to expand the annotation to allow trade in parts and derivatives, but with a zero quota for such trade in the present. South Africa additionally sought support for open and transparent discussions with practitioners of traditional Chinese medicine concerning the possibility of a limited, tightly controlled trade in rhinoceros horn in the future, arguing that such a development would generate funds for conservation and reduce incentives for illegal trade. The proposal failed to receive a two-thirds' majority and was rejected but will undoubtedly arise again in the near future as white rhinoceros populations rebound.

Other notable recent resolutions concerned bears and tigers. One such resolution asked parties to "demonstrably" reduce illegal trade in bear parts and derivatives by the eleventh meeting in Indonesia in 1999, through strengthening laws, increasing penalties, improving wildlife law enforcement training, and educating the public about CITES regulations relating to bears.[5] In addition, parties were asked to quantify their domestic demand for bear parts and derivatives, to work with traditional medicine interests to reduce consumer demand, and to promote use of substitutes that do not endanger wild species. A revision to a past resolution (proposed by India, Nepal and the Russian Federation) was adopted in regard to tiger specimens, which was intended to identify countries which need additional legislative and law enforcement measures to minimize illegal trade in order to encourage stronger measures to stop poaching of tigers and illegal trade in tiger parts and derivatives.

These observations will be commented on in respect to the formulated model. Sections 3, 4 and 5 describe the subgame perfect equilibria of the two stage game in question. The second stage is detailed in the next section, in which the individual poachers choose their harvest levels given the legal harvest and enforcement level set by the government in the first stage. This is followed by the strategic choice of these variables by the government in sections 4 (pure profit objective) and 5 (profit-and-stock objective), whereby the government accounts for how individual and total poaching will be affected.

[5] Efforts aimed to reduce demand will generally be excluded in the present analysis.

3.3 Individual and Total Poaching Choice

Consider a fixed and finite number of risk-neutral poachers, n, with identical cost structures. If we let h_j^P be the harvest of poacher j, using the superscript P to differentiate poaching from the legal or sanctioned harvest, and S be the stock level, the cost of harvesting (which is stock-dependent) will be $c(S)h_j^P$, with $c' < 0$ and $c'' \leq 0$. The inclusion of stock-dependent costs provides an incentive to leave a larger proportion of the stock unharvested than constant costs, although simply to keep harvesting costs lower.[6] The harvest of all poachers other than poacher j, denoted h_{-j}^P, can then be written

$$h_{-j}^P = \sum_{i \neq j}^{n} h_i^P \tag{3.1}$$

As in the above mentioned studies, the market for legal and illegal products is the same: there is a single demand curve for the product in question, independently of the method by which it was provided.[7] A representative poacher maximizes expected individual profits, given the legal harvest H^L and the government enforcement level K^L as determined by the first stage (and thus are constant for the purposes of poaching choice), and the harvests of all other poachers, h_{-j}^P,

$$E(\pi_j^P) = P(h_j^P + h_{-j}^P + H^L)h_j^P - c(S)h_j^P - \alpha(K^L)\gamma(h_j^P) \tag{3.2}$$

where the final stock level will simply be its initial value less the sum of the total harvest of poachers and the legal harvest, or $S = \bar{S} - (h_j^P + h_{-j}^P + H^L) > 0$, given the demand function P (where $P' < 0$, $P'' \geq 0$), exogenous convex punishment function γ, and the enforcement technology $\alpha(K^L)$, whereby the probability of catching a poacher is increasing in the government-chosen level of enforcement ($\alpha' > 0$) with

[6] For more on this "marginal stock effect," see Clark (1973).

[7] This could alternately be modelled, however, as two distinct but interrelated demand curves, one for legal merchandise, one for illegal.

non-increasing returns ($\alpha'' \leq 0$) The profit-maximizing condition which yields the reaction function $h_j^P(h_{-j}^P, H^L)$ of poacher j is

$$P'h_j^P + P - c + c'h_j^P - \alpha\gamma' = 0 \tag{3.3}$$

Hence, poachers harvest until the benefit of harvesting one additional unit, the price received from output, equals the sum of the marginal cost of harvesting that unit, the increase in the expected fine (which is increasing in the level of enforcement) and the profit lost through the resulting decrease in the price of output. Assuming a symmetric Cournot equilibrium among poachers (as in Crabbé and Long) for a given H^L, the reaction function for total poaching would be

$$\begin{aligned} P'\left(H^P + H^L\right)\frac{H^P}{n} + P\left(H^P + H^L\right) - c\left(\bar{S} - H^P - H^L\right) + \\ +c'\left(\bar{S} - H^P - H^L\right)\frac{H^P}{n} - \alpha(K^L)\gamma'\left(\frac{H^P}{n}\right) = 0 \end{aligned} \tag{3.4}$$

where the total harvests by all poachers is given by

$$H^P \equiv h_j^P + h_{-j}^P = nh_j^P \tag{3.5}$$

by symmetry. The total poaching harvest can then be written as

$$H^P = n\left[\frac{c + \alpha\gamma' - P}{P' + c'}\right] \tag{3.6}$$

or that each Cournot poacher receives a price for each harvested unit greater than the sum of the cost and expected punishment from the last unit, under the assumption that there is both poaching and legal activity. Consequently, corner solutions between legal and illegal harvesting occur when either (a) legal harvesting has a significant cost advantage or enforcement is sufficiently high or effective, so that the price associated with the optimizing legal harvest is lower than the expected cost and punishment associated with the first unit poached, or (b) poachers have a huge cost advantage and enforcement is sufficiently ineffective, so that positive levels of the legal harvest, when combined with the optimizing level of poaching, result in a market price net of expected fine revenues lower than legal harvesting costs. These two possibilities, the former in which poaching can be completely deterred by optimal legal harvesting and enforcement, and the latter in which only poaching occurs, will be discussed further, although the brunt of the analysis presented here will be the intermediary case when there is both legal harvesting and poaching despite enforcement.

Returning to the poaching choice, we can observe (by total differentiation of (3.6)) that the reaction of total poaching to legal harvest levels is

$$\frac{dH^P}{dH^L} \equiv \frac{dH^P}{dH^L}\bigg|_{dK^L=d\bar{S}=dn=0} = \frac{-\frac{H^P}{n}P'' - P' - c' + c''\frac{H^P}{n}}{\frac{H^P}{n}P'' + P' + \frac{P'}{n} + c' - c''\frac{H^P}{n} - \frac{\alpha\gamma''}{n}} < 0 \tag{3.7}$$

which is strictly negative by virtue of the convexity of the demand function, cost function and punishment for poaching, and the second-order condition. Further, we know that total poaching will decrease by less than one unit when legal harvesting increases by one unit, or

$$0 < \left|\frac{dH^P}{dH^L}\right| < 1 \tag{3.8}$$

This follows from two elements: that firms can collectively exercise some degree of market power, and that enforcement is effective here, as

$$\frac{dH^P}{dK^L} \equiv \frac{dH^P}{dK^L}\bigg|_{dH^L=d\bar{S}=dn=0} = \frac{\alpha'\gamma'}{\frac{H^P}{n}P'' + P' + \frac{P'}{n} + c' - c''\frac{H^P}{n} - \frac{\alpha\gamma''}{n}} < 0 \tag{3.9}$$

unlike several other related papers where the poacher's first order conditions (and thus choice of output) are independent of enforcement. This allows the government, in setting the enforcement level, to do more than simply usurp funds from caught poachers. The total poaching level is positively related to the initial stock level, as

$$\frac{dH^P}{d\bar{S}} \equiv \frac{dH^P}{d\bar{S}}\bigg|_{dH^L=dK^L=dn=0} = \frac{c' - c''\frac{H^P}{n}}{\frac{H^P}{n}P'' + P' + \frac{P'}{n} + c' - c''\frac{H^P}{n} - \frac{\alpha\gamma''}{n}} \tag{3.10}$$

again less than one. Lastly, the total harvest is sensitive to the number of poachers; specifically,

$$\frac{dH^P}{dn} \equiv \frac{dH^P}{dn}\bigg|_{dH^L=dK^L=d\bar{S}=0} = \frac{P' + c'H^P - \alpha\gamma''H^P}{n^2\left[\frac{H^P}{n}P'' + P' + \frac{P'}{n} + c' - c''\frac{H^P}{n} - \frac{\alpha\gamma''}{n}\right]} \tag{3.11}$$

which is strictly positive, implying more poaching will occur as the number of poachers increases, with a lower harvest and lower profits to each individual poacher. For a given number of poachers and initial stock level, the reaction function for total poaching is downward sloping in both enforcement and legal harvest, confirming the initial presumption that enforcement and legal harvests are deterrents for poaching. From here we move to the first stage of the game in which these two government choice variables are chosen taking into account the reactions of H^P to both H^L and K^L.

3.4 The Profit-Maximizing Government

3.4.1 Legal Harvesting, Poaching and Enforcement

Initially, we assume that the government is not directly concerned with the species in question and simply maximizes the sum of legal harvesting profits and expected fines from the apprehension and conviction of poachers. This may be the case when control over harvesting is made by a resource manager concerned only with the direct return from the stock, and will serve as a benchmark for the following section, where welfare will depend on stock management.[8] Such an objective is also justified in ignoring

[8] Other government objectives, including achieving a particular stock level by selling licensing fees and balancing their budget, are distinct possibilities but are outside the scope of this paper.

consumer surplus on the basis that there is often little or no end-use consumption in the countries in question. To allow for differences in the cost structures between the identical poachers and the legal harvesters, but retaining the assumption of stock-dependent unit harvesting costs, we will let the legal harvest cost function be $C(S)H^L$. Here we consider the government to have either direct control over harvesting or distributes individual quotas which sum to the total legal harvest H^L, the latter being consistent with Appendix II of *CITES*.[9] With quotas, any distributive effects are ignored, so that the government may freely distribute or charge a fee for the quotas, the legal harvesting sector becomes passive in the sense that legal harvest choices of individual firms are given by the distribution of quotas. Enforcement capital, K^L, is purchased on a competitive international market at a parametric price r, normalized to one. The total expected return from legal harvesting and enforcement is

$$E(\Pi^L) = P\left(H^P + H^L\right)H^L - C\left(\bar{S} - H^P - H^L\right)H^L + n\alpha\left(K^L\right)\gamma\left(\frac{H^P}{n}\right) - K^L \tag{3.12}$$

so that the (interior) legal take of species is given by

$$P + P'\frac{dH^P}{dH^L}H^L + C'H^L\left[\frac{dH^P}{dH^L} + 1\right] = C - P'H^L - \alpha\gamma'\frac{dH^P}{dH^L} \tag{3.13}$$

with $\frac{dH^P}{dH^L}$ from (3.7) above, and enforcement expenditures by

$$P'H^L\frac{dH^P}{dK^L} + C'H^L\frac{dH^P}{dK^L} + n\alpha'\gamma = 1 - \alpha\gamma'\frac{dH^P}{dK^L} \tag{3.14}$$

with $\frac{dH^P}{dK^L}$ from (3.9). These two conditions can be interpreted in a relatively straightforward manner. The marginal benefit of harvesting, or the left-hand-side of (3.13), is comprised of the direct additional revenues from selling the last unit at the market

[9] Quotas here are simply a form of quantity commitment on the part of legal harvesters and are obviously not binding with respect to the sum of legal offtake and poaching. An alternative specification would have the legal quota as some set total offtake quantity less poaching, although this would make the poachers the first-mover and is an entirely different case.

price and the indirect additional revenues generated from the decrease in unit harvesting costs and the increase in the price, each through the (negative) relationship between legal harvesting and poaching. For efficient harvest choice, this just obviously equals the marginal cost of harvesting, the right-hand-side of (3.13), composed of the direct additional cost of harvesting the last unit and the indirect costs of the lost revenues on all units sold from a higher harvest and the expected lost revenues from fines (again as more legal harvesting implies less poaching). Similarly with respect to K^L and (3.14), an additional dollar spent on enforcement has the benefits of a higher price of (and revenue from) the harvested good and a lower unit harvesting cost (from lower poaching) and a higher probability of catching poachers (and thus higher expected fines), but has the expense of the dollar itself and the expected lost fine revenue (again from less poaching).

From (3.13), the legal harvest will be zero and only poaching will occur when, among other factors, legal harvesting costs are prohibitively high, such as when the stock is very small and poaching is more efficient or when poaching levels are high, so that the price is low relative to costs, as is potentially the case when the number of poachers, n, is large. Thus, when enforcement is costly, poaching may not occur at all, may occur in conjunction with legal harvesting, or only poaching may occur, depending on the relative costs and the effectiveness and profitability of enforcement. To illustrate, consider the example provided in Figures 3.1 to 3.11, using the following assumptions:[10]

$$P(H^P + H^L) = A - b(H^P + H^L)$$

$$c(S) = \frac{\bar{S} - S}{\bar{S}} = \frac{H^P + H^L}{\bar{S}}$$

$$\alpha(K^L) = a\sqrt{K^L}$$

$$\gamma\left(\frac{H^P}{n}\right) = d\left(\frac{H^P}{n}\right)^2$$

$$U(E(\Pi^L), S) = \xi E(\Pi^L) + zS$$

Figure 3.1 shows that the total poaching harvest asymptotically converges to the legal harvest as the number of poachers increases when poachers and legal harvesters share the same cost function. At low numbers of poachers, both legal harvests and enforcement are more effective in reducing poaching, as poachers utilize their collective market power to trade-off units poached for higher product prices. As competition increases among poachers however, this trade-off disappears and the reaction of total poaching to legal harvesting approaches negative one (that is, if there were an infinite number of poachers, an increase in legal harvesting by one unit would reduce poaching by a single unit), and enforcement becomes less effective.[11] This generates an increasingly flatter marginal cost curve (since costs are stock dependent) for both legal harvesting and poaching and the harvests converge. The first move of the government nonetheless ensures a higher harvest and higher profits than total poaching

[10]Most, if not all, of the conclusions and inferences that follow are general and thus not restricted to the example in question. The exogenous parameters assumed are: demand function maximum $A = 100$, demand function slope coefficient $b = 3$, probability coefficient $a = 0.0001$, initial stock level $\bar{S} = 1000$, punishment coefficient $d = 100$, and the weight on profits in social utility if stock-and-profit oriented $\xi = 0.5$, and (when not otherwise varied) the number of firms $n = 10$ and the coefficient on the stock in the utility function $z = 10$. Partial output and enforcement levels are permitted for simplicity. The objective function U will be described further in section 3.6.

[11]Enforcement becomes less effective because each poacher harvests a smaller and smaller share of the total harvest as the number of poachers increases. If n were infinite (given H^P is finite), each poacher would harvest an infinitely small amount, thus making the expected punishment infinitely small, and enforcement completely ineffective.

for any finite number of poachers. When the government is a more efficient harvester than poachers, as illustrated in Figure 3.2, the gap between legal harvesting and the total poaching level initially declines (from the increased market power of a small number of poachers), but eventually increases as the cost advantage allows greater legal harvesting (and consequently higher enforcement levels relative to the identical cost case) at the expense of poaching levels. At some critical number of (potential) poachers, total poaching would be zero. Figure 3.3 shows the opposite case: when poachers have a cost advantage over legal harvesters. In this situation, the lower harvesting costs may allow poachers to overcome the first-mover advantage of legal harvesters and earn higher profits as poaching levels exceed legal harvests, again beyond some critical number of poachers (about 40 in the example). In summary, under free trade: the legal harvest will always be positive and greater than total poaching if any harvesting occurs with identical costs; with a legal cost advantage, legal harvests will always be positive although poaching may be totally deterred; and with a poaching cost advantage, the total poaching harvest and profit level each may exceed the legal values, and legal harvests may in fact be zero.[12]

3.4.2 The Impact of a Ban on Poaching and Enforcement

Identical Enforcement Technology Under a Ban

Bans on legal harvesting can be implemented under agreements such as *CITES*, or can be unilaterally enforced by importing or exporting countries. As an example in the case of ivory, several countries such as the USA, Kenya and those in Europe had already banned trade when the *CITES* ban of 1989 was announced. Suppose initially that the probability of catching poachers function remains the same after the

[12]If the legal offtake is in fact zero, there will be no effect of a ban on trade.

implementation of a ban. In the following section, the alternative case of a higher probability (for the same non-zero enforcement level) under a ban will be considered. Clearly, a ban on legal harvesting will reduce H^L to zero, which has the effect of increasing poaching through the price of output. However, to ascertain the overall impact on poaching, we must examine the impact on legal enforcement as well. Under a ban, poachers will collectively harvest $\hat{H}^P$ to satisfy

$$P'\left(\hat{H}^P\right)\frac{\hat{H}^P}{n}+P\left(\hat{H}^P\right)-c\left(\bar{S}-\hat{H}^P\right)+c'\left(\bar{S}-\hat{H}^P\right)\frac{\hat{H}^P}{n}-\alpha(\hat{K}^L)\gamma'\left(\frac{\hat{H}^P}{n}\right)=0 \quad (3.15)$$

or

$$\hat{H}^P = n\left[\frac{c+\alpha(\hat{K}^L)\gamma' - P}{P'+c'}\right] \quad (3.16)$$

implying, as in the no ban case, that each firm makes positive profits (price exceeds cost and expected fine) if supply is to be positive.

In this case, there is no legal harvesting but the relationship between H^P and K^L remains negative and unchanged from (3.8), and the government simply maximizes the expected profit earned from enforcement, or

$$E(\hat{\Pi}^L) = \alpha(\hat{K}^L)\gamma(\hat{H}^P) - \hat{K}^L \quad (3.17)$$

Enforcement is thus chosen according to

$$n\alpha'\gamma = 1 - \alpha\gamma'\frac{dH^P}{dK^L} \quad (3.18)$$

which differs from its counterpart (3.14) by the exclusion of both the benefit of a higher price of the harvested good and lower unit harvesting cost from lower poaching, as the stock in question is no longer legally harvested. Thus, for the same poaching harvest, enforcement will have a smaller marginal benefit and will decrease. However, the increased poaching associated with the reduction in legal harvesting will increase the marginal benefit of enforcement and decrease its marginal cost, pushing enforcement upwards. If the reaction of total poaching choice to the legal harvest is relatively large, both H^P and K^L could increase as a result of a trade ban, leading to a higher species stock level (from the fact that poaching increases by less than one unit for each unit left unharvested by the government). This possibility is illustrated in Figures 3.4 (enforcement) and 3.5 (stock). Another potential outcome is that enforcement could increase and the poaching harvest could decrease (leading to a much higher stock level under a trade ban), as when enforcement is highly effective and legal harvest changes have small effects on poaching choice (especially when the number of poachers is small).

Overall, then, it is possible that enforcement increases or decreases after a ban is implemented, and further, that poaching can increase or decrease. Total poaching, however, is unlikely to equal the sum of legal and illegal harvesting without a ban, and as such trade bans can be generally said to be more conservative than when legal harvesting is permitted. However, this is true only when legal harvesting is positive when allowed (that is, the government would not specialize in enforcement alone); otherwise, a ban has no effect on total harvesting. In section 3.2, it was noted in the case of the African elephant that several range states have recorded decreases in poaching despite lower enforcement expenditures and staff. This is not possible in the scenario detailed so far: here poaching will go down after implementation only if either enforcement increases substantially or enforcement increases and is highly effective. Nonetheless, this situation can be explained in this framework if the probability of catching poachers increases by enough, as explained in the following section.

Improved Enforcement Technology Under a Ban

When legal trade is present, it is difficult to ascertain whether goods were obtained legally or illegally, but once a ban is instituted, illegal products cannot enter countries in the guise of legal goods. Greece, for example, has recently run into conflicts with international customs officials as several shops in Athens were found to be openly displaying banned animal skins and other prohibited products related to endangered species, which was easily observed in random customs inspections. A ban may then have the effect of increasing the probability of catching poachers, even if enforcement and the poaching quantity do not change, say from $\alpha(K^L)$ to $\theta(K^L)$, where $\theta(x) > \alpha(x)$ and $\theta'(x) > \alpha'(x)$ for all $x > 0$. In other words, the enhancement of the enforcement technology serves to rotate the probability function upwards. If this were the case, allowing legal offtake would have the additional negative effect of reducing enforcement effectiveness. The reaction function of all poachers is then

$$P'\left(\hat{H}^P\right)\frac{\hat{H}^P}{n}+P\left(\hat{H}^P\right)-c\left(\bar{S}-\hat{H}^P\right)+c'\left(\bar{S}-\hat{H}^P\right)\frac{\hat{H}^P}{n}-\theta(\hat{K}^L)\gamma'\left(\frac{\hat{H}^P}{n}\right)=0 \quad (3.19)$$

so that

$$\frac{d\hat{H}^P}{d\hat{K}^L}=\frac{\theta'\gamma'}{\frac{\hat{H}^P}{n}P''+P'+\frac{P'}{n}+c'-c''\frac{\hat{H}^P}{n}-\frac{\theta\gamma''}{n}}<0 \quad (3.20)$$

and enforcement will satisfy

$$n\theta'\gamma=1-\theta\gamma'\frac{dH^P}{dK^L} \quad (3.21)$$

When the probability of being caught poaching increases for every level of enforcement (except zero), we can see from (3.20) that enforcement is now more effective in reducing the total quantity of poaching, as the marginal probability increases at each K^L and poaching would therefore decrease if the enforcement level were to remain constant at the level of the previous section (despite the partially offsetting effect of reducing the marginal fine). This would imply that the expected fines would strictly decrease. However, the poaching level decrease may cause expected fines lost - the second-term on the right-hand-side of (3.21) - to increase or decrease, depending on the change in poaching $\frac{dH^P}{dK^L}$ and probability of being caught θ. If lost fines were in fact to decrease, the marginal cost of enforcement would decrease and enforcement would unambiguously fall (as the marginal benefit has increased as well). However, if lost fines were to increase, enforcement could increase or decrease depending on the sensitivity of H^P to enforcement expenditures, the steepness of the fine function (or the increase in the marginal fine, γ''), and the degree to which enforcement becomes more effective under a ban (or $\theta - \alpha$). This ambiguity on the effect of a ban on enforcement translates into ambiguity on the poaching level relative to that with a constant probability, although it is possible that poaching could fall, even when enforcement is lower, as long as the change in the probability of catching poachers is sufficiently large.[13]

3.5 Profit-Maximization under a Negotiated Harvest Constraint

3.5.1 Legal Harvesting, Poaching and Enforcement

In the previous chapter, negotiated international agreements and the resulting national harvests were found which maximized a measure of national welfare; that is, to meet the prescribed harvests were in the best interest of each country. Without illegal

[13] Although this possibility is consistent with the African elephant data, we cannot definitively say this was the case. Here demand is held constant after a ban and there is always the possibility that demand for banned products is lower. This would, in fact, be the case if there are separate demands for legal and illegal merchandise.

poaching, there is no reason to expect that the negotiated national harvest and the actual offtake would differ, as the government could issue (or sell) individual quotas that sum to the national quota. When poaching can occur, however, a legal offtake that does not recognize the illegal harvest level or its relation to the legal harvest or enforcement level may lead to an overall harvest (legal and illegal) that exceeds the national quota. To say that international bargaining considers only legal harvesting would be unrealistic, as the concern internationally is the species stock level and not whether individual units were obtained legally or illegally.[14] Here, the analysis of the previous section is extended to examine the impact of an internationally negotiated harvest constraint on the choices of the government. Again, the illegal harvest can be manipulated by the legal harvest (through the price) and the enforcement level (through the expected punishment), but instead of using these impacts to simply maximize the return from the legal harvest, the government manipulates the poaching level to achieve the set national quota while earning as much rent from the stock as possible. Relative to the unconstrained maximization, the government will earn lower profits but will not violate the terms of its international agreement, and by doing so would not induce a non-cooperative outcome at the international level. Thus, the government maximizes the return from its legal harvest, net of enforcement costs, subject to the constraint

$$\bar{H} \geq H^P + H^L \tag{3.22}$$

where $\bar{H}$ is the national quota. If the shadow price of an additional unit of the constraint is denoted by λ, the interior legal harvest will be given by

$$P + -P'H^L\left[\frac{dH^P}{dH^L}+1\right] + C'H^L\left[\frac{dH^P}{dH^L}+1\right] - C + \alpha\gamma'\frac{dH^P}{dH^L} - \lambda\left[\frac{dH^P}{dH^L}+1\right] = 0 \tag{3.23}$$

[14]It has been suggested that national pollution compliance problems have arisen under recent pollution agreements due to lack of control over illegal emissions, for example.

and enforcement by

$$P'H^L\frac{dH^P}{dK^L}+C'H^L\frac{dH^P}{dK^L}+n\alpha'\gamma-1+\alpha\gamma'\frac{dH^P}{dK^L}-\lambda\frac{dH^P}{dK^L}=0 \tag{3.24}$$

Poaching relations are unchanged, so that

$$\frac{dH^P}{dH^L}+1>0 \tag{3.25}$$

and

$$\frac{dH^P}{dK^L}<0 \tag{3.26}$$

implying that the international quota represents an additional cost to legal harvesting (as exceeding the quota becomes more likely) and an additional benefit to enforcement. Ceteris paribus, and assuming that the total harvest exceeds the national quota in the absence of the constraint (or that the constraint is binding) we can expect harvesting to decrease and enforcement to increase. However, since these two changes have opposite influences on poaching levels, there are three potential overall effects. First, legal harvesting may increase and enforcement increase so that poaching decreases by more than the increase in the legal harvest. This could be the case when enforcement is particularly effective. Second, legal harvesting may increase and enforcement decrease such that poaching again decreases by more than the increase in legal offtake, as when legal harvesting is a very significant deterrent to poaching (such as if demand is inelastic). Finally, legal harvesting may decrease and enforcement decrease, but where the increase in poaching does not exceed the decrease in legal harvesting. This may be the case when demand is price sensitive (elastic) and enforcement is ineffective, so that reductions in enforcement have little effect on poaching, and large reductions in the legal offtake have little influence on the price (and thus poaching as well).

3.6 The Social or Conservation-Minded Government

3.6.1 Legal Harvesting, Poaching and Enforcement

With profit maximization as the only objective, there is no accounting for stock level changes, and thus no direct interest in endangered species or their protection. Except in the case when the government chooses not to harvest in the absence of a ban, such implementation would result in strictly lower profits for the government and thus a ban would never be optimal (zero harvesting is always a potential alternative). However, when a government takes into account that private individuals may hold non-use values or species may provide indirect benefits not captured in trade markets, the lower harvest levels associated with trade restrictions may make them preferred over the free market.[15] In this case, the total poaching reaction function will be unchanged, but the government will maximize

$$U(E(\Pi^L), S) \tag{3.27}$$

which will be assumed, for simplicity, to be additively separable and quasi-linear in expected profits, or equivalently that the marginal utility of profits is unaffected by the stock level and vice versa. The alternate case when the marginal utility of profits depends positively on the stock will be discussed further below. The social value function can then be written

$$U = \xi E(\Pi^L) + v(S) \tag{3.28}$$

where ξ is the constant, positive weight placed on expected profits, and $v' > 0$ and $v'' \leq 0$, or there is positive diminishing marginal utility from the stock level. This

[15]The market here, except for enforcement, is unregulated in the sense that no taxes or other measures can be employed to correct the market failure.

objective can be thought of as sort of a "green" national income maximization, where the government considers both the income generated by the direct utilization of the stock in addition to values derived externally to the market in question.[16] Given that poaching will react to its harvest and enforcement level according to (3.7) and (3.9), respectively, the legal harvest is chosen according to

$$P + P'H^L\left[1 + \frac{dH^P}{dH^L}\right] - C + C'H^L\left[1 + \frac{dH^P}{dH^L}\right] +$$
$$\alpha\gamma'\frac{dH^P}{dH^L} - \frac{v'}{\xi}\left[1 + \frac{dH^P}{dH^L}\right] = 0 \qquad (3.29)$$

and enforcement according to

$$P'H^L\frac{dH^P}{dK^L} + C'H^L\frac{dH^P}{dK^L} + n\alpha'\gamma + \alpha\gamma'\frac{dH^P}{dK^L} - 1 - \frac{v'}{\xi}\frac{dH^P}{dK^L} = 0 \qquad (3.30)$$

From the profit-maximizing choices, the variation here is generated by the additional marginal cost of harvesting in (3.29) in the amount of the utility lost from increased harvesting and the resulting stock decrease (net of the reduction in poaching), and the additional benefit from enforcement in (3.30) from the stock increase generated by reduced poaching. The presence of the stock in welfare then serves to decrease legal harvesting (see Figure 3.6) and increase enforcement (Figure 3.9). Poaching may increase or decrease, depending on these relative changes, so that poaching will increase if enforcement is particularly ineffective (implying that the change in the marginal cost with a ban is small) or if poaching is not very sensitive to changes in legal harvesting. Overall, any increase in the level of total poaching will not exceed the reduction in legal harvesting, and the stock level will be higher relative to the case of pure profit maximization, as shown in Figure 3.11.

[16]This would assume that the stock is used only for the market under consideration, so that sectors in the economy are independent and individual-market income maximization and gross national product maximization do not conflict.

With identical costs, this implies that poaching may well exceed the legal harvest (Figure 3.6). With a cost advantage to legal harvesters, it is possible that the increasing market power of a small number of poachers may allow poaching to exceed legal harvesting, but at higher numbers of poachers the legal harvest will exceed the poaching harvest as the cost advantage dominates the stock effects. It is possible in this case for poaching to be completely deterred if n is sufficiently large, as illustrated in Figure 3.7. When poachers have a cost advantage, the first move of legal harvesters will allow the legal offtake to exceed the poaching level only when the number of poachers is very small. Beyond some small critical mass of poachers, the market power and cost advantage effects will dominate the first-mover advantage, allowing poaching to exceed the legal offtake and poaching profits to exceed legal profits, possibly to the point where the legal harvest falls to zero, as shown in Figure 3.8. Enforcement levels under these three relative cost possibilities are illustrated in Figure 3.10. Enforcement tends to be highest when poachers have a cost advantage and lowest when the legal harvesters have a cost advantage.

3.6.2 The Impact of a Ban on Poaching and Enforcement and International Existence Values

For completeness, here we examine the impact on enforcement of a ban when there is concern for the stock level of the endangered species in question. Optimal enforcement in this case is given by

$$\alpha'\gamma + \alpha\gamma'\frac{d\hat{H}^P}{d\hat{K}^L} - 1 - \frac{v'}{\xi}\frac{d\hat{H}^P}{d\hat{K}^L} = 0 \tag{3.31}$$

which differs again from the profit-maximizing case in that there is an additional enforcement benefit derived from the larger stock as poaching falls. This would imply that enforcement would be higher than with bans and no existence value, and lower poaching would result as well, an intuitively appealing result.

While it is interesting to look at the national optimum, in reality such an equilibrium may still not be obtainable. As mentioned previously, often resource managers are faced with incentives based exclusively on profits. If people hold existence values, or if there are other benefits not captured in the market for the harvested good, the private optimum will diverge from the national optimum. Alternatively, and potentially more importantly, we may want to think of a situation in which existence values for a species are not held by domestic individuals but by those in other countries, as in the case when domestic individuals have more urgent concerns than the survival of a particular neighboring species (as the demand for environmental amenities is usually assumed to be increasing in income). Under *CITES*, decisions regarding species are made during the bi-annual Convention of Parties, in which the majority of members represent countries other than those which contain the species themselves. A perusal of reservations towards species' listings (countries which object to a particular classification or trade restriction) shows that most are made by the host countries. Without direct control over the resource itself, the maximum welfare from Section 3.1 could not be achieved. The question then arises as to whether a ban on harvesting is superior to the mismanagement of the profit-maximizing resource manager. A ban has the benefit of a lower stock level, but the profits from legal harvesting are absent. If the organization which sets the ban does not receive the profits, obviously a ban will prevail. However, and more realistically, *CITES* must consider both profits and stock levels when making the decision to ban trade in a species, and thus a ban will only be preferable in this scenario when marginal existence values are high, and equilibrium fines per unit are high and enforcement is effective (so that poaching does not substantially increase with a ban, reducing the stock so much that lost profits are not offset).

3.7 Extension: Stock Dynamics

To keep the analysis clear, to this point stock dynamics and consideration of multiple period objectives have been ignored. In this section, the model of previous sections is extended to two periods, incorporating a natural growth function for the stock $F(S)$ so that the stock at any point in time t is

$$S_t = S_{t-1} + F(S_{t-1}) - H_t^P - H_t^L \tag{3.32}$$

or specifically in period 1

$$S_1 = S_0 + F(S_0) - H_1^P - H_1^L \tag{3.33}$$

and in period 2

$$S_2 = S_1 + F(S_1) - H_2^P - H_2^L \tag{3.34}$$

given an initial stock level S_0. For tractability, individual poaching again is characterized by limited entry and static profit maximization, so that the choice of poaching for individual j will be a function of the current harvests of all other poachers, the current legal harvest quota, the current enforcement level, and the beginning of the period stock level.[17] In this way, the decisions made in prior periods influence current decisions (through the stock level), although this is not explicitly accounted for in individual poaching decisions. The government is assumed to be an intertemporal discounted profit (or profit and stock) maximizer, choosing each period's harvest quota and enforcement level to maximize

$$E(\Pi_1) + rE(\Pi_2) \tag{3.35}$$

[17]It must be noted that with certain stock dependent unit cost functions, the poaching decisions will be independent of the initial stock. As these possibilities are uninteresting, they are ignored in the examination.

if the government maximizes profits alone, where r is discount factor of the government, so $0 \leq r \leq 1$, and

$$EU(\Pi_1, S_1) + \delta EU(\Pi_2, S_2) \tag{3.36}$$

if the government maximizes a combination of profits and the stock level, where δ is social rate of time preference ($0 \leq \delta \leq 1$). Assuming unit harvesting costs are given by

$$c(S_t) = \frac{1}{S_t} \tag{3.37}$$

demand for harvested goods is time-independent and linear, or

$$P(H_t^P + H_t^L) = A - b(H_t^P + H_t^L) \tag{3.38}$$

in each period t, the probability of catching poaching is

$$\alpha(K^L) = \sqrt{K^L} \tag{3.39}$$

and punishment is quadratic

$$\gamma\left(\frac{H_t^P}{n}\right) = \left(\frac{H_t^P}{n}\right)^2 \tag{3.40}$$

total poaching in period 1 would be

$$H_1^P = \frac{n\left(A - bH_1^L - \frac{1}{S_1}\right)}{2\sqrt{K_1^L} + (n+1)b - \frac{1}{S_1^2}} \tag{3.41}$$

and total poaching in period 2 would be

$$H_1^P = \frac{n\left(A - bH_2^L - \frac{1}{S_2}\right)}{2\sqrt{K_2^L} + (n+1)b - \frac{1}{S_2^2}} \tag{3.42}$$

As

$$S_1 = S_0 + F(S_0) - H_1^P - H_1^L \tag{3.43}$$

and

$$S_2 = S_1 + F(S_1) - H_2^P - H_2^L = S_0 + F(S_0) + F(S_0 - H_1^P - H_1^L) - H_1^P - H_1^L - H_2^P - H_2^L \tag{3.44}$$

total poaching in the first period will depend on the legal harvest and enforcement in that period only, although total poaching in the second period will depend on the legal harvest and enforcement in that period, the legal harvest and enforcement in the previous (first) period, as well as total poaching in the previous period. Specifically, total poaching is increasing in the initial stock level, decreasing in the current legal harvest and decreasing in current enforcement. With respect to previous harvest and enforcement for total poaching in the second period, the effect on H_2^P is ambiguous. Accordingly, a government concerned with the discounted return from the stock over the two period maximizes

$$PV(\Pi) = [A - b(H_1^P + H_1^L)]H_1^L - \frac{H_1^L}{S_1} + \frac{\sqrt{K_1^L}}{n^2}\left(H_1^P\right)^2$$
$$+\delta\left\{[A - b(H_1^P + H_1^L)]H_1^L - \frac{H_1^L}{S_1} + \frac{\sqrt{K_1^L}}{n^2}\left(H_1^P\right)^2\right\} \tag{3.45}$$

such that the poaching harvests in each period are given by (3.41) and (3.42) and the stock levels in each period are given by (3.43) and (3.44). Interior legal harvests in each period are given by

$$[A - bH_1^P - bH_1^L] - bH_1^L\left[\frac{\partial H_1^P}{\partial H_1^L}\right] - bH_1^L - \frac{1}{S_1} - \frac{H_1^L}{S_1^2}\left[\frac{\partial H_1^P}{\partial H_1^L} + 1\right] + \frac{2\sqrt{K_1^L}H_1^P}{n}\left[\frac{\partial H_1^P}{\partial H_1^L}\right]$$
$$-\delta bH_2^L\left[\frac{\partial H_2^P}{\partial H_1^L}\right] - \delta\frac{H_2^L}{S_2^2}\left[\left(\frac{\partial H_1^P}{\partial H_1^L} + \frac{\partial H_2^P}{\partial H_1^L} + 1\right)(1 + F')\right] + \frac{2\delta\sqrt{K_2^L}H_2^P}{n}\left[\frac{\partial H_2^P}{\partial H_1^L}\right] = 0 \tag{3.46}$$

for H_1^L and

$$[A - bH_2^P - bH_2^L] - bH_2^L \left[\frac{\partial H_2^P}{\partial H_2^L}\right] - bH_2^L - \frac{1}{S_2} - \frac{H_1^L}{S_2^2}\left[\left(\frac{\partial H_2^P}{\partial H_2^L} + 1\right)(1 + F')\right] + \frac{2\sqrt{K_2^L}H_2^P}{n}\left[\frac{\partial H_2^P}{\partial H_2^L}\right] = 0 \tag{3.47}$$

for H_2^L (assuming $\delta \neq 0$), while enforcement expenditures in each period are given by

$$-bH_1^L\left[\frac{\partial H_1^P}{\partial K_1^L}\right] - \frac{H_1^L}{S_1^2}\left[\frac{\partial H_1^P}{\partial K_1^L}\right] + \frac{\left(H_1^P\right)^2}{2n\sqrt{K_1^L}} + \frac{2\sqrt{K_1^L}H_1^P}{n}\left[\frac{\partial H_1^P}{\partial K_1^L}\right] - 1$$

$$-\delta bH_2^L\left[\frac{\partial H_2^P}{\partial K_1^L}\right] - \delta\frac{H_2^L}{S_2^2}\left[\left(\frac{\partial H_1^P}{\partial K_1^L} + \frac{\partial H_2^P}{\partial K_1^L}\right)(1 + F')\right] + \frac{2\delta\sqrt{K_2^L}H_2^P}{n}\left[\frac{\partial H_2^P}{\partial K_1^L}\right] = 0 \tag{3.48}$$

for K_1^L and

$$-bH_1^L\left[\frac{\partial H_1^P}{\partial K_2^L}\right] - \frac{H_1^L}{S_1^2}\left[\frac{\partial H_1^P}{\partial K_2^L}\right] + \frac{\left(H_2^P\right)^2}{2n\sqrt{K_2^L}} + \frac{2\sqrt{K_2^L}H_2^P}{n}\left[\frac{\partial H_2^P}{\partial K_2^L}\right] - 1 = 0 \tag{3.49}$$

for K_2^L (again assuming $\delta \neq 0$).

On the other hand, a myopic social planner (that is, maximizes a one-period objective ignoring the influence of its own harvest, resulting poaching, and enforcement in the first period on the value of the objective in the second period) would select its legal harvest quota in each period H_i^L, $i = 1, 2$ according to

$$[A - bH_i^P - bH_i^L] - bH_i^L\left[\frac{\partial H_i^P}{\partial H_i^L} + 1\right] - bH_i^L - \frac{1}{S_i} - \frac{H_i^L}{S_i^2}\left[\frac{\partial H_i^P}{\partial H_i^L} + 1\right] + \frac{2\sqrt{K_i^L}H_i^P}{n}\left[\frac{\partial H_i^P}{\partial H_i^L}\right] = 0 \tag{3.50}$$

and the enforcement level in each period K_i^L, $i = 1, 2$ such that

$$-bH_i^L\left[\frac{\partial H_i^P}{\partial K_i^L}\right] - \frac{H_i^L}{S_i^2}\left[\frac{\partial H_i^P}{\partial K_i^L}\right] + \frac{\left(H_i^P\right)^2}{2n\sqrt{K_i^L}} + \frac{2\sqrt{K_i^L}H_i^P}{n}\left[\frac{\partial H_i^P}{\partial K_i^L}\right] - 1 = 0 \tag{3.51}$$

The intertemporal-objective government thus accounts for the effects of its first period harvest and enforcement on the value of its objective function, the illegal harvest and the growth of the stock in the second period, while the myopic government does not.

As can be seen from comparing (3.47) and (3.50, with $i = 2$), and (3.49) and (3.51, with $i = 2$), the second period harvest and enforcement decision rules between a myopic government and a government with an intertemporal objective are similar, but with significant differences. If the stock level remaining after the first period was the same in each case, there would be no variation in the two harvests and enforcement levels. However, examination of the first-order conditions for the first period variables, (3.46), (3.46), (3.50, with $i = 1$), and (3.51, with $i = 1$), shows that this will not be the case. Specifically, the stock level affects the effectiveness of enforcement expenditures and the relationship between legal harvesting and total poaching. As the stock increases, unit harvesting costs decrease, implying that poaching can increase without decreasing profits (for a given enforcement level) and thus, ceteris paribus, a higher stock level increases poaching. Second-period enforcement then becomes more effective at reducing total poaching and second-period legal harvesting becomes less of a deterrent to poaching if the stock level remaining after the first period is higher for an intertemporal objective maximizing government than for a myopic objective government, and the opposite is true if the remaining stock is higher for the myopic government.

Comparing (3.46) with (3.50, with $i = 1$), the government with an intertemporal objective also takes into account the effects of its first period harvest quota and enforcement on second period poaching and stock growth, and subsequently, on its own second period harvest. Again, whether the legal harvest quota will be greater or less than the single-period maximizing choice will depend on several factors, including the effectiveness of enforcement, the magnitude of the punishment, the number of poachers and the sensitivity of poaching to the legal quota. Specifically, if the term

$$-\delta b H_2^L \left[\frac{\partial H_2^P}{\partial H_1^L}\right] - \delta \frac{H_2^L}{S_2^2} \left[\left(\frac{\partial H_1^P}{\partial H_1^L} + \frac{\partial H_2^P}{\partial H_1^L} + 1\right)(1 + F')\right] + \frac{2\delta\sqrt{K_2^L H_2^P}}{n} \left[\frac{\partial H_2^P}{\partial H_1^L}\right] \quad (3.52)$$

is greater than zero, then the difference between the marginal benefit and marginal cost of the legal harvest has increased and the legal quota will be increased, and the opposite if the term is negative, and if the term

$$-\delta b H_2^L \left[\frac{\partial H_2^P}{\partial K_1^L}\right] - \delta \frac{H_2^L}{S_2^2} \left[\left(\frac{\partial H_1^P}{\partial K_1^L} + \frac{\partial H_2^P}{\partial K_1^L}\right)(1 + F')\right] + \frac{2\delta\sqrt{K_2^L H_2^P}}{n} \left[\frac{\partial H_2^P}{\partial K_1^L}\right] \quad (3.53)$$

is positive, then enforcement will be higher than with a myopic government, and vice versa. The overall effect on the stock level remaining after the first period will depend on the directions and magnitudes of these effects.

3.8 Conclusion

Poaching of endangered species is a significant problem facing governments and resource managers, particularly when values are held but not captured in output markets. If enforcement were costless and resources unconstrained, this would not be the case. However, despite the positive costs of enforcement, it is possible for a manager with the first move in setting the legal harvest and enforcement level to completely deter poaching (with limited entry). This would nonetheless require either a highly effective and efficient enforcement method or a significant cost advantage on behalf of legal harvesters. More likely is the case of partial deterrence, where poaching can be controlled only to a point.

In order to regulate trade in endangered species, *CITES* has typically employed trade bans and harvest quotas. The latter is ineffective in that poachers do not respect quotas, by definition, and simply reflect the allowed or desired legal offtake of species. When a resource manager or government simply maximizes the rents received from legal harvests, a trade ban unambiguously reduces profits and may result in higher or lower enforcement levels. Assuming that the probability of catching poachers does not change when implementing a ban, enforcement will never increase enough to generate reductions in total poaching. This last fact was observed in several countries after the 1989 ban on trade of elephants and elephant derivatives. However, if bans make detection of poaching and poached goods easier, so that the expected fine from poaching increases, it is possible that the overall level poaching goes down after implementing a ban, as in the elephant case. Regardless of this probability, the positive effectiveness of enforcement expenditures on poaching levels generally (but not always) results in higher species stock levels, as the increase in poaching does not completely offset the reduced legal harvest. This again does not conflict with the rebounding stock levels of African elephants commonly observed in elephant range states, particularly when one considers the myriad of other pressures placed on populations, including civil wars and habitat destruction. To a resource manager or government concerned with the stock level as well as profits from legal activity, a trade ban becomes more appealing than with a profit-maximizing objective alone due to the higher stock level, but is still likely to be sub-optimal. If existence values are held by individuals outside the countries containing the endangered species (that is, if endangered species are global public goods), we can also explain the preference for trade bans. The potential for monetary transfers dominating trade bans would require the explicit modelling of consumption and existence values in the consumer country as well as the transfer mechanism in a cooperative framework and is therefore left for future work.[18]

[18] Other possible research directions include differentiating legal and illegal markets (demand), the incorporation of harvesting and stock dynamics, and interjurisdictional conflicts and interactions.

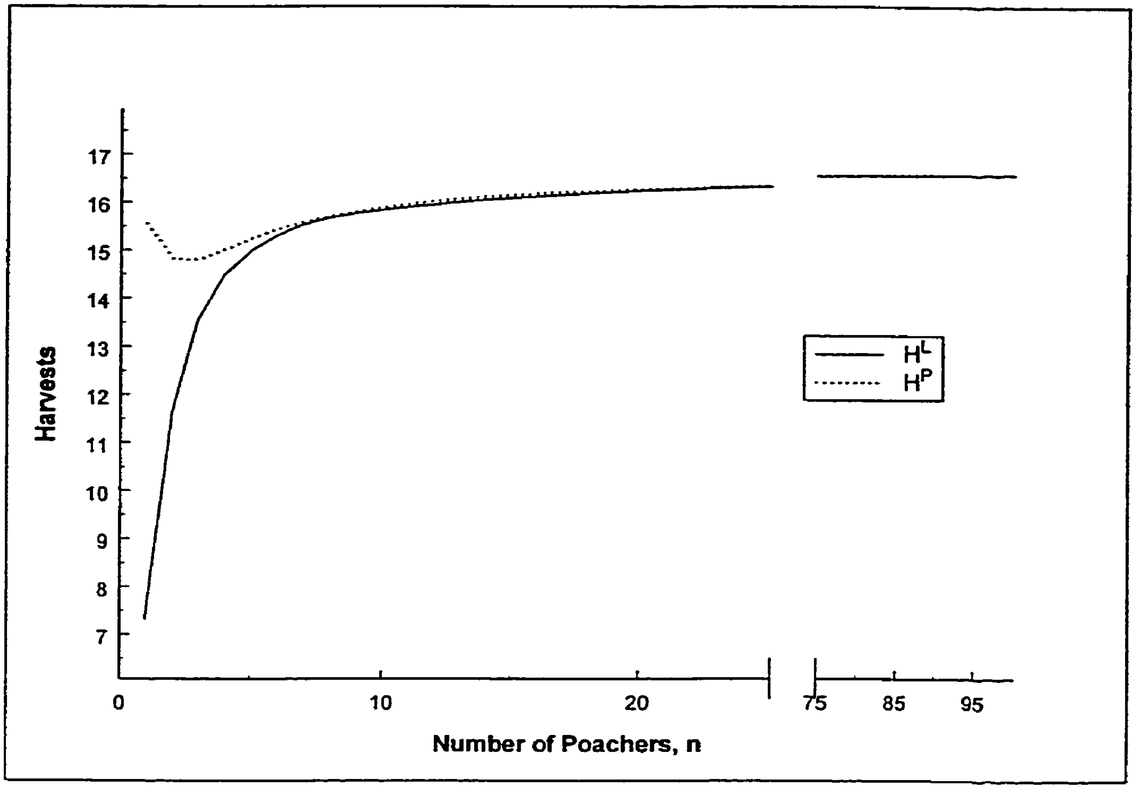

Figure 3.1 Legal and poaching harvests with pure profit objective and identical costs.

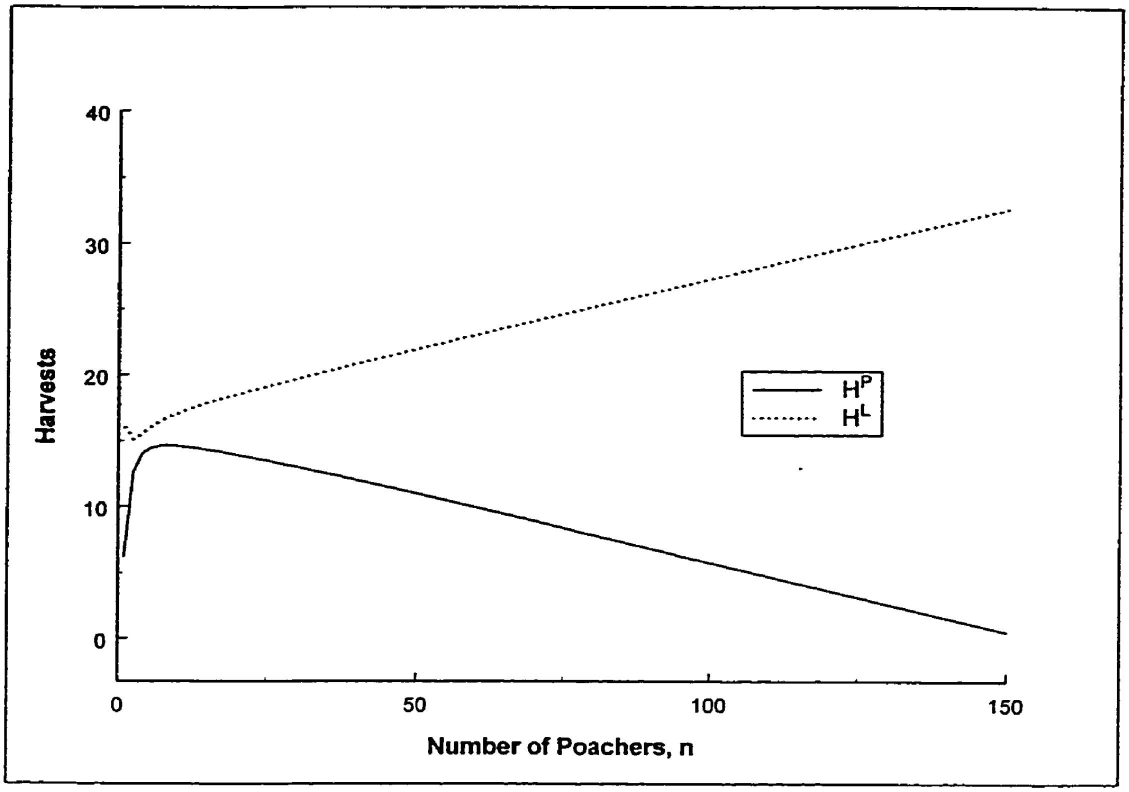

Figure 3.2 Legal and poaching harvests with pure profit objective and a cost advantage to government harvesters.

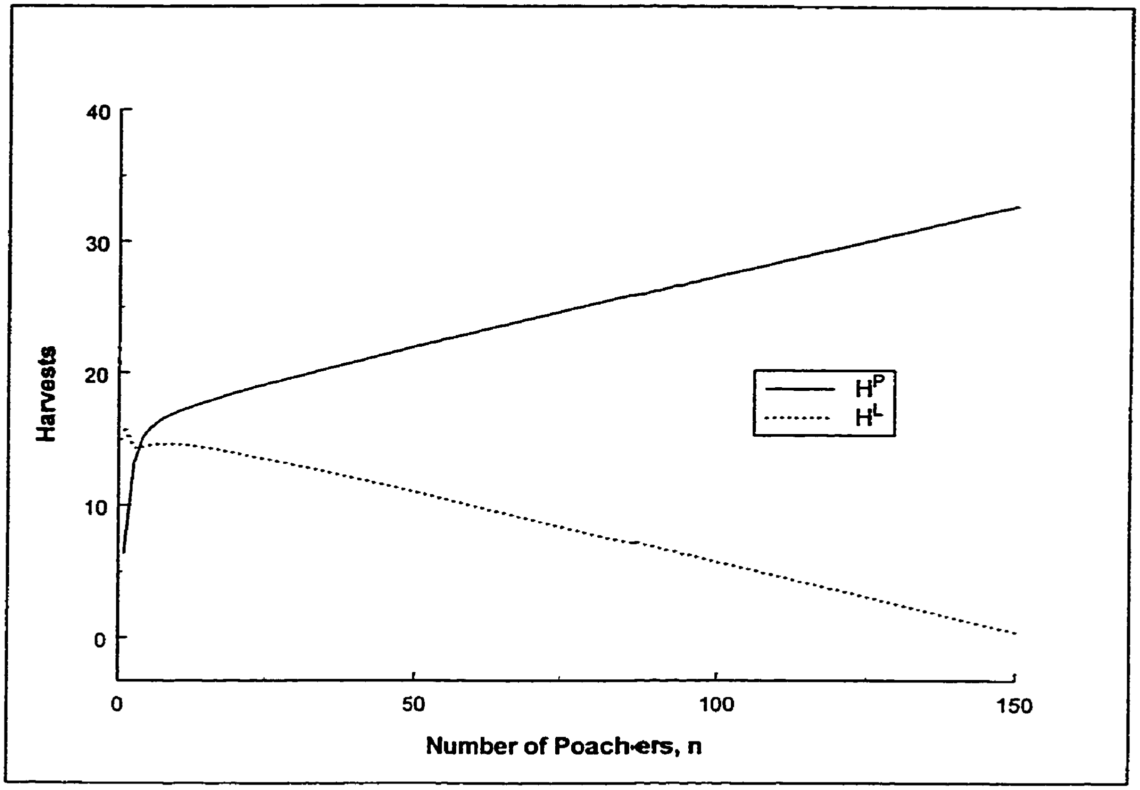

Figure 3.3 Legal and poaching harvests with pure profit objective and a cost advantage to poachers.

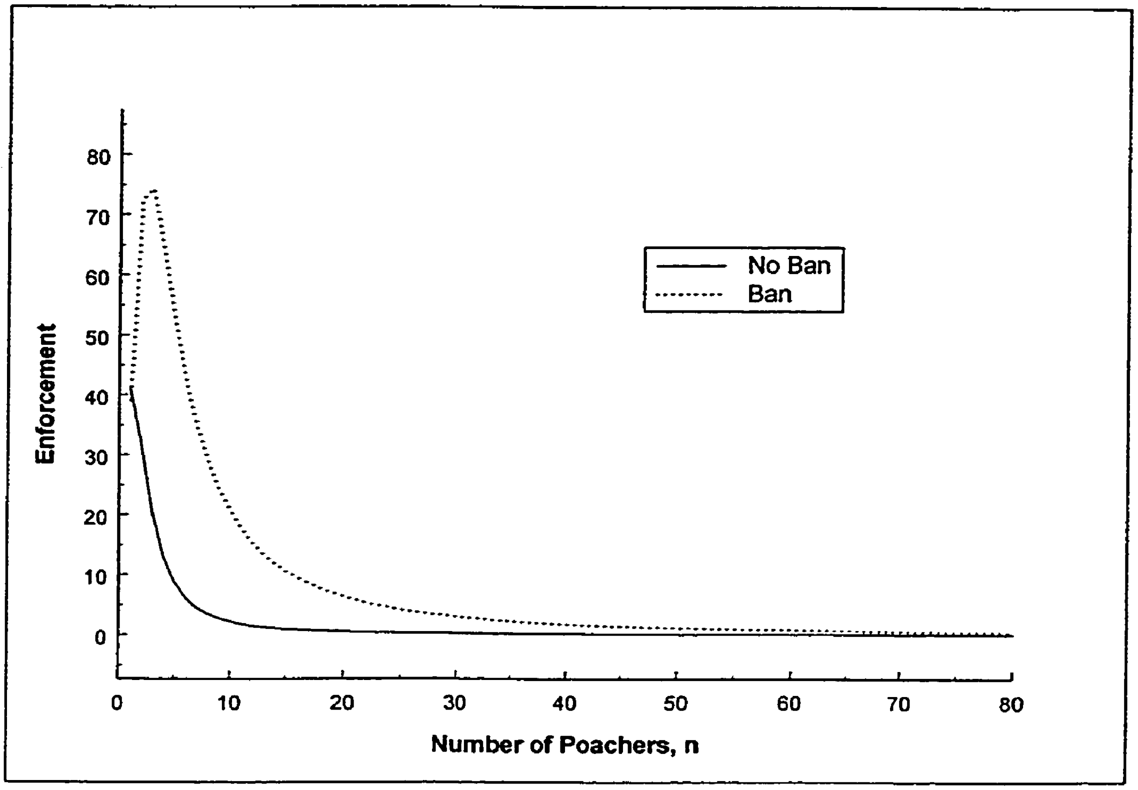

Figure 3.4 Enforcement expenditure under a trade ban and under free trade.

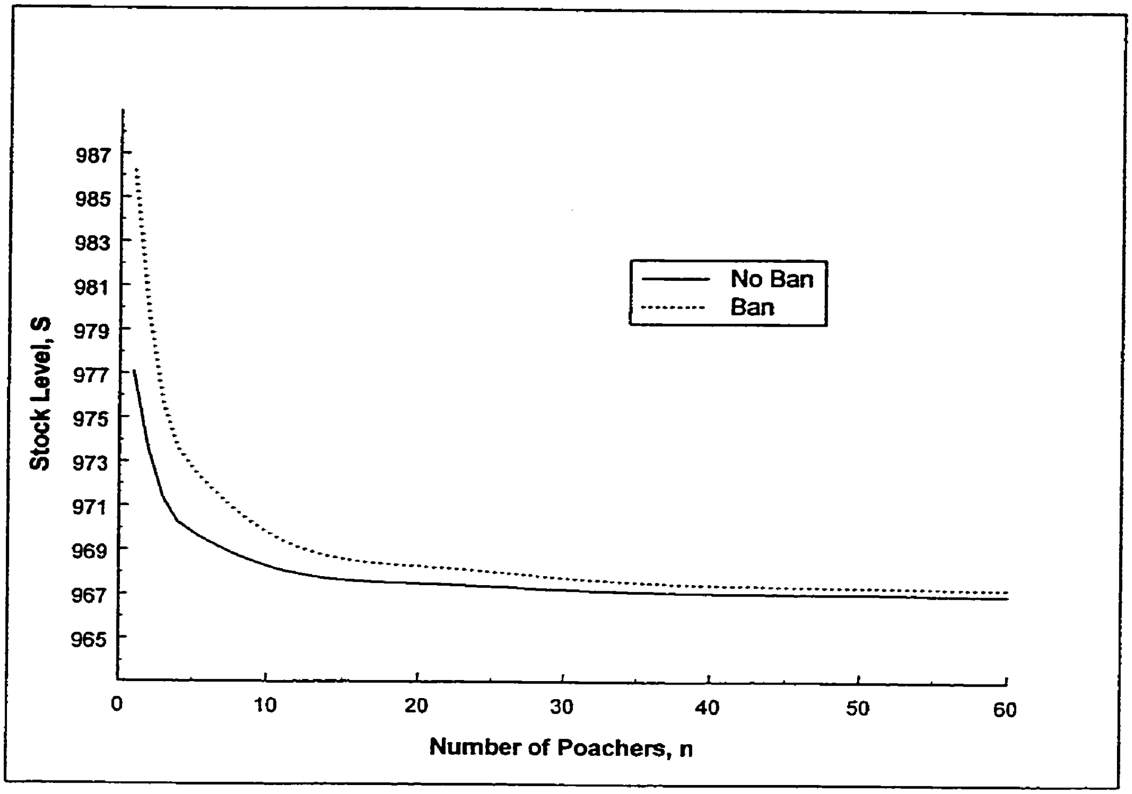

Figure 3.5 Stock levels under a trade ban and under free trade.

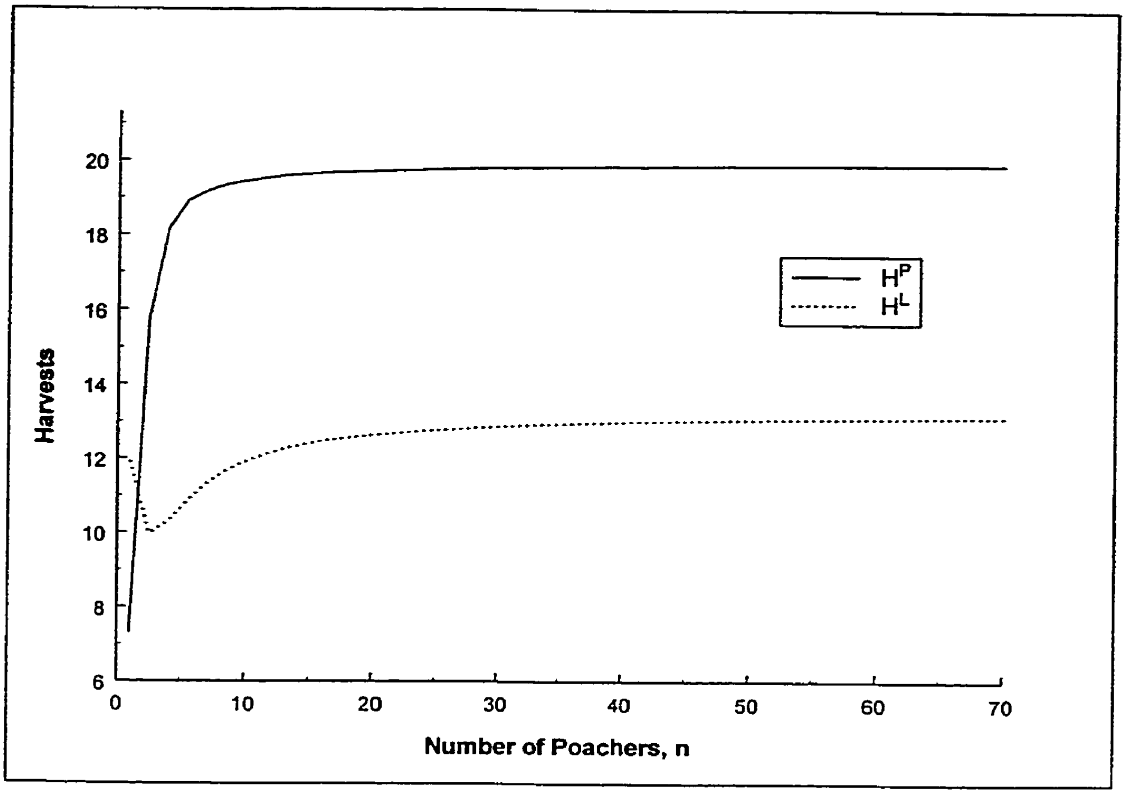

Figure 3.6 Legal and poaching harvests with stock-and-profit objective with identical costs.

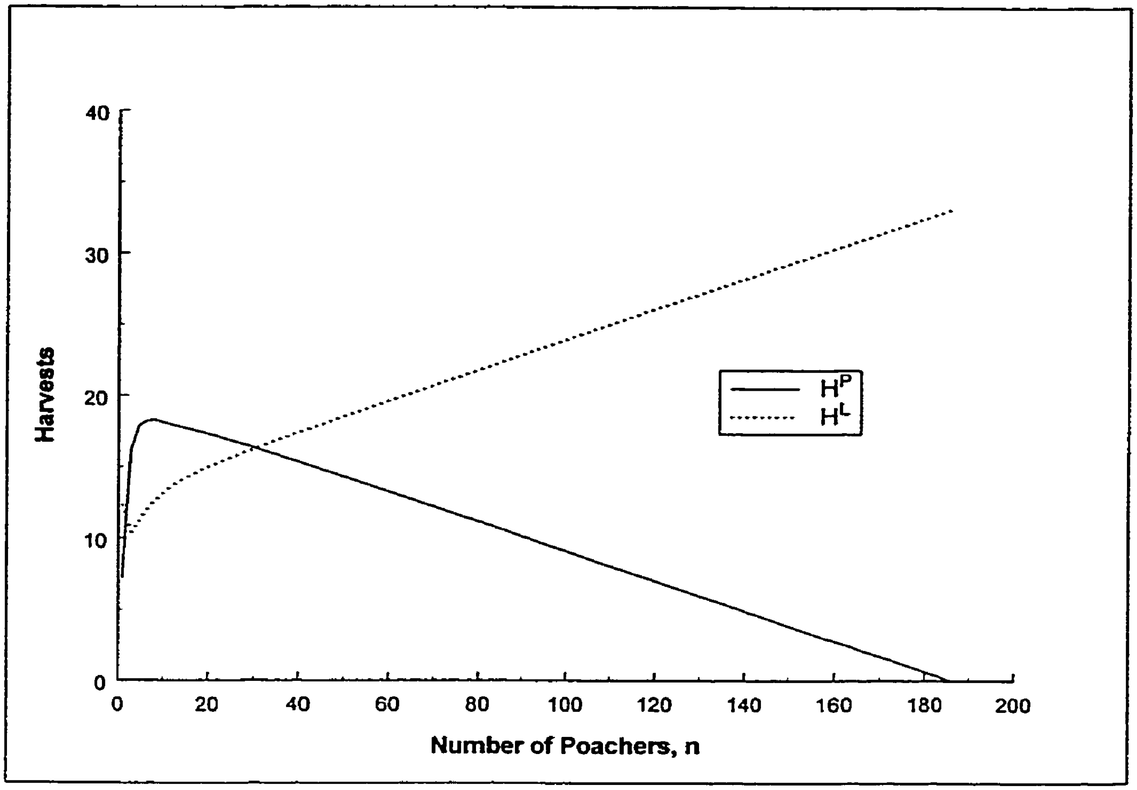

Figure 3.7 Legal and poaching harvests with stock-and-profit objective and a cost advantage to government harvesters.

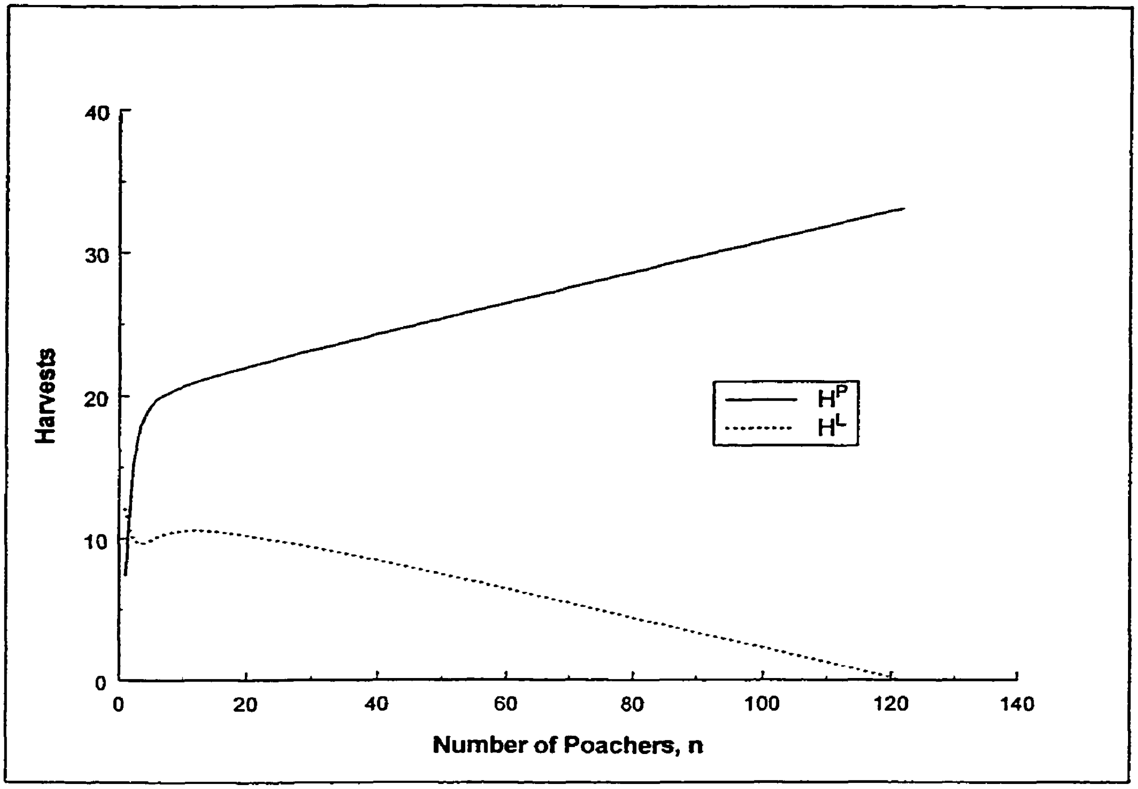

Figure 3.8 Legal and poaching harvests with stock-and-profit objective and a cost advantage to poachers.

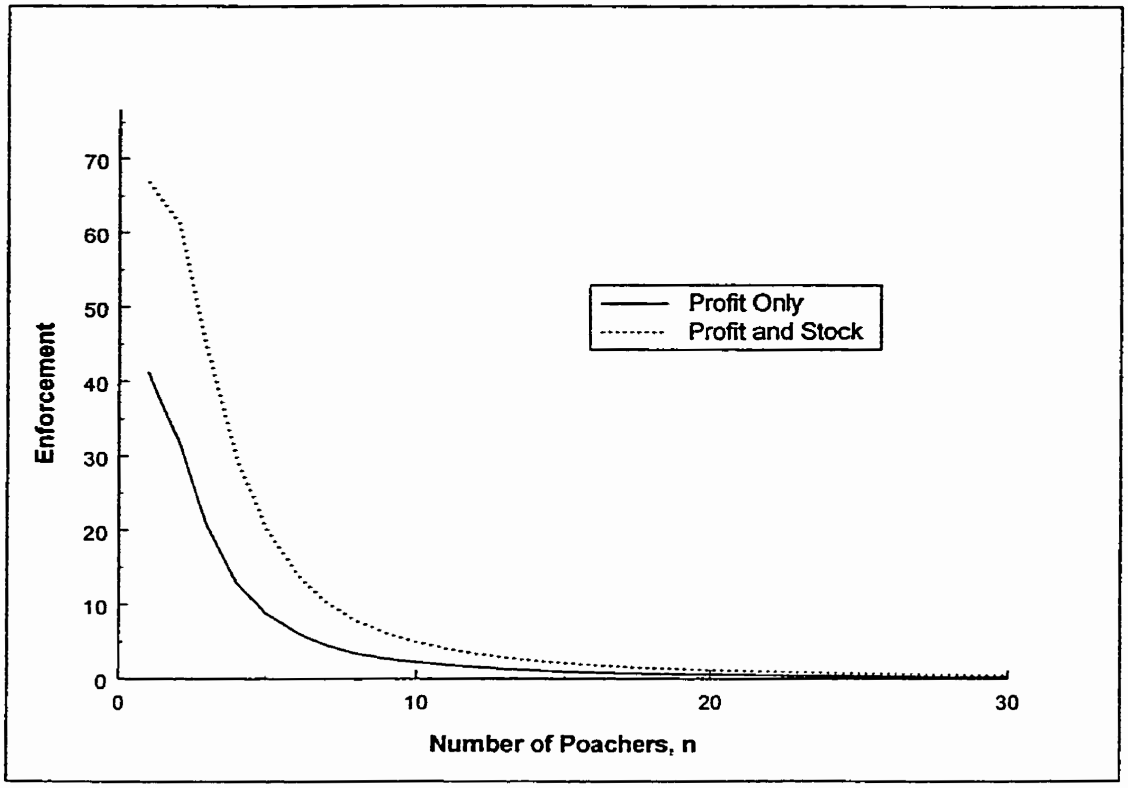

Figure 3.9 Enforcement levels (K^L) under pure profit and profit-and-stock objectives.

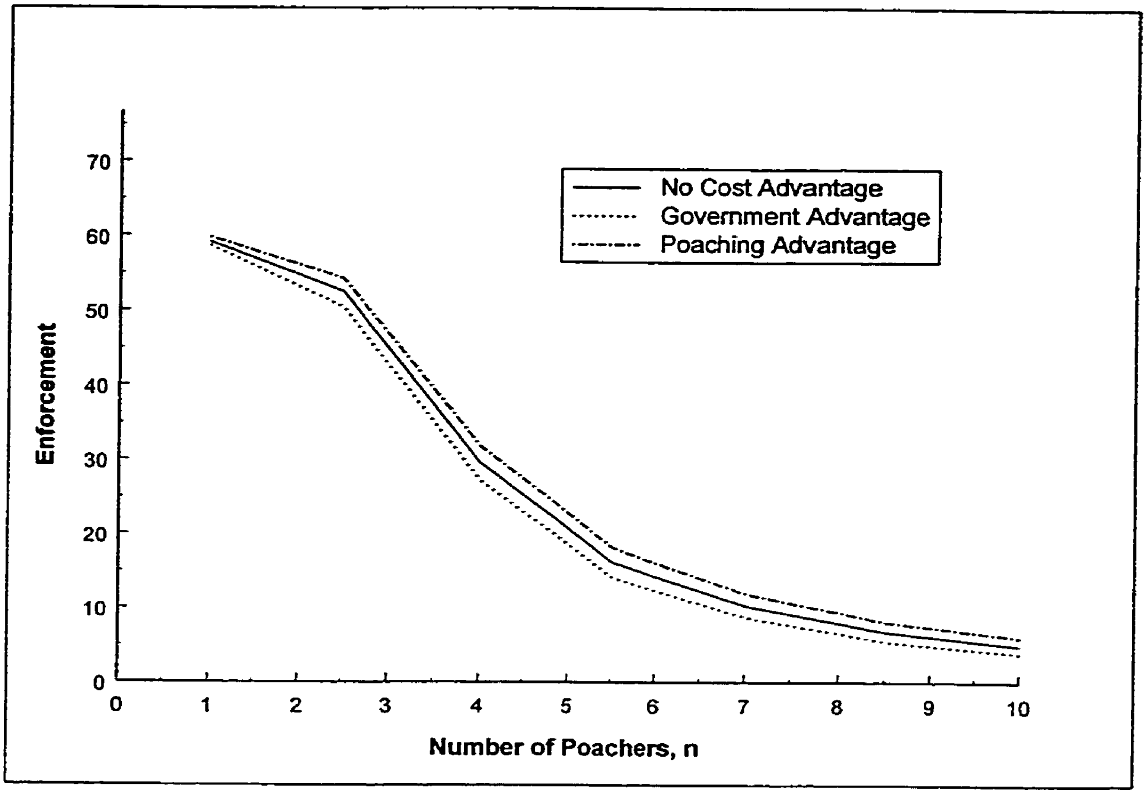

Figure 3.10 Enforcement levels (K^L) under stock-and-profit maximization.

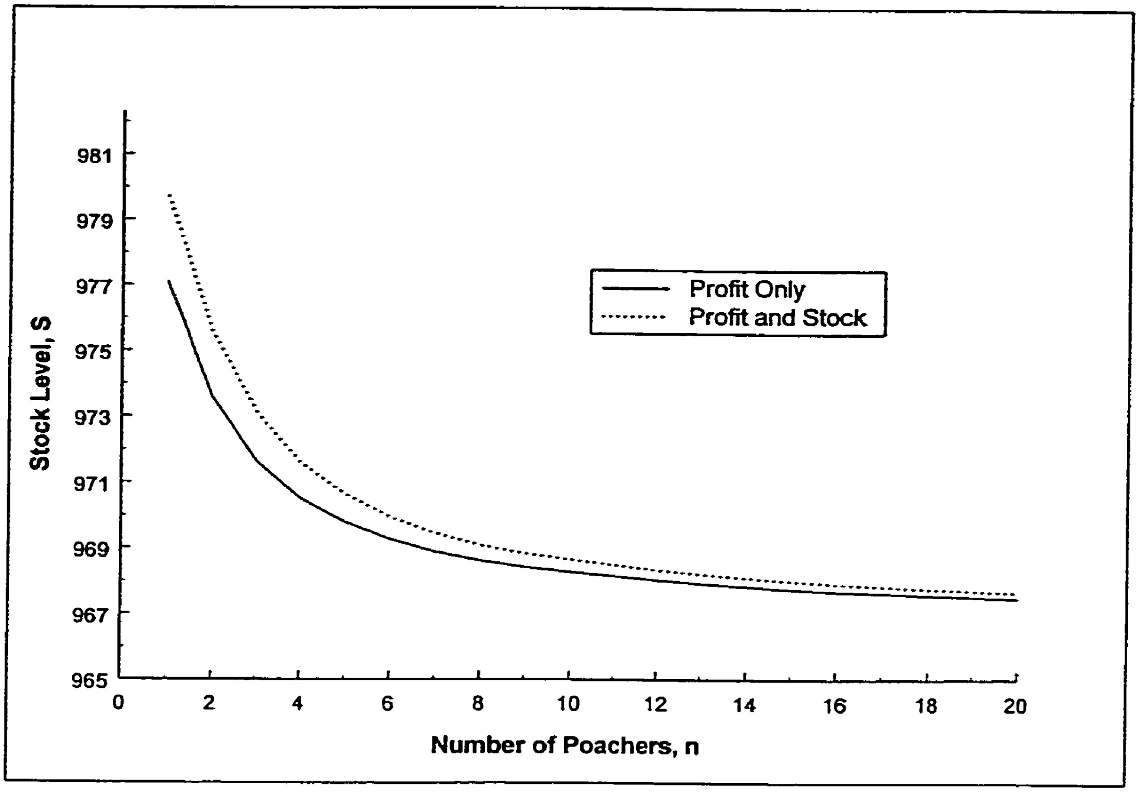

Figure 3.11 Stock levels under pure profit and stock-and-profit objectives.

Chapter 4

Strategic Policy and the Financing of Conservation

4.1 Introduction

Biodiversity preservation, or the protection of variety among species, is of a significant concern to many governments. While individuals may derive benefits (whether direct, indirect or other non-use in nature) from the species and their diversity, the public good aspect of these resources makes it difficult to finance the costs of conservation. One method of particular interest, gaining in popularity of use, is biodiversity prospecting, or the investigation of natural sources for commercially valuable pharmaceutical products or biotechnology. Recently, a number of governments have offered private firms the opportunity to sample species from within their borders in return for a share of the revenues (royalty) from any products resulting from the research and testing of the samples. A formal framework is developed to assess the effectiveness of royalties in extracting part of the surplus of firms and the influence of royalties on sampling practices.

Unlike other articles on biodiversity prospecting, such as Simpson et al. (1996) and Polasky and Solow (1995), the concern here is not directly the value of a particular species or collection thereof, but on the strategic manipulation of private incentives in order to achieve social objectives regarding sampling intensity to finance biodiversity conservation. Further, individual species are not assumed to have a single potential use, but a myriad of possible uses, which may result in several products, a single product, or none at all. In a related article, Barbier and Aylward (1996) consider a firm which chooses "information-generating effort" and "protection effort," but to assume that firms have a significant incentive to protect biodiversity (especially under the additional assumption of a potentially limitless supply of biochemical raw material) is quite suspect.[1] While correctly noting that the government must invest (or encourage firms to invest) in species information-generation, the claim that the returns from biodiversity prospecting will be insufficient to cover protection costs may be correct when royalties are involved but is less likely to be when more efficient surplus extraction methods are employed (that is, when the government appropriately selects a surplus extraction method combined with optimal sampling incentives). As will be shown below, the introduction of a royalty on revenues will necessarily reduce the total extractable surplus by decreasing the expected number of successful products.

4.2 Background and Literature

The obvious reason for sampling and testing species is to gain information. This information may be directly useful, such as natural chemicals which inhibit or cure human diseases or genes which can be used to enhance agricultural products, or may simply provide insights into the likelihood of other species containing useful information. For

[1] In their article, Barbier and Aylward assume that the supply of species available to be sampled depends on the amount of protected habitat, or protection effort, by the firm. More realistically, here it is assumed that governments protect habitat but must finance conservation by extracting part of the surplus of the prospecting firms.

an example of the latter, one may think of the rosy periwinkle of Madagascar, from which two important anti-cancer drugs (vincristine and vinblastine) have been derived, thus suggesting that the close relatives of this tropical plant are more likely to contain anti-cancer agents than other species. Even tested species with no successful applications provide information, given that their close relatives are similarly likely to be useless as sources of new products. In table 1, a number of pharmaceutical companies and agencies which have explored or are currently examining species for potential new products, including some of the world's largest, as well as the biological species being tested by each, are listed.

A significant issue in biodiversity prospecting is property rights, given the public good nature of biological or genetic resources (genotypes). While rights for developed products are well-defined by patent law in the developed world, international ownership of genetic material and species is much more problematic. For the purposes of this study, it is assumed that nations have sovereignty over their genetic resources, as provided for in the Rio Convention of the 1992 United Nations Conference on Environment and Development. Under the conditions of the Convention, countries also have the responsibility for conserving their biological resources and for using them in a sustainable manner. "In situ" conservation of ecosystems and natural habitats is expensive in terms of both preservation costs and the lost alternative use of land, and if biodiversity prospecting were a substantial and continual revenue generator for governments, the pressures against the conservation of biodiversity in developing countries could be lessened or even eliminated through compensation for lost opportunity costs. This is particularly important for "biodiversity rich" developing countries, as illustrated by the fact that 70 percent of the 3,000 species known to have anti-cancer properties are found in tropical forests (Sedjo, 1992).

Several authors have suggested that biodiversity prospecting can be used as a potential tool for conservation, such as Farnsworth and Soejarto (1985), Principe (1989), Wilson (1992), Reid et al. (1993), and Rubin and Fish (1994). Another subsequent branch of the literature, including Simpson et al. and Barbier and Aylward have questioned the effectiveness of such a tool, citing either low values of the "marginal" species or low royalty revenues to source governments. Regarding the latter, Hyde and Sedjo (1992) have graphically shown royalties to be both inefficient in extracting rents from logging firms and ineffective in inducing optimal deforestation rates, in addition to subjecting the country to significant risk. Similarly, lump sum charges will be shown here to dominate royalties in each of these respects.

Company	Items Collected	Cancer	AIDS	Inf.	C-V	G-I	O
Abbott Laboratories	M/P				•		•
Boehringer Ingelheim	M/P				•		•
Bristol-Myers Sqibb	F/M/MP	•					•
CIBA-GEIGY	M/MP	•		•	•		•
Eli Lilly	P/A	•			•		•
Glaxo Group Res.	F/M/MP	•		•	•	•	•
Inverni della Beffa	P			•	•		•
Merck and Co.	F/M/MP	•		•	•	•	•
Miles	M/P/MF				•		•
Monsanto	M/P			•	•		•
National Cancer Inst.	P/M/I/MF/A/IV	•				•	
Pfizer	P/SV	•		•	•	•	•
Pharmagenesis	TM			•			•
Phytopharmaceuticals	P	•					
Rhone-Poulenc Rorer	P/MM	•	•		•		•
Shaman Pharm.	P						•
SmithKline Beecham	M/MP			•		•	•
Sphinx Pharm.	P/MF/A	•				•	
Sterling Winthrop	M/MP	•		•			
Syntex Labratories	P/M	•		•	•		•
Upjohn Company	P/M		•		•		•

Table 4.1. Natural Item Collection and Screening by Company and Treatment Sought, 1950 to the present. M=microbes, P=plants, F=fungi, MP=marine plants,

A=algae, MF=marine fungi, I=Insects, IV=Invertebrates, SV=spider venom, TM=traditional Asian medicines, MM=marine microbes, Inf.=Inflammation, C-V=cardio-vascular problems, G-I=Gastro-intestinal problems, O=Other. Source: World Resources Institute (1990).

Low marginal values of some species in the wild, due to the sheer numbers of species existing on the planet, are indeed the appropriate concern for normative questions such as "how many species we should protect" (although only if social values were added to private prospecting values), but cannot be employed in positive questions such as "can rent extraction from pharmaceutical prospecting cover the costs of biodiversity preservation?" or "what proportion of existing biodiversity can be protected using rent extraction from prospecting firms?" As an example, suppose the millionth species in a collection has a negligible (private) marginal value (as shown by Simpson et al. for reasonable assumptions) which is slightly less than its marginal protection cost, implying that efficient resource use would dictate that this species should be allowed to disappear. Even at the firm level, such a species would not be sampled for potential pharmaceutical use. However, if one considers the first species in a collection, the same calculations suggest that marginal value will not be negligible (as would be expected), and clearly will exceed its marginal protection cost. Thus, pharmaceutical firms will have a significant expected surplus on species sampled earlier, which may be used to offset the losses incurred on later unsampled species, if such a surplus can be extracted by source governments and applied to conservation. In situations of uncertainty regarding future values and given the irreversibility of current actions, it is quite plausible that some species be protected despite marginal costs below their currently known marginal benefits (see Pindyck, 1991).

A logical question to ask is why a country would want to protect species in such a situation. While prospecting marginal costs and benefits may be relevant in an analysis of private incentives and decisions, there exists substantial work on social values that would suggest that biological species provide significant values to society beyond simple prospecting profits.[2] Low private values from prospecting may suggest that there is no incentive for firms to protect a large proportion of existing biodiversity but that is not to say that a social decision maker would not. To recapitulate, it is not the intention here to disprove prior studies which find low private marginal values, but to suggest that effective rent extraction may not be the poor conservation tool that it has recently been portrayed to be, and to detail the impact of available policy alternatives on sampling choice, knowledge accumulation and surplus extraction both in a steady state and over the period leading to such a stationary equilibrium. This is achieved in a dynamic model of capital (knowledge) accumulation in which private incentives and social incentives do not necessarily coincide due to insufficient information sharing and information spillovers.

4.3 A Bioprospecting Model

Consider a risk-neutral firm choosing the number of species to be sampled at each point in time t, s_t, in the search for new pharmaceuticals or biotechnology, among many similar firms. Sampling and testing for viable products has a cost which depends on the number of species sampled, $c(s_t)$, with $c_s > 0$ and $c_{ss} \geq 0$. Other previous articles on biodiversity prospecting assume that the probability of finding a successful product is constant, but another possibility, to be described here, is that firms accumulate information, or knowledge, over time, which allows them to increase the likelihood of finding a successful product, in the manner of capital theory.

Denote the knowledge or information accumulated by a firm in question up to time t as k_t. The probability of any given species yielding a successful product is a priori constant, but knowledge allows the firm to better choose the species to be tested, so that the probability of finding a successful product at time t is higher as both

[2] Contingent valuation and travel cost studies of estimating existence and option values for different environmental amenities, such as Pearce (1990), Barbier et al. (1994) or Brown and Henry (1993), suggest that social values not included in private decisions may be significant.

knowledge and the number of species sampled increase, or $\pi(k_t, s_t)$, where $\pi_k > 0$, $\pi_{kk} \leq 0$, $\pi_s > 0$, $\pi_{ss} < 0$ and $\pi_{sk} = 0$. For simplicity, the probability of finding multiple successful products at any particular point in time t is zero. The value (net of production and development costs) of a successful product is constant at $\bar{v}$, and all products yield the same amount of profit (this value arises from the monopoly profits gained from a patent on the product for a finite period). One may think of more complex models in which the value of a successful product declines as the number of successes increases or increases as the total stock of biodiversity decreases. However, it is not clear whether the added value of such modifications will outweigh the costs of additional complexity.

4.3.1 Knowledge Accumulation and Sampling Intensity of the Firm

A representative firm's expected profits at each point in time t are given by

$$\Pi_t = \pi(k_t, s_t)\bar{v} - c(s_t) \tag{4.1}$$

or the expected net value of successful products less sampling costs. At time t, the firm's knowledge set includes the information accumulated in the past, net of depreciation, information generated from newly sampled species, and information derived from the past products of other firms in the industry. Knowledge thus accumulates according to

$$\frac{dk}{dt} \equiv \dot{k} = \phi(s_t) - \theta k_t \tag{4.2}$$

where $\phi(s_t)$ is the knowledge generated by the sampling of species, and θ is the "obsolescence rate" of information: as time progresses, some proportion of the knowledge accumulated becomes obsolete and worthless, with $0 < \theta < 1$. Typical in the biodiversity prospecting literature is the assumption that the number of potential samples is infinite (see Barbier and Aylward, for example) as there are millions of known species and countless products which may be derived from each species. This assumption, made for consistency and comparability across articles, is strengthened by the increasing resistance of virus strains to current products and new infectious diseases that are "discovered" regularly. Over an infinite horizon, the firm maximizes the discounted stream of profits, or

$$\int_0^\infty e^{-\delta t} \left[\pi(k_t, s_t)\bar{v} - c(s_t)\right] dt \tag{4.3}$$

where δ is the private discount rate. The corresponding Hamiltonian is

$$H = \pi(k_t, s_t)\bar{v} - c(s_t) + \mu[\phi(s_t) - \theta k_t] \tag{4.4}$$

where μ is the co-state variable, in this case the shadow price of information. Direct application of the Maximum Principle yields the optimality conditions

$$\pi_s \bar{v} - c_s + \mu\phi_s = 0 \tag{4.5}$$

$$\dot{\mu} = \mu(\delta + \theta) - \pi_k \bar{v} \tag{4.6}$$

and the transversality condition,

$$\lim_{T\to\infty} \mu_T k_T e^{-\delta T} = 0 \tag{4.7}$$

Equation (4.5) states that the sum of the expected benefit from an additional sampled species and the implicit marginal value of knowledge imparted by that species must equal the marginal cost of sampling, while (4.6) describes the movement of the shadow price of biodiversity. In the steady state, $\dot{\mu} = \dot{k} = 0$, implying

$$\mu = \frac{\pi_k \bar{v}}{\delta + \theta} > 0 \tag{4.8}$$

and

$$\phi(s) = \theta k_t \tag{4.9}$$

Using these conditions, the slope of the $\dot{k} = 0$ locus is positive and given by

$$\left.\frac{ds}{dk}\right|_{\dot{k}=0} = \frac{\theta}{\phi_s} > 0 \tag{4.10}$$

as $\theta > \rho$. From the time derivative of (4.5), $\dot{s} = 0$ in the steady state as well. Using (4.5) and $\dot{\mu} = \dot{s} = 0$,

$$\left.\frac{ds}{dk}\right|_{\dot{s}=0} = \frac{\pi_{kk}\bar{v}\phi_s}{c_{ss} - \pi_{ss}\bar{v} - \frac{\pi_k\bar{v}\phi_{ss}}{\delta+\theta}} < 0 \tag{4.11}$$

so that the $\dot{s} = 0$ locus is downward-sloping. These loci result in a unique saddle-point equilibrium and a negatively sloped optimal trajectory (or stable path).

4.3.2 Social Knowledge Accumulation and Sampling Intensity

One plausible objective of a government is to protect some positive proportion of its current biological diversity, presumably from the solution of a resource management problem accounting for alternative use values and benefits derived by individuals from the resource. A commonly cited difficulty in achieving such an objective is finding a source of funding. In addition to the recovery of biodiversity protection financing costs from bioprospecting, the social planner or government must take into account the knowledge accumulated by other firms but not observed by the individual firm under consideration.[3] This section will examine the solution to the social objective maximization in order to evaluate the methods of financing conservation in addition to determining how the government can modify the economic incentives a prospecting firm faces in order to achieve the sampling of species which is socially optimal. As in Simpson et al., the social ecological, moral or aesthetic values of biodiversity are ignored, as are the benefits of habitat protection (including ecotourism and recreation), so that the focus here is strictly on prospecting incentives. The social

[3] It is assumed that firms are not competing for identical products to ensure there are no problems of "first discovery" or information-masking.

knowledge dynamics are

$$\dot{k} = \phi(s_t) - \theta(k_t + K_t) \tag{4.12}$$

where K_t is the knowledge accumulated by other firms. Here, the social planner takes into account the current knowledge accumulated by other firms, which is not observed by the firms when its decisions are made. In this way, the social planner serves to remedy information sharing barriers between firms. In addition to accounting for the positive knowledge externality, the government can extract the surplus by charging an entry fee, $F \geq 0$, which will not distort sampling choice. With risk-neutral firms, it is possible for the government to set F such that zero profits are earned by each firm (more on surplus extraction and the magnitude of F will follow later). From a social perspective, the probability of finding a successful product is a function of the total information accumulated in the economy, $k + K$. For simplicity, the social rate of time preference is assumed to be equal to the private discount rate, so that the planner's Hamiltonian is then

$$H = \hat{\pi}(k + K, s)\bar{v} - c(s) - F + q[\phi(s) - \theta(k + K)] \tag{4.13}$$

where q is the co-state variable, or the social shadow price of knowledge, and the resulting optimality conditions are given by

$$\pi_s \bar{v} - c_s + q\phi_s = 0 \tag{4.14}$$

$$\dot{q} = (\delta + \theta)q - \hat{\pi}_k \bar{v} \tag{4.15}$$

and

$$\lim_{T \to \infty} q_T z_T e^{-\delta T} = 0 \tag{4.16}$$

When $\dot{q} = 0$ (as in the steady state),

$$q = \frac{\hat{\pi}_z \bar{v}}{\delta + \theta} \tag{4.17}$$

Comparing the social and private optimality conditions, as long as $K > 0$, the number of species sampled (s) is certainly larger in the social case, as

$$q < \mu \tag{4.18}$$

and π is concave. In the social steady state,

$$\hat{\pi}_s \bar{v} - c_s + \frac{\hat{\pi}_k \bar{v}}{\delta + \theta} \phi_s = 0 \tag{4.19}$$

and

$$\phi(s) = \theta(k + K) \tag{4.20}$$

Accordingly, the slope of the zero-$\dot{s}$ locus is negative,

$$\left.\frac{ds}{dk}\right|_{\dot{s}=0} = \frac{\hat{\pi}_{kk} \bar{v} \phi_s}{c_{ss} - \hat{\pi}_{ss} \bar{v} - \frac{\hat{\pi}_k \bar{v} \phi_{ss}}{\delta + \theta}} < 0 \tag{4.21}$$

and the slope of the zero-$\dot{k}$ locus is positive,

$$\left.\frac{ds}{dk}\right|_{\dot{k}=0} = \frac{\theta}{\phi_s} > 0 \tag{4.22}$$

From the last equation and the steady state condition for knowledge, the $\dot{k} = 0$ locus has the same position (and slope) as in the private case. However, the social $\dot{s} = 0$ locus has a steeper slope and lies above the private locus. Dynamics off of these loci are given by

$$\frac{d\dot{k}}{ds} = \phi_s > 0 \tag{4.23}$$

and

$$\frac{d\dot{s}}{dk} = \frac{\hat{\pi}_{kk} \bar{v} \phi_s}{\hat{\pi}_{ss} \bar{v} - c_{ss} + q \phi_{ss}} > 0 \tag{4.24}$$

as illustrated by the arrows in the phase diagram of Figure 1. In the following section, a method for inducing a private firm to make its decisions correspond to the social optimum is presented.

4.4 Achieving Optimality through Government Subsidization

The previous section has shown that the private firm will undersample species (or biodiversity) relative to the social optimum. In order to induce the private firm to take into account the fact that the knowledge it accumulates also benefits other firms, the government can implement a subsidy for exploration,[4] financed by a lump-sum tax to balance the government budget. The subsidy is of the form λs, where λ is the subsidy per unit sampled. This modifies the private firm's profit function to

$$\Pi = \pi(k, s)\bar{v} - c(s) + \lambda s - F \tag{4.25}$$

The resulting optimality conditions are

$$\pi_s \bar{v} - c_s + \lambda + \mu \phi_s = 0 \tag{4.26}$$

and (4.6). The optimal subsidy to achieve the first-best is then

$$\lambda = (q - \mu)\phi_s \tag{4.27}$$

at each point in time and reflecting the difference between the two shadow prices of information. At the steady state the optimal subsidy becomes

$$\lambda = \frac{(\pi_k - \hat{\pi}_k)\bar{v}}{\delta + \theta}\phi_s \tag{4.28}$$

Therefore, the source government must provide a subsidy on sampling which depends on the difference in the marginal probabilities of a successful find between the social and private information set, the value of a successful discovery, the marginal information gained by sampling the last species, and the rates of knowledge obsolescence

[4]Here, as in other literature on the topic, perfect information regarding sampling and sampling costs is assumed. If there are informational asymmetries or costs of monitoring or measuring firm sampling, so that the optimal subsidy cannot be accurately determined, it may be possible that other rent extraction alternatives (such as auctioning of sampling rights, which also has the benefit of shifting risk onto prospecting firms) may be superior to both royalties and the alternative discussed here.

and time preference.[5] Specifically, and intuitively, the subsidy must be higher if the expected number of successful finds is higher, the information gained from another sample is larger, or the value derived from a successful product is larger.

4.5 Comparative Statics

To this point, the model parameters have been considered constant, but it is often interesting to examine how the steady state levels of knowledge and sampling are affected by changes in the values of the parameters, particularly by the rate of time preference, value of successful products (possibly from changes in patent life or imposed royalties) or the rate of information obsolescence and information sharing. With this goal, the total derivatives of the steady-state conditions can be written as

$$\begin{bmatrix} \phi_s & -\theta \\ \pi_{ss}\bar{v} - c_{ss} + \pi_k \bar{v}\phi_{ss} & \frac{\pi_{kk}\bar{v}\phi_s}{\delta+\theta} \end{bmatrix} \begin{bmatrix} ds \\ dk \end{bmatrix} =$$

$$\begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{21} & z_{22} & z_{23} & z_{24} \end{bmatrix} \begin{bmatrix} d\theta \\ d\delta \\ d\bar{v} \\ dK \end{bmatrix}, \qquad (4.29)$$

or

$$Ax = Zb$$

where

$$z_{11} = k + K$$

$$z_{12} = z_{13} = 0$$

$$z_{14} = \theta$$

[5]The subsidy could instead be applied to exploration costs, and by doing so the optimal subsidy would depend inversely on the marginal sampling cost.

$$z_{21} = \frac{\pi_k \bar{v} \phi_s}{(\delta + \theta)^2}$$

$$z_{22} = \frac{\pi_k \bar{v} \phi_s}{(\delta + \theta)^2}$$

$$z_{23} = \frac{-\pi_k \phi_s}{\delta + \theta}$$

and

$$z_{24} = \frac{-\pi_{kk} \bar{v} \phi_s}{\delta + \theta}$$

The determinant of the matrix A is thus

$$|A| = \frac{\pi_{kk} \bar{v} (\phi_s)^2}{\delta + \theta} + \theta \left[\pi_{ss} \bar{v} - c_{ss} + \pi_k \bar{v} \phi_{ss} \right] < 0 \tag{4.30}$$

One of the most significant parameters, and one of the most important features of biodiversity prospecting itself, is the value of a successful product, $\bar{v}$. Using Cramer's rule, (4.29) and (4.30),

$$\frac{ds}{d\bar{v}} = \frac{-\theta}{|A|} \left\{ \frac{\pi_k \phi_s}{\delta + \theta} \right\} > 0 \tag{4.31}$$

and

$$\frac{dk}{d\bar{v}} = \frac{1}{|A|} \left\{ \frac{-\pi_k (\phi_s)^2}{\delta + \theta} \right\} > 0 \tag{4.32}$$

As would be expected, when the value of a successful find increases, the number of species sampled and the knowledge accumulated in the steady state increase. A higher value, other things constant, increases expected revenue, and thus increases marginal revenue above the marginal cost of sampling. Sampling intensity increases as a result, until equality between marginal cost and marginal benefit is restored. A royalty, which reduces the value of a successful product to the firm by the amount of the tax, would then decrease the number of species sampled, contributing to enhance the undersampling problem associated with unregulated firms (see the following section). In the steady state, any increase in the number of species sampled must be accompanied by an increase in knowledge (from (4.9)), given that the newly acquired information (from sampling and information sharing) and the depreciated knowledge are the same.

With respect to the rate of time preference,

$$\frac{ds}{d\delta} = \frac{\theta}{|A|}\left\{\frac{\pi_k \bar{v}\phi_s}{(\delta+\theta)^2}\right\} < 0 \tag{4.33}$$

and

$$\frac{dk}{d\delta} = \frac{1}{|A|}\left\{\frac{\pi_k \bar{v}(\phi_s)^2}{(\delta+\theta)^2}\right\} < 0 \tag{4.34}$$

As firms (and society) become less future oriented (that is, have a higher discount rate), accumulated knowledge becomes less important, as the use of that knowledge in later periods generates revenues which are of lower consequence to the firm. In other words, the shadow price of knowledge is lowered, which in turn decreases the knowledge accumulated. As above, any decrease in the steady state level of knowledge necessarily decreases the number of species sampled as well.

As mentioned previously, to capture the social public good aspect of information, the newly accumulated knowledge of other firms, described above by K. For the steady state,

$$\frac{ds}{dK} = \frac{\theta\pi_{kk}\bar{v}\phi_s}{(d+\theta)}\frac{1}{|A|}\left\{\frac{1-\delta-\theta}{\delta+\theta}\right\} \tag{4.35}$$

which is ambiguous in sign, and

$$\frac{dk}{dK} = \frac{1}{|A|}\left\{\frac{-\phi_s\pi_k\bar{v}\phi_s}{\delta+\theta} - \theta(\pi_{ss}\bar{v} - c_{ss} + \pi_k\bar{v}\phi_{ss})\right\} < 0 \tag{4.36}$$

As the knowledge of other firms increases, the social benefit of the individual firm's knowledge accumulation also decreases from the decreasing marginal probability, and accordingly knowledge in the steady state for the firm in question decreases. However, since the higher K also implies more capital is depreciating at the steady state, this may imply that the individual firm samples more than it did prior to the increase in K.

As the optimal subsidy also depends on the rate of obsolescence of knowledge, it may also be worthwhile to examine the effect of a change in this rate on the steady state values. In this particular case, the effect is given by

$$\frac{ds}{d\theta} = \frac{1}{|A|}\left\{\frac{(k+K)\pi_{kk}\bar{v}\phi_s}{\delta+\theta} + \theta\frac{\pi_k\bar{v}\phi_s}{(\delta+\theta)^2}\right\} \tag{4.37}$$

which is ambiguous in sign. The relationship between optimal knowledge (or information) accumulation and this parameter is nonetheless unambiguously negative, given by

$$\frac{dk}{d\theta} = \frac{1}{|A|}\left\{\frac{\pi_k\bar{v}(\phi_s)^2}{(\delta+\theta)^2} - (k+K)\left[\pi_{ss}\bar{v} - c_{ss} + \pi_k\bar{v}\phi_{ss}\right]\right\} < 0 \tag{4.38}$$

As the rate of knowledge obsolescent increases, accumulating knowledge has less value in the long term, and therefore less knowledge is accumulated in the steady state. The ambiguity of number of species sampled with respect to the rate of obsolescence follows from this, as sampling must decrease if the decrease in knowledge offsets the increase in the obsolescence rate (implying that less knowledge is depreciating in the steady state) and increase if the opposite is true.

4.6 Comparative Dynamics

This section details the behaviour of the control and state variables over time, as described by a linear approximation of the stable path around the steady state, of both the private and social solutions. Comparisons of paths to the steady state was achieved through a computer simulation which, given the linear approximation and initial conditions, iterated to a steady state numerically.[6] The private accumulation of knowledge requires the private Jacobian evaluated at the private steady state (k^*, s^*, μ^*)

$$J_P^* = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix} = \begin{bmatrix} -\theta & c_{ss}^* - \pi_{ss}^*\bar{v} - \mu^*\phi_{ss}^* \\ -\pi_{kk}^*\bar{v} & \delta+\theta \end{bmatrix} \tag{4.39}$$

[6] Although the variables approach the steady state asymptotically, this section refers to the "time required to reach the steady state" as being number of periods necessary for the state and choice variables to become within $0.1*10^{-9}$of their steady state values.

The eigenvalues (ξ_1^*, ξ_2^*) of this private Jacobian matrix are such that

$$\begin{vmatrix} j_{11} - \xi_1^* & j_{12} \\ j_{21} & j_{22} - \xi_2^* \end{vmatrix} = 0 \tag{4.40}$$

the solution of which yields

$$\xi_1^* = \frac{1}{2}\left[\delta + \sqrt{\delta^2 + 4\theta\delta + 4\theta^2 - 4\bar{v}\pi_{kk}^* c_{ss}^* + 4\bar{v}\pi_{kk}^* \phi_{ss}^* + 4\bar{v}\pi_{kk}^* \mu^* \phi_{ss}^*}\right] \tag{4.41}$$

and

$$\xi_2^* = \frac{1}{2}\left[\delta - \sqrt{\delta^2 + 4\theta\delta + 4\theta^2 - 4\bar{v}\pi_{kk}^* c_{ss}^* + 4\bar{v}\pi_{kk}^* \phi_{ss}^* + 4\bar{v}\pi_{kk}^* \mu^* \phi_{ss}^*}\right] \tag{4.42}$$

A linear approximation of the stable path around the private steady state is given by

$$\mu = \mu^* + \frac{j_{21}}{\xi_1^* - j_{22}}(k_0 - k^*) = \mu^* - \frac{\pi_{kk}^* \bar{v}}{\xi_1^* - \delta - \theta}(k_0 - k^*) \tag{4.43}$$

The social knowledge accumulation Jacobian evaluated at the social steady state $(\tilde{k}, \tilde{s}, \tilde{q})$ is

$$J_S^* = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} \theta & \tilde{c}_{ss} - \tilde{\pi}_{ss}\bar{v} - \tilde{q}\tilde{\phi}_{ss} \\ -\tilde{\pi}_{kk}\bar{v} & \delta + \theta \end{bmatrix} \tag{4.44}$$

which has eigenvalues $(\tilde{\xi}_1, \tilde{\xi}_2)$ such that

$$\begin{vmatrix} a_{11} - \tilde{\xi}_1 & a_{12} \\ a_{21} & a_{22} - \tilde{\xi}_2 \end{vmatrix} = 0 \tag{4.45}$$

so

$$\tilde{\xi}_1 = \frac{1}{2}\Bigg[-\delta - \Bigg(\Bigg(\delta^2 - 2\delta^2 + 4\theta\delta + 4\theta^2$$

$$-4\bar{v}\tilde{\pi}_{kk}\tilde{q}\tilde{\phi}_{ss} + 4\bar{v}^2\tilde{\pi}_{kk}\tilde{\pi}_{ss} - 4\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} + 8\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} - 4\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} - 8\bar{v}^2\tilde{\pi}_{kk}\tilde{\pi}_{ss}$$

$$+4\bar{v}^2\tilde{\pi}_{kk}\tilde{\pi}_{ss} + 4\bar{v}\tilde{q}\tilde{\pi}_{kk}\tilde{\phi}_{ss} \Bigg)^{1/2}\Bigg)\Bigg] \tag{4.46}$$

and

$$\tilde{\xi}_2 = \frac{1}{2}\Bigg[-\delta + \Bigg(\Bigg(\delta^2 - 2\delta^2 + \delta^2 + 4\theta\delta + 4\theta^2$$

$$-4\bar{v}\tilde{\pi}_{kk}\tilde{q}\tilde{\phi}_{ss} + 4\bar{v}^2\tilde{\pi}_{kk}\tilde{\pi}_{ss} - 4\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} + 8\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} - 4\bar{v}\tilde{\pi}_{kk}\tilde{c}_{ss} - 8\bar{v}^2\tilde{\pi}_{kk}\tilde{\pi}_{ss}$$

$$+4\bar{v}^2\bar{\pi}_{kk}\bar{\pi}_{ss} + 4\bar{v}\tilde{q}\bar{\pi}_{kk}\bar{\phi}_{ss}\Big)^{1/2}\Big)\Big] \tag{4.47}$$

A linear approximation of the stable path around the social steady state is given by

$$\mu = \tilde{\mu} + \frac{a_{21}}{\bar{\xi}_1 - a_{22}}(k_0 - \tilde{k}) = \tilde{\mu} - \frac{\bar{\pi}_{kk}\bar{v}}{\bar{\xi}_1 - \delta - \theta}(k_0 - \tilde{k}) \tag{4.48}$$

Using again the numerical example, the private and social dynamics of knowledge accumulation (k_t) and number of species sampled (s_t) over time, given the private stable trajectory approximation in (4.43) and the social stable path approximation in (4.48), are shown in Figures 4.2 and 4.3. Because of the additional benefits derived from information sharing, knowledge tends to be accumulated more rapidly by the social planner (or regulated firms) than by unregulated private firms. This requires that sampling in earlier periods be higher in the social solution, but social sampling also remains higher - eventually levelling off at a higher sampling intensity than the unregulated sampling level. Further, it is obvious that the social sampling rate and knowledge level reach a steady state much earlier than the private sampling rate and knowledge level, following from the lesser private incentives to accumulate knowledge and thus to sample relative to social incentives. In such a case, it is possible for the steady state levels of both situations to be relatively close but to also have even larger extractable surplus losses over the period in which the private accumulations continue to adjust while the social accumulations are at their steady state (as the private choice of s and thus k lies strictly below the corresponding social steady state levels).

As it has now been shown that both the private steady state and private dynamics are inferior to social dynamics, the remainder of this section will focus on the extent of changes in social dynamics as a result of changes in model parameters. For a decrease in θ, as shown in Figures 4.4 and 4.5, knowledge accordingly accumulates at a slower rate, although to a higher steady state level. A higher obsolescence rate implies that additional sampling is necessary to offset natural losses, and despite higher sampling, knowledge is lower at the steady state and it takes more time to reach its new level. In contrast to the effects of these changes, a reduction in the value of a successful product has very little or no impact on the time of adjustment for s and k, despite significantly different steady state levels of both variable, as shown in Figures 4.6 and 4.7. This suggests that royalties, which reduce the value to the firm of a success, would not greatly affect the time of adjustment to the new steady state. Further analysis of the effects of royalties is left to the following section.

4.7 Expropriating the Surplus of Firms

In practice, royalty agreements have been employed to share profits between the firms and the source country, as intended by the Biodiversity Convention. Royalties are usually based on the expected value of the potential product, with royalty figures typically ranging from 1 to 5 percent. In probably the most publicized agreement, Costa Rica's Instituto Nacional de Biodiversidad (INBio) signed a contract with US pharmaceutical multi-national Merck & Co. in 1991 to pay $1 million over two years for the opportunity to search for sources of new pharmaceuticals from 1000 samples from the diverse species of Costa Rica's tropical forests, in return for royalties paid on the therapeutics developed. INBio, as a non-governmental organization, cannot sell the exclusive rights to any particular species, but its mission to integrate Costa Rica's biodiversity into a sustainable development strategy is consistent with the Biodiversity Convention. The Merck-INBio agreement was renewed in 1994 (Zebich-Knos, 1997), under similar terms.

If the objective of the government is to expropriate the surplus gained by firms in addition to achieving the optimal sampling intensity, it only has to increase the amount of the lump-sum tax F. When looking at the sampling intensity alone, the government sets the lump-sum tax such that the subsidy paid out to firms is exactly offset. However, substantial profits are earned by the firm when a successful product is found, which may not accrue to the nation providing the samples, as in the case where pharmaceutical companies of the developed world purchase the samples from developing countries. Like the Costa Rica-Merck agreement, most contracting of this type has involved a royalty paid on successful products, and sometimes an up-front fee to cover costs.[7] A constant royalty rate, r, would modify the periodic expected profit of a firm to

$$(1-r)\pi(k_t, s_t)\bar{v} - c(s_t) + \lambda_t s_t \tag{4.49}$$

From the above analysis, we can see that such a policy results not only in the sub-optimal sampling incurred due to the externality effect, but compounds this problem by reducing the value of the successful product by the amount of the tax/royalty. In other words, the positive tax (royalty) on successful finds forces firms to sample fewer products than they would with no regulation, which then reduces the expected number of successful products found and results in a lower extractable surplus. Referring once again to the numerical example, the reduction in the total extractable surplus at various royalty rates, given social optimality (that is, a sampling subsidy of λ_t which satisfies (4.28)), over 50 periods is shown graphically in Figure 4.12. Surplus loss in increasing in the tax rate (r), to the point of no sampling and zero surplus under a 100 percent royalty, so that the total extractable surplus maximizing royalty rate is in fact zero. It should be noted that the suboptimality of royalties, while true in the circumstances described here, may not hold if the assumption of the risk-neutrality of firms is abandoned and/or uncertainty is introduced.

With a subsidy and lump-sum tax, it is possible to induce firms to sample the socially optimal number of species while still expropriating some or all of the surplus earned from successful products.[8] As mentioned earlier, choosing an F that is inde-

[7] In addition to covering costs, ten percent of the up-front fee in the Costa Rica-Merck agreement is to go toward conservation efforts.

[8] For a graphical exposition of the extraction of rents from firms in the overuse of land, see Hyde and Sedjo (1992).

pendent of sampling intensity has the benefit of not distorting the decision making of the firms, unlike a royalty, and allows the risk associated with uncertain search to be completely shifted onto the firms performing the exploration, a point particularly relevant to developing countries. Here it is assumed that there is no competition among countries - one can think only of endemic species, of a global context, or of other reasons why this would be the case. Nonetheless, competition would be as likely under a royalty-based system as with other rent extraction alternatives.[9] The maximum F a government could set would be given by the firm's expected profits, or

$$F = \pi(k,s)\bar{v} - \lambda(c(s) - s) \tag{4.50}$$

given knowledge accumulation dynamics and λ from (4.27).

In order to evaluate the extent to which rent extraction can finance conservation, it is necessary to know the value of biodiversity prospecting. A number of articles, including Farnsworth and Soejarto (1985), Principe (1989), McAllister (1991), Harvard Business School (1992), Pearce and Puroshothamon (1992), Aylward (1993), and Barbier and Aylward have attempted to place values on untested species in situ, with results ranging from US$44 to US$23.7 million. Barbier and Aylward estimate the expected royalty per sample to be US$233, which implies (given the assumed 2 percent royalty) that the expected net revenues per sample is $11650. Using their estimates (40 years, 2000 samples per year, 10 percent discount rate), full surplus extraction would yield a present value of almost $228 million, compared to just $4.6 million by royalties, to the government. The estimated costs (net of sampling fees and collection costs) of protecting all 500,000 species for the 40 year period (although only 40000 species are sampled with 2 samples per species) in Costa Rica is $244 million, which suggests that this country would lose $17 million by lump sum taxation compared to a loss of $240 million by royalties (see Table 4.2), or would cover 93.4 percent

[9] These international conflicts are also ignored in Simpson, Sedjo and Reid, and in Barbier and Aylward.

of conservation costs. However, this assumes that the number of species sampled is constant across the two alternatives. As can be seen from the above analysis, more species would be sampled in both the no intervention situation and the subsidization case. If the number of species sampled were to increase by 5 percent (column 4), the source country would lose just $6 million over costs, and if sampling were to increase by 10 percent as a result of the subsidization of costs (column 5), it would be possible for the government to break even if the present value of the subsidies were not to exceed $5.12 million (or $238 dollars per sample). These figures, although based on pharmaceutical industry data and sampling history, are clearly for illustrative purposes only, but they do show the possibility of governments extracting enough of the surplus of prospecting pharmaceutical firms to cover the costs of biodiversity preservation. Further, as biodiversity has values other than new products (harvesting of species, ecosystem support, existence values to individuals, etc.), the burden of covering all the costs of conservation should not necessarily be placed upon prospecting. Nonetheless, this straightforward exposition based on reasonable estimates suggests that covering costs is at least possible, if not probable.

	Royalty	Lump-Sum	Lump-Sum	Lump-Sum
Number of Samples	2000	2000	2100	2200
Expropriated Surplus	4.56	227.85	239.24	250.64
Sample Fees	1.23	1.23	1.29	1.36
Total Government Revenues	5.79	229.08	240.53	251.76
Costs of Biodiversity Protection	244.48	244.48	244.48	244.48
Costs of Collection	0.98	0.98	1.03	1.08
Costs of Taxonomic Information	0.98	0.98	1.03	1.08
Total Government Costs	246.44	246.44	246.54	246.64
Government Profit (Loss)	(240.65)	(17.36)	(6.01)	5.12

Table 4.2. Present Values of Costs and Extracted Surplus, Royalties v.. Lump-Sum Taxes, in millions of US dollars, extrapolated Aylward and Barbier data.

This analysis can be extended to incorporate a variety of assumptions of success probabilities, net revenues and number of species sampled found in the literature and protection cost data from the Guanacaste National Park in Costa Rica (from Aylward and Barbier) in order to suggest possible estimates of potential surplus extraction and percentage of Costa Rican biodiversity protected. Estimates of revenues net of production, marketing, distribution and research and development costs typically range from \$50 million to \$300 million (or \$6 million to \$36.6 million per year over an 18 year patent life with a discount rate of 10 percent), which may seem high to some but one only has to look so far as net income from pharmaceutical companies such as Merck and Company, which made profits of almost US\$4 billion in 1996, and Eli Lilly Pharmaceutical Co. which made net profits of almost \$88 million from vincristine and vinblastine in 1985 alone (Farnsworth, 1988). From data from US Food and Drug Administration, reported in Simpson et al., there were on average 23.8 new drugs approved from 1981 to 1993 (with no discernible trend). Approximately one-third of current pharmaceuticals are derived or synthesized from natural products, or roughly 8 products per year. One must be careful when comparing the costs of biodiversity preservation of a single country to revenues from biodiversity prospecting in general. However, the chosen sampling intensities have low expected numbers of hits except when the probability of success is relatively very high. For Costa Rica, which contains or shares more than one quarter of the known species on earth, it is not unreasonable to assume that some positive proportion could be appropriated by its government, particularly when many species are endemic to Costa Rica. Using the most extreme assumptions, biodiversity prospecting may be expected to protect from 2 percent per year (present value net revenues of \$50 million, 1000 samples per year, and a success probability of 1 in 200,000 samples) to 27,500 percent per year or

275 times the biodiversity that currently exists (present value net revenues of $275 million, 5000 samples per year, and a success probability of 1 in 200 samples). The latter would not be sustainable for long periods due to the large numbers of samples performed each year, but these assumptions are not as unreasonable as one may initially perceive, falling within the parameters from certain articles described above. Conservative estimates from the pharmaceutical industry and other literature would suggest that the present value of net revenues would be roughly $125 million ($15 million per year), the number of samples per year as 1,500 and a success probability of around 1 in 13,333 samples, suggesting that revenues from prospecting alone could finance the protection of over 56 percent of Costa Rican biodiversity. Lastly, more reasonable estimates of $150 million net revenues, 2,500 samples and a 0.001 probability would provide revenues exceeding the level necessary to protect all of the 500,000 species. The probability of finding a successful product may in fact be substantially higher, given the limited screening technology and effort that has generated some 2,000 naturally-derived pharmaceuticals currently prescribed in the developed world. The exact protection-financing ability of prospecting would of course require more accurate information than currently available, but it seems plausible that prospecting could in fact generate funds to protect a more significant proportion of biodiversity conservation than previously claimed.

4.8 Concluding Remarks

Many countries, particularly those at lesser stages of development, have recently become increasingly concerned with the ability of biodiversity contracts to finance conservation efforts. Initial agreement attempts have employed royalties, or a tax on net revenues, as a means to this end, but such methods will necessarily reduce the extractable surplus available for governments. Instead of taxing successful products via royalties, source governments must combine subsidies on sampling (or sampling costs) with up-front lump sum fees. In this way, governments can achieve the targets of inducing the socially optimal level of sampling intensity and extracting the entire surplus earned by firms above normal profits, to be applied to biodiversity preservation, in addition to shifting the risk associated with exploration onto those firms performing the search. Royalties and low up-front fees, as seen in recent agreements, force developing countries to not only pay for biodiversity conservation themselves but also bear some of the risk associated with exploration. Zero royalties and annual up-front fees, on the other hand, allow developing governments to finance some proportion of biodiversity, an attractive proposition given the limitations of other sources of funding. Even with respect to risk-sharing, smaller lump-sum charges would dominate royalties by increasing the total surplus earned (and divided).

Some recent studies have suggested that low values of the "marginal species" necessarily imply that biodiversity prospecting is a poor tool for conservation. Due to the extremely large numbers of species existing currently, it is virtually uncontestable that *private* values from these species is negligible and below their marginal protection cost, despite potentially high social values not captured in market transactions. However, pharmaceutical patents provide firms with substantial monopoly profits which normally exceed research and development, production and distribution costs, so that rent extraction may indeed be a viable option for governments desiring to finance biodiversity conservation. Employing data from the pharmaceutical industry and Costa Rica, it has been shown that it is not unreasonable that a significant proportion of preservation costs could be paid through surplus extraction from biodiversity prospecting.

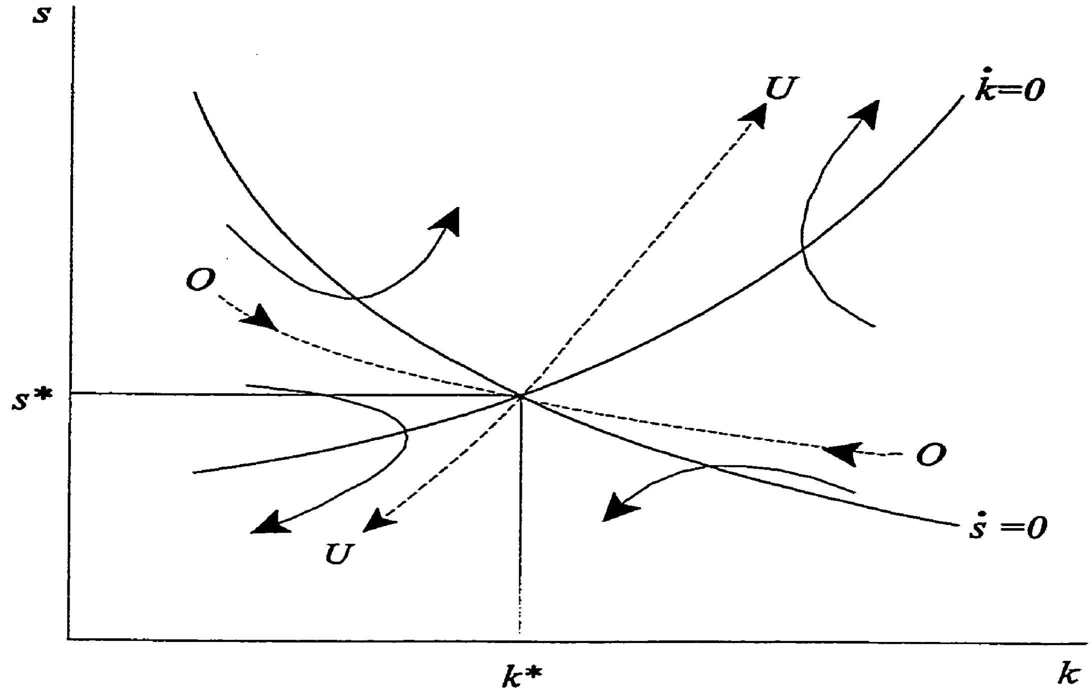

Figure 4.1 Phase diagram in (s,k)-space. The steady state is (s*,k*), the stable trajectory is *OO*, and the unstable trajectory is *UU*.

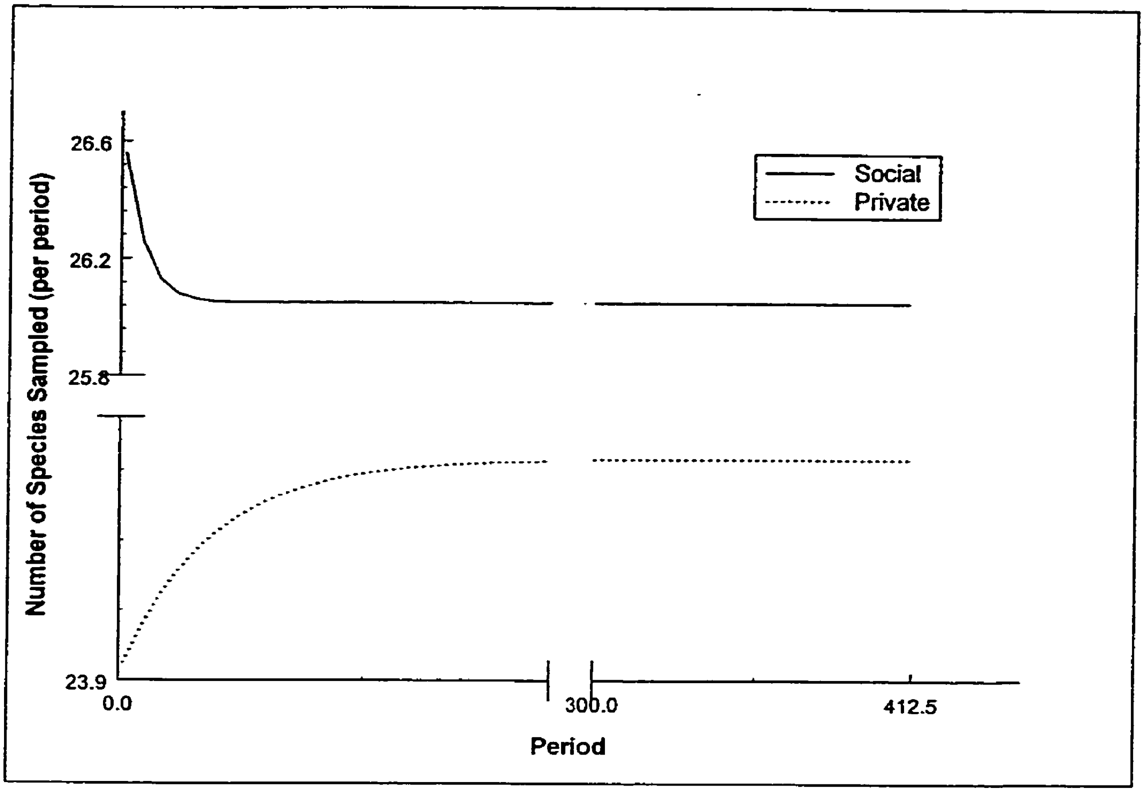

Figure 4.2. Social and private sampling rates.

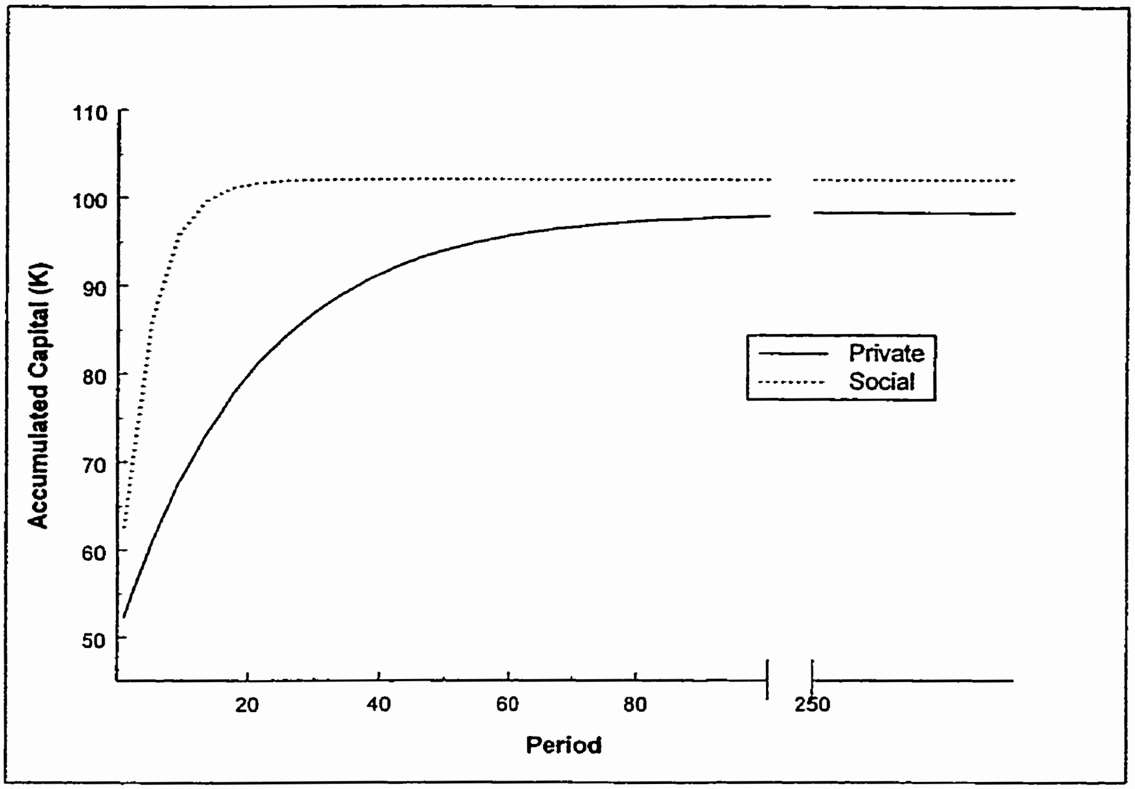

Figure 4.3 Social and private knowledge accumulation.

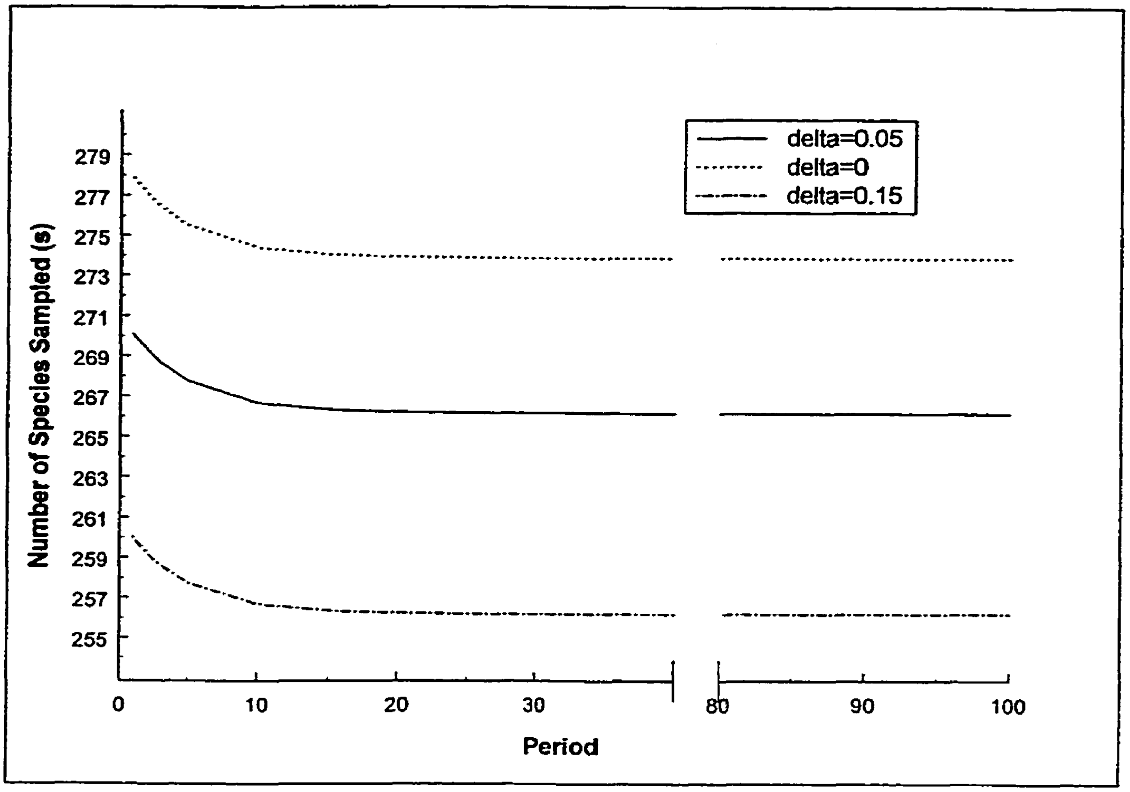

Figure 4.4 Social sampling rates at different discount rates.

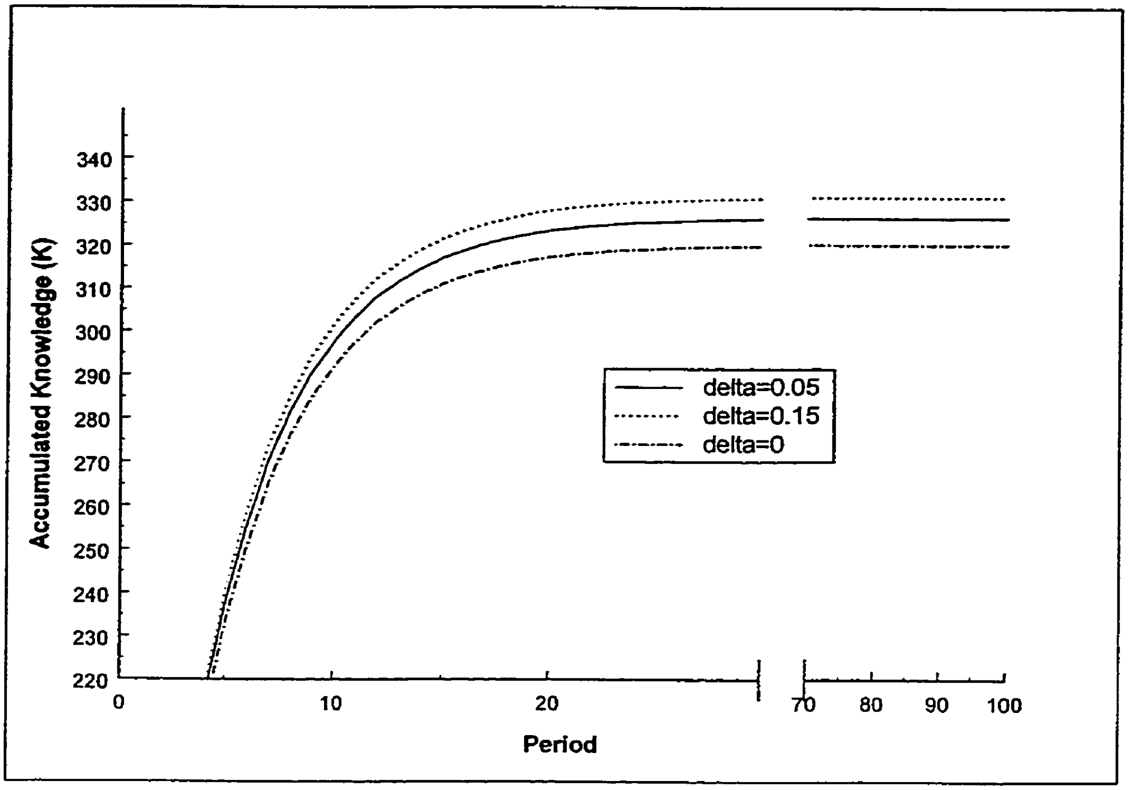

Figure 4.5 Social knowledge dynamics under different discount rates.

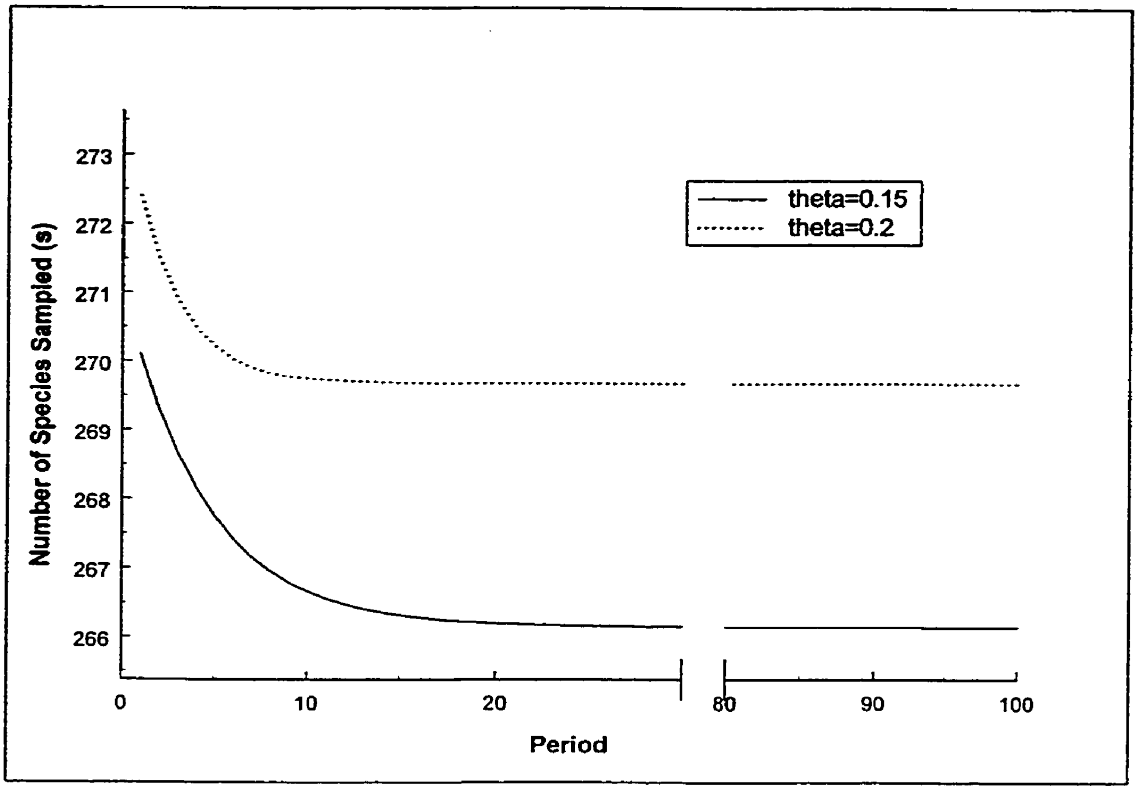

Figure 4.6 Social sampling rates at difference rates of knowledge obsolescence.

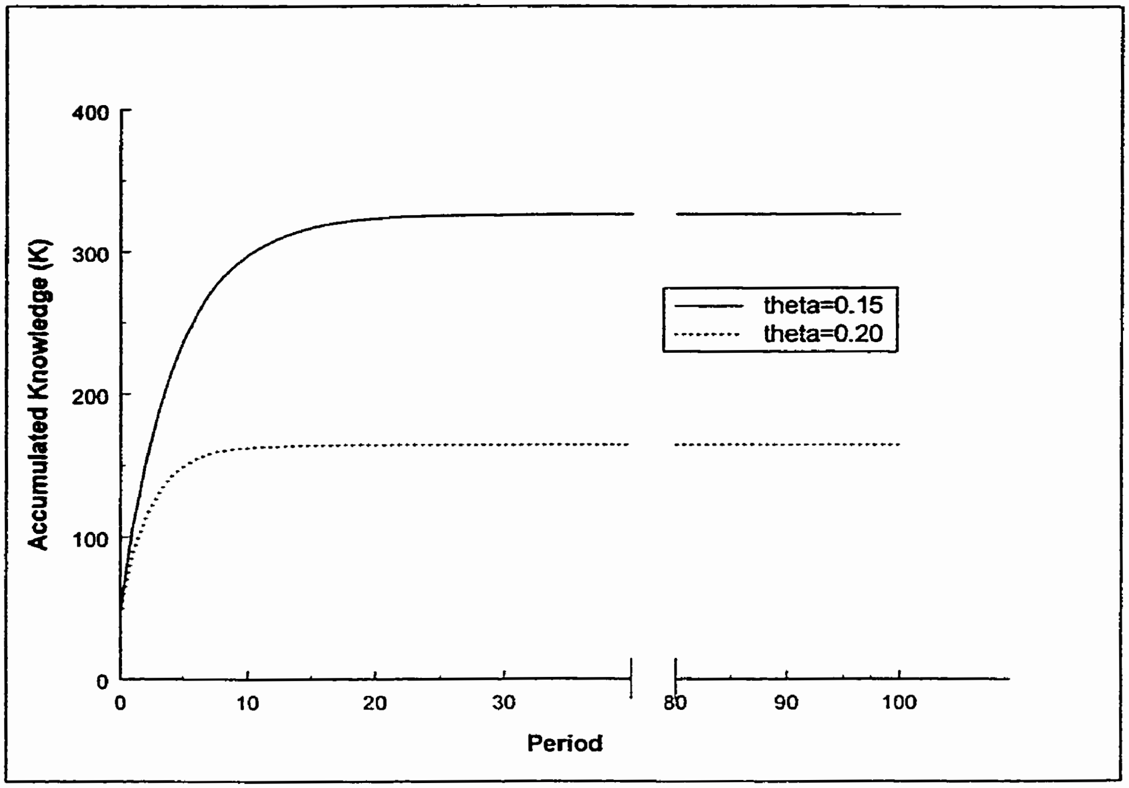

Figure 4.7 Social knowledge accumulation at different rates of knowledge obsolescence.

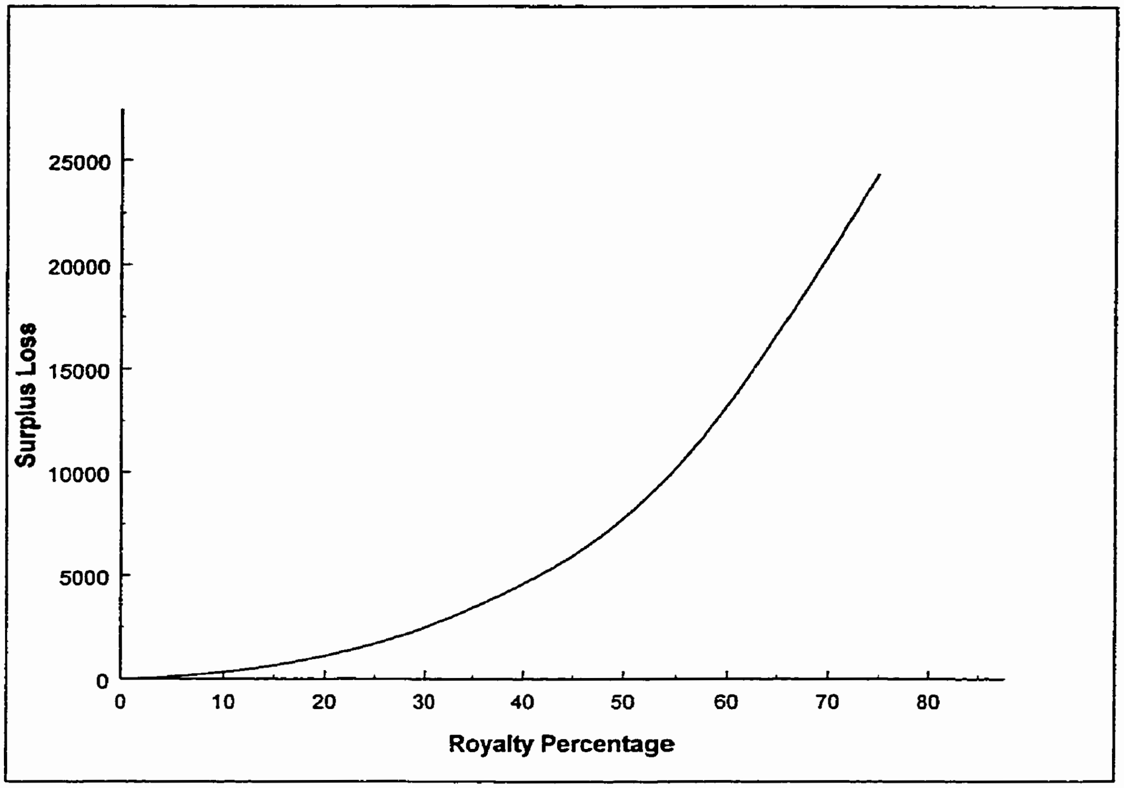

Figure 4.8 Total extractable surplus loss at different royalty rates.

Bibliography

[1] Anderson, Lee G., and Dwight R. Lee (1986), "Optimal Governing Instrument, Operation Level and Enforcement in Natural Resource Management: The Case of the Fishery," *American Journal of Agricultural Economics* 68, 678-690.

[2] Arrow, Kenneth J., and Anthony C. Fisher (1974), "Environmental Preservation, Uncertainty, and Irreversibility," *Quarterly Journal of Economics* 88, 312-319.

[3] Aylward, Bruce A., *The Economic Value of Species Information and Its Role in Biodiversity Conservation: Case Studies of Costa Rica's National Biodiversity Institute and Pharmaceutical Prospecting - Report to the Swedish International Development Authority* (Environmental Economics Centre, London, 1993).

[4] Barbier, Edward B., and Bruce A. Aylward (1996), "Capturing the Pharmaceutical Value of Biodiversity in a Developing Country," *Environmental and Resource Economics* 8, 157-181.

[5] Barbier, Edward B., J. C. Burgess, and Carl Folke, *Paradise Lost? The Ecological Economics of Biodiversity* (Earthscan, London, 1994).

[6] Barbier, Edward B., Joanne C. Burgess, Timothy Swanson, and David W. Pearce, *Elephants, Economics and Ivory* (Earthscan Publications Ltd.: London, 1990).

[7] Barnes, J. I. (1996), "Changes in the Economic Use Value of Elephant in Botswana: the Effect of International Trade Prohibition," *Ecological Economics* **18**, 215-230.

[8] Barrett, Scott (1992), "Economic Growth and Environmental Preservation, *Journal of Environmental Economics and Management* **23(3)**, 289-300.

[9] Barrett, Scott (1995), "On Biodiversity Conservation," in *Biodiversity Loss: Economic and Ecological Issues*, Charles Perrings et al., eds. (Cambridge University Press, New York, 1995).

[10] Bergeron, Nancy (1998), "The Black Market in Endangered Species, Economic Incentives and CITES Policy," Mimeo.

[11] Bishop, Richard C., and Michael P. Welsh, "Existence Values in Benefit-Cost Analysis and Damage Assessment," *Land Economics* **68**: 405-417.

[12] Brown, Gardner, and David Layton (1997), "Saving Rhinos," Mimeo.

[13] Brown, Gardner M. and W. Henry, "The Economic Value of Elephants," in *Economics and Ecology: New Frontiers and Sustainable Development,* E. B. Barbier, editor (Chapman and Hall, London, 1993).

[14] Bulte and Van Kooten (1996), "A Note on Ivory Trade and Elephant Conservation," *Environmental and Development Economics* 1(4), 433-443.

[15] Chen, Zhiqi (1997), "Negotiating an Agreement on Global Warming: A Theoretical Analysis," *Journal of Environmental Economics and Management* **32(2)**, 170-188.

[16] Clark, Colin W. (1973), "Profit Maximization and the Extinction of Animal Species," *Journal of Political Economy* **81**, 163-173.

[17] Clark, Colin W., *Mathematical Bioeconomics: The Optimal Management of Renewable Resources* (John Wiley & Sons, Inc.: New York, 1976).

[18] Csuti, Blair, Stephen Polasky, Paul H. Williams, Robert L. Pressey, Jeffrey D. Camm, Melanie Kershaw, A. Ross Kiester, Brian Downs, Richard Hamilton, Manuela Huso and Kevin Sahr (1995), "A Comparison of Reserve Selection Algorithms Using Data on Terrestrial Vertebrates in Oregon," *Biological Conservation*, forthcoming.

[19] Conrad, Jon M. (1997), "Global Warming," *Land Economics* **73(2)**, 164-173.

[20] Cox, D. R., and H. D. Miller, *The Theory of Stochastic Processes*, John Wiley and Sons, Inc., New York, 1965.

[21] Crabbé, Phillipe, and Ngo Van Long (1993), "Entry Deterrence and Overexploitation of the Fishery," *Journal of Economic Dynamics and Control* **17**, 679-704.

[22] Dennis, R. L. H., *Butterflies and Climate Change*, Manchester University Press, Manchester, UK, 1993.

[23] Dixit, Avinash K., and Robert S. Pindyck, *Investment Under Uncertainty*, Princeton University Press, 1994.

[24] Douros, J. and M. Suffness (1980), "The National Cancer Institute's Natural Products Antineoplastic Development Program," *Recent Results in Cancer Research 70,* 21-44.

[25] Dublin, H. T., T. Milliken and R. F. W. Barnes, *Four Years After the CITES Ban: Illegal Killing of Elephants, Ivory Trade and Stock Piles* (IUCN and Traffic WWF: Gland, Switzerland, 1995).

[26] Eisner, Thomas (1989), "Prospecting for Nature's Chemical Riches," *Issues in Science and Technology* **6**, 31-34.

[27] Eiswerth, Mark E., and J. Christopher Haney (1992), "Allocating Conservation Expenditures: Accounting for Inter-Species Genetic Distinctiveness," *Ecological Economics* 5(2), 235-249.

[28] Farnsworth, Norman R., "Screening Plants for New Medicines," in *Biodiversity,* Edward O. Wilson, editor, (National Academy Press, Washington DC, 1988).

[29] Farnsworth, Norman R., and Djaja D. Soejarto (1985), "Potential Consequences of Plant Extinction in the United States on the Current and Future Availability of Prescription Drugs," *Economic Botany* **39** (July-Sept), 231-240.

[30] Ferrara, Ida and Paul C. Missios (1995), "Transboundary Renewable Resource Management: A Dynamic Game with Differing Non-Cooperative Payoffs," *Marine Resource Economics.*

[31] Fischer, Anthony C, John V. Krutilla and Charles J. Cicchetti (1972), "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis," *American Economic Review*, 605-619.

[32] Hartwick, John M. (1995), "Decline in Biodiversity and Risk-Adjusted Net National Product," in *The Economics and Ecology of Biodiversity Decline,* T. Swanson (ed.), Cambridge University Press, Cambridge, 1995.

[33] Harvard Business School, "The INBio/Merck Agreement: Pioneers in Sustainable Development," *Paper No. NI-593-015* (Harvard Business School, Boston MA, 1992).

[34] Hertzler, Greg, and Maxwell Gomera (1998), "Has the Convention on International Trade in Endangered Species Saved the African Elephant?," Mimeo.

[35] Holten, J. I., "Potential Effects of Climate Change on the Distribution of Plant Species," in Holten, Paulsen and Oechel (eds.), *Impacts of Climatic Change on Natural Ecosystems with Emphasis on Boreal and Arctic Alpine Areas,* Norwegian Institute for Nature Research, Trondheim, Norway, 1993.

[36] Hyde, William F., and Roger A. Sedjo (1992), "Managing Tropical Forests: Reflections on the Rent Distribution Discussion," *Land Economics* 68(3), 343-350.

[37] International Institute for the Environment and Development (IIED) and World Resources Institute (WRI), *World Resources 1988-89*, Basic Books, New York (NY), 1989.

[38] Kahn, James R., *The Economic Approach to Environmental and Resource Management* (Dryden Press, Harcourt Brace: Toronto, 1998).

[39] Khanna, Jyoti, and Jon Harford (1996), "The Ivory Trade Ban: Is It Effective?" *Ecological Economics* **19**, 147-155.

[40] Krutilla, John V. (1967), "Conservation Reconsidered," *American Economic Review* **57**: 777-786.

[41] Levhari, David and Leonard J. Mirman (1980), "The Great Fish War: An Example Using a Dynamic Cournot-Nash Equilibrium," *Bell Journal of Economics* **11**: 322-334.

[42] MacArthur, R. and Edward O. Wilson, *The Theory of Island Biogeography,* Princeton University Press, Princeton (NJ), 1967.

[43] McAllister, D. (1991), "Estimating the Pharmaceutical Value of Forests, Canadian and Tropical," *Canadian Biodiversity* **1(1)**, 16-25.

[44] Mendelsohn, Robert, and Michael J. Balick (1995), "The Value of Undiscovered Pharmaceuticals in Tropical Forests," *Economic Botany* **49** (June), 223-228.

[45] Milliman, Scott R. (1986), "Optimal Fishery Management in the Presence of Illegal Activity," *Journal of Environmental Economics and Management* **13**, 363-381.

[46] Milner-Gulland, E. J. (1993), "An Econometric Analysis of Consumer Demand for Ivory and Rhino Horn," *Environmental and Resource Economics* 3, 73-95.

[47] Missios, Paul C. and Charles Plourde (1997), "Transboundary Renewable Resource Management and Conservation Motives," *Marine Resource Economics.*

[48] Munro, Gordon R. (1979), "The Optimal Management of Transboundary Renewable Resources," *Canadian Journal of Economics* **12**: 355-376.

[49] Munro, Gordon R. and Robert L. Stokes (1989), "The Canada-United States Pacific Salmon Treaty," *Canadian Oceans Policy: National Strategies and the New Law of the Sea,* D. McRae and G. R. Munro, eds, (U.B.C. Press), 17-35.

[50] Nash, John F. (1953), "Two-person Cooperative Games," *Econometrica* **21**: 128-140.

[51] Pearce, David W., "An Economic Approach to Saving the Tropical Forests," *LEEC Discussion Paper 90-05* (LEEC, London, 1990).

[52] Pearce, David, and Seema Puroshothamon, "Preserving Biological Diversity: The Economic Value of Pharmaceutical Plants," *CSERGE Discussion Paper 92-27* (CSERGE, London, 1992).

[53] Pindyck, Robert S. (1991), "Irreversibility, Uncertainty and Investment," *Journal of Economic Literature* **29**, 1110-1148.

[54] Plourde, Charles (1999), "Applications of Game Theory in Natural Resources and Environmental Economics," *International Journal of Development Planning Literature* **14(2)** April-June, 201-218.

[55] Plourde, Charles and David Yeung (1989), "Harvesting of a Transboundary Replenishable Fish Stock: A Non-cooperative Game Solution," *Marine Resource Economics* **6**: 57-70.

[56] Polasky, Stephen, and Andrew Solow (1996), "Conserving Biological Diversity with Scarce Resources," working paper.

[57] Polasky, Stephen, and Andrew Solow (1995), "On the Value of a Collection of Species," *Journal of Environmental Economics and Management*, **29(2)**, 298-303.

[58] Principe, Peter, *The Economic Value of Biodiversity Among Medicinal Plants* (OECD, Paris, 1989).

[59] Reid, Walter V., Sarah A. Laird, Rodrigo Gámez, Ana Sittenfeld, Daniel H. Janzen, Michael A. Gollin, and Calestous Juma, "A New Lease on Life," in *Biodiversity Prospecting: Using Genetic Resources for Sustainable Development,* W. V. Reid, editor (World Resources Institute, Washington, 1993).

[60] Richards, J. F. (1990), "Land Transformation," in Turner, B. L. (ed.), *The Earth as Transformed by Human Action*, 163-178.

[61] Richter, A. R., S. R. Humphrey, J. B. Cope and V. Brack Jr. (1993), "Modified Cave Entrances, Thermal Effect on Body Mass and the Resulting Decline of Endangered Indiana Bats (Myotis sodalis), *Conservation Biology* 7(2), 407-415.

[62] Rowthorn, Bob, and Gardner Brown (1995), "Biodiversity, Economic Growth and the Discount Rate," in *The Economics and Ecology of Biodiversity Decline,* T. Swanson (ed.), Cambridge University Press, Cambridge (UK), 1995.

[63] Rubin, Steven M., and Stanwood C. Fish (1994), "Biodiversity Prospecting: Using Innovative Contractual Provisions to Foster Ethnobotanical Knowledge,

Technology and Conservation" *Colorado Journal of International Environmental Law and Policy* **5** (Winter), 23-58.

[64] Said, M.Y., R. N. Chunge, G. C. Craig, C. R. Thouless, R. F. W. Barnes, and H. T. Dublin, *African Elephant Database 1995* (IUCN: Gland, Switzerland, 1995).

[65] Sedjo, Roger A. (1992), "Property Rights, Genetic Resources, and Biotechnological Change," *Journal of Law and Economics* 35(April), 199-213.

[66] Sedjo, Roger A., and R. David Simpson (1995), "Property Rights, Externalities and Biodiversity," in *the Economics and Ecology of Biodiversity Decline: The Forces Driving Global Change,* T. M. Swanson, editor (Cambridge University Press, Cambridge, 1995).

[67] Silberberg, Eugene (1990), *The Structure of Economics: A Mathematical Analysis* (McGraw-Hill, Inc.), second edition..

[68] Simpson, R. David, Roger A. Sedjo and John W. Reid (1996), "Valuing Biodiversity for Use in Pharmaceutical Research," *Journal of Political Economy* **104(1)**, 163-185.

[69] Simpson, R. David, and Roger A. Sedjo (1996), "Investments in Biodiversity Prospecting and Incentives for Conservation," *Resources for the Future Discussion Paper 96-14*, April 1996.

[70] Solow, Andrew, Stephen Polasky, and James Broadus (1993), "On the Measurement of Biological Diversity," *Journal of Environmental Economics and Management* **24(1)**, 60-68.

[71] Sutinen, Jon G., and Peder Andersen (1985), "The Economics of Fisheries Law Enforcement," *Land Economics* 61(4), 387-397.

[72] Swanson, Timothy M. (1994a), "The Economics of Extinction Revisited and Revised: A Generalised Framework for the Analysis of the Problems of Endangered Species and Biodiversity Loss," *Oxford Economic Papers* **46(5)**, 800-821.

[73] Swanson, Timothy M. (1994b), *The Economic Regulation of Extinction*, New York University Press, New York, 1994.

[74] Swedish NGO Secretariat on Acid Rain, "Forest Damage in Europe," in *Environmental Factsheet No. 1*, Swedish NGO Secretariat on Acid Rain, Goteborg (Sweden), 1992.

[75] Turnovsky, Stephen, *Methods of Macroeconomics*, 1995.

[76] Vislie, Jon (1987), "On the Optimal Management of Transboundary Renewable Resources: A Comment on Munro's Paper," *Canadian Journal of Economics* **20**: 870-875

[77] Weitzman, Martin L. (1992), "On Diversity," *Quarterly Journal of Economics* **107(2)**, 363-405.

[78] Weitzman, Martin L. (1993), "What to Preserve? An Application of Diversity Theory to Crane Conservation," *Quarterly Journal of Economics* **108(1)**, 157-183.

[79] Wilson, Edward O., "The Current State of Biological Diversity," in *Biodiversity*, E. O. Wilson (ed.), National Academy Press, Washington D.C., 1988.

[80] Wilson, Edward O., *The Diversity of Life* (Belknap, Cambridge MA, 1992).

[81] World Conservation Monitoring Centre (WCMC), *Global Biodiversity: Status of the Earth's Living Resources*, Brian Groombridge (ed.), Chapman & Hall, London, 1992.

[82] World Resources Institute (WRI), *World Resources 1994-1995*, Oxford University Press, Oxford, 1994.

[83] Zebich-Knos, Michele (1997), "Preserving Biodiversity in Costa Rica: The Case of the Merck-INBio Agreement," *Journal of Environment and Development* 6(2), 180-186.