ABSTRACT

Title of Dissertation:	COSTLY RENEWABLE RESOURCE MANAGEMENT AND INTERNATIONAL TRADE
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Degree and year:	Degree of Doctor of Philosophy, 2007
Dissertation directed by:	Professor Lars J. Olson Agricultural and Resource Economics Department

Renewable resource management is necessary to avoid the dissipation of inter-temporal rents due to open access exploitation. In reality management is costly, which implies that the first best solution is not appropriate. Management costs must be considered explicitly in optimization problems, to find the appropriate second best solutions. This is the focus of this dissertation, which contains applied theoretical analyses of dynamic bio-economic models, where moving away from open access exploitation of a renewable resource is costly.

Partial equilibrium problems of harvesting a scarce renewable resource are analyzed, where economic incentives of poachers, who are punished if caught, are included. Harvest, enforcement and resource price are endogenously determined. The punishment increases poachers' expected marginal costs and the resource market price, which forces at least some poachers out of the market.

Different relative harvest cost structures are considered between social planner and poachers, which drives the manner in which the market supply is optimally shared between them. Corrective policies are given for a pseudo-monopolist seeking to maximize his discounted profit instead of total economic surplus. Further policy adjustments are characterized, in case the resource entails non-market values.

A two-good, two-variable-factor bio-economic trade model is also developed for a small country. Open access, first and second best resource management models are analyzed, assuming that instantaneous gains are independent of the resource stock and that resource management incurs a flow of instantaneous fixed cost. The most empirically realistic model allows for resource management regime switches, which is influenced by the trade regime and the world price of the resource good.

Different cases are characterized in relation to changes in welfare and conservation, following a move from autarky to free trade. Free trade is unambiguously beneficial in some cases, but not always. Specifically, if open access is the second best management regime in autarky, then a small comparative advantage in the resource good could be detrimental to the home country. There exists a greater comparative advantage in the resource good, above which free trade would be beneficial. Understanding what drives the empirically relevant detrimental consequences of free trade can be helpful for policy-making. The second best trade model developed in this dissertation constitute an effort in that direction.

COSTLY RENEWABLE RESOURCE MANAGEMENT AND INTERNATIONAL TRADE

by

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2007

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DEDICATION

Je dédie cette dissertation à la mémoire de mon père, qui souvent disait avec humour: "La folie ne porte pas toujours à tuer!" Manifestement!

ACKNOWLEDGMENTS

I wish to thank three professors who were especially important in my graduate learning experience: Professors Lars J. Olson and Ramón E. López from the University of Maryland, and Professor Stephen Polasky from the University of Minnesota.

I am also grateful for the comments of seminar participants where I presented my dissertation work at different stages. These are participants to the 1998 CREESG meeting in Ottawa, the 1999 CEA Meetings in Toronto, the 3èmes Journées GREEN-CIRANO (1999) in Sainte-Foy, Professor Nguyen Van Quyen and other seminar participants to the CREE 2002 Meeting in Montreal, seminar participants at Laval University (2002 GREEN seminar), seminar participants and at McGill University, MacDonald Campus (2002), seminar participants from the Economics Department of the University of Ottawa (2003), and finally, seminar participants from the Economics Department at Laval University (2004).

Financial support was greatly appreciated from the Department of Agricultural and Resource Economics Department and the Graduate School of the University of Maryland, from Resources For the Future, and from GREEN and the Research Chair on the Economics of Electric Energy at the Department of Economics, Laval University.

Finally, I could not have done this PhD without the warmth and support of friends and family, especially Thérèse C. Bergeron, Connie Chan-Kang, Line Verreault, Steve Polasky, Ana Gabriela Rosales Benitez and Lynda Khalaf. Many thanks to you all.

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CHAPTER 1. INTRODUCTION

For decades, economists have known that renewable resources tend to be exploited in open access, which leads to economic overexploitation. This can be avoided if a clear property right exists for the resource (Gordon, 1954; Scott, 1955; Coase, 1960; Hardin, 1968; Smith, 1968; Clark, 1990), or if a policy is put in place that makes resource harvesters behave as if they had a property right to the resource (Clark, 1990). Economic overexploitation results because individuals, who do not own the resource, harvest until their net marginal benefit is zero, as in a static optimization problem. However, the unexploited stock of renewable resource could be considered as an investment capital for society because some of it can be saved for future consumption, because the size of the resource stock can affect the instantaneous net benefits derived from it, and also because it regenerates through biological growth and thus provides dividends. Therefore, a benevolent social planner would maximize the discounted social welfare generated by the exploited resource, *i.e.*, he would consider the problem as a dynamic one. The social planner's problem leads to the optimal exploitation path, where for economically scarce resources, at any point in time, exploitation should occur at a level where net marginal benefit is greater than zero. The amount of marginal *net* benefit on the last unit harvested is called the resource rent, *i.e.*, the discounted marginal return on investment in the resource for the future.

A “clear property right” can be understood as defined in western civilization: legally binding, enforceable and owned for example by an individual, a company or an association. There also exist renewable resources held as common-property, *i.e.*, whose property right exists by custom or tradition, is not necessarily legally binding, often is self-enforced, and is typically owned by a group of individuals in a specific geographic area, as is sometimes found in less developed economies (Ostrom, 1990). In the absence of clear property rights, western style or common-property, policies that create incentives for harvesters to behave optimally are taxes and harvest quotas, possibly tradable quotas, which mimic actual property rights to the resource (*e.g.*, Clark (1990), chapter 8).

The main motivation for this dissertation is that, even though the property right problem and policy prescriptions are clear, open access exploitation is still observed empirically. Renewable resources are rarely managed as prescribed, and property rights are typically not perfectly enforced. At times, despite renewable resource management policies, resources are exploited illegally, at least in part, by others than the designated harvesters. Specifically, despite existing policies, black markets in renewable resources are observed worldwide, these resources often being endangered species. What then could explain the discrepancy between policy prescriptions what we observe?

The simplest dynamic models leading to the tax and quota prescriptions generally suppose only one economic distortion, or departure from optimality: the lack of property right on a renewable resource. In reality however, there can be several distortions. In this dissertation, the costs of resource management are explicitly considered. These can also be called transactions costs, policy costs, agency costs or enforcement costs, depending on the details of the analysis. Indeed, it is perfectly intuitive that resource management policies are not free, that they are costly to the social planner or resource manager, be it a government or a private resource owner, and that it uses up inputs that could have been otherwise productive in the economy.

Another motivation for this dissertation is the growing interest in the impact of free trade of natural resources. Hence, costly resource management is considered not only in partial equilibrium, but also in trade analyses, where welfare and resource conservation are analyzed, moving from autarky to free trade.

Accordingly, in the context of a renewable resource that is costly to manage, the objectives of this dissertation are to:

i. characterize the optimal policy for the management of a scarce renewable resource;

ii. explain how it may be optimal to observe legal and illegal harvests separately or simultaneously;

iii. provide policy prescriptions for a scarce renewable resource that is owned by a sole owner who wishes to act as a monopolist;

iv. provide policy prescriptions for a scarce renewable resource that not only has market value, but also stock value, *i.e.*, its existence is valuable;

v. characterize how resource management costs affect the conservation of the resource;

vi. characterize the impact of free trade on social welfare and on the conservation of the resource under open access exploitation of the resource;

vii. characterize the impact of free trade on social welfare and on the conservation of the resource under costless management of the resource, *i.e.*, under the first best policy;

viii. characterize the impact of free trade on social welfare and on the conservation of the resource under costly management of the resource, *i.e.*, under a second best policy;

ix. characterize the cases where the resource management regime could change due to free trade following autarky (open access *versus* costly management); and finally,

x. characterize the cases where the move from autarky to free trade can be welfare decreasing, and by extension, where some level of barrier to trade would be better; and finally,

xi. characterize the cases where the move from autarky to free trade can cause the extinction of the renewable resource.

Objectives i. to v. are addressed in Chapters 3 and 4, where management cost is assumed to be either an enforcement cost on the resource property right or an instantaneous fixed cost of taxation. The rest of the objectives are addressed in Chapter 5, where the management cost is assumed to be an instantaneous fixed cost, necessary for the collection and re-distribution of a tax on harvest. Applied theoretical bio-economic models are used to reach those eleven objectives. Dynamic problems in continuous time are solved, making use of the Maximum Principle developed in optimal control theory.

Chapter 2 is a review of literature related to the issues analyzed in the rest of the dissertation. Chapter 3 is a partial equilibrium model where the optimal harvest of a scarce renewable resource is analyzed, the scarcity implying some level of market power. The economic incentives of potential or actual poachers, who are punished if caught, are explicit and endogenous to the bio-economic model. The punishment increases poachers' expected marginal costs and the resource market price, which forces at least some of them out of the market. Harvest, enforcement and resource price are all endogenously determined. We find that different relative harvest cost structures between social planner and poachers are what drives the manner in which the market supply is optimally shared across legal and illegal harvesters. Indeed, the optimal resource supply can be legal only, illegal only, or both, and this composition can change over time. We also find that corrective policies are necessary in order to influence a pseudo-monopolist who seeks to maximize his own profit instead of total economic surplus. In fact, as long as he keeps the fines collected from poachers, the pseudo-monopolist' harvesting behavior is second best optimal, but his property right enforcement level is not. We characterize alternative policies that make the pseudo-monopolist's enforcement efforts second best optimal. Further corrective policies are also necessary in case the resource has value over and above its market value, and we solve for them under two different valuation assumptions.

Chapter 4 is a natural extension of Chapter 3: for a slightly different partial equilibrium model, we provide phase diagram analyses with varying levels of resource management costs. In order to analyze the phase diagrams for the general model where instantaneous net gains are stock-dependent, the model needs to be simplified. The same simplification as in Cropper *et al*. (1979) is made for the harvest cost function, in order to compare our results with costly resource management (second best world) to theirs, which is based on the assumption of costless resource management (first best world). We consider the possibility that costly resource management regime may include open access, which leads to the realization that, whatever the discount rate, the costlier is resource management, the more likely is the extinction of the resource, especially if the initial stock is small.

Chapter 5 is also a natural extension of Chapter 3. We use the simpler model where instantaneous gains from the renewable resource are not stock-dependent, but this time international trade is explicitly considered. A two-good, three-factor (two variable, one fixed) trade model is amended in order to include a dynamic bio-economic model with a fixed instantaneous resource management cost. First, assuming a pristine resource, the general equilibrium autarkic dynamics is characterized up to the feasible autarkic steady states. Then, assuming that the resource stock has reached a positive steady state stock in autarky, we consider free trade. Discounted and steady state welfare changes are characterized for the home country, assuming a trade regime change from autarky to free trade. Attention is also given to whether or not free trade could cause the extinction of the renewable resource. We find that conservation and welfare change due to free trade are related.

This is done for a home country that takes world prices as given, under different resource management regimes: (i) under open access exploitation; (ii) with costless resource management; (iii) with costly resource management; and finally, (iv) considering possible resource management regime switches between open access and costly management. With the empirically realistic possibility of resource management regime switches, different cases are characterized. In some cases, moving from autarky to free trade is welfare increasing and it helps the conservation of the resource. In other cases however, free trade with proper management of the resource can lead to welfare losses because proper second best management could be open access. It could also cause the extinction of the resource. Delineating the different cases in relation to welfare and conservation can be helpful for policy-making, which is what motivates Chapter 5.

Chapter 6 is the overall conclusion of the dissertation. Important results are summarized and potential further research endeavours are discussed.

Throughout the dissertation, a number, n, in subscript refers to the derivative of a function with respect to its n^{th} argument, while a prime in superscript, " ' ", refers to the derivative of a function with respect to its unique argument. A starred variable refers to its short-run equilibrium value, a starred variable with the subscript "∞" refers to its steady state equilibrium value and time is represented by the variable t.

CHAPTER 2. REVIEW OF LITERATURE

In economics, well-defined property rights are often prescribed as a cure against the over-exploitation of renewable resources. Property rights theoretically provide proper incentives to work out the socially optimal solution, at least when there are no transactions costs (Coase, 1960). Under nonzero transactions costs however, *"Property rights develop to internalize externalities when the gain of internalization becomes larger than the cost of internalization"* (Demsetz, 1967, p.350). This means that, while property rights may exist on paper, their effectiveness does depend on the costs associated with them. The cost of internalization may include the administrative costs of policy-making or agency costs for the government. They may also include the cost of property right enforcement, since individual agents often have incentives not to follow the optimal policy and costly efforts are necessary to prevent them from cheating. Therefore, while an unmanaged natural resource will lead to open access exploitation and economic over-harvesting (Gordon, 1954; Scott, 1955; Hardin, 1968), the textbook optimal policy is in reality not optimal because it ignores the costs of the policy; the world is second best and the decision process must take that into account.

Smith (1968) wrote one of the first dynamic models of resource management using the Maximum Principle, although his model did not allow for discounting; instead, he maximized steady state utility. Clark's book (1990) has become a classic reference on bio-economic modeling that summarizes issues of open access exploitation and dynamic optimization with discounting. Not surprisingly, it has been shown that open access, *i.e.*, economic over-exploitation, of a renewable resource can lead to extinction (Gould, 1972; Hoel, 1978; Berck, 1979). However, we now also know that dynamic optimization does not preclude the optimal extinction of a renewable resource, even when its growth is purely compensatory, *i.e.*, concave in stock. This has been shown, namely, by Clark (1973) in a discrete time maximization of present value profit from competitive exploitation of a renewable resource where the optimal path is a most rapid approach path (MRAP). Clark (1973) shows that if the marginal natural growth of the resource close to extinction is small as compared to the discount rate, then extinction could result, even though the exploitation regime is not open access. Cropper *et al.* (1979) do a similar analysis, only in a continuous time model, for which the optimal path is smooth and with endogenous price, since they analyze the social planner's problem. They get a result similar to Clark (1973). Specifically, extinction can be optimal if the discount rate is greater than the marginal natural growth rate of the resource close to zero. In Cropper *et al.* (1979) however, since several steady states are possible, whether extinction occurs or not also depends on the initial resource stock.

While an unmanaged resource will lead to open access exploitation and economic over-harvesting (Gordon, 1954), naïve management of a renewable resource, *i.e.*, management that ignores potential or actual illegal actions, may trigger perverse incentives. Specifically, resource management is likely to attract poachers attempting to capture the positive rent remaining from the resource stock at any point in time. Hence, costly enforcement efforts are required in order to avoid reverting to open access exploitation due to poaching, and these efforts ought to be considered endogenous to the problem. Costly enforcement is considered explicitly in Chapters 3, 4 and 5 of this dissertation.

Becker (1968) first analyzed rational illegal behavior using micro-economic theory, and the models of Chapter 3 combine the same approach with a bio-economic model to address the problem of an illegally harvested renewable resource or species. A number of earlier papers have looked at the costly enforcement of property rights in fisheries and wildlife markets. Sutinen and Andersen (1985) used the Becker approach to crime and punishment with costly enforcement as a control variable, but taking the legal harvest level as given. In another fisheries model, Milliman (1986) went one logical step further, as he made legal harvest an endogenous variable simultaneously with costly enforcement. Anderson and Lee (1986) added the proposition that the policy instrument itself ought to be endogenous since with costly resource management, economic policy instruments are not necessarily superior to other instruments. Skonhoft and Solstad (1996) used the same underlying ideas as Milliman (1986), but in a context of wildlife management in East Africa where poachers are local people hunting for subsistence. In contrast, in a fisheries model, Crabbé and Long (1993) used legal harvest only as a control variable in a Stackelberg model where the home-nation is the leader. In these papers, price is exogenous while legal harvest and enforcement efforts are used to avoid open access exploitation, so that the resource stock will be exploited at a lower rate and scarcity rents will not be entirely depleted at every point in time.[1]

[1] Brown and Layton (1997) and Kremer and Morcom (2000) offer storage as a control variable for storable traded resource goods, with speculators storing more of the resource as they expect it to become extinct. Models presented in Chapter 3 and Chapter

The models from Chapter 3 and 4 are more general than previous ones since the price of the resource, the legal harvest level and the property right enforcement level are all endogenous. Also, different relative harvest cost structures across legal and illegal harvesters are allowed. Under these more general assumptions, the models in these chapters encompass several previous models.

The proposed models are also linked to the entry deterrence literature of industrial organization in the sense that the decision-maker modifies his behavior to deter entry into the market, here entirely or partially. Enforcement efforts and legal harvest levels are decided upon, given poachers' incentives. As in the papers mentioned above, successful policies will steer harvesters away from open access exploitation, thus leaving a higher stock than under open access exploitation (although not strictly).

Renewable resources are often traded internationally. Freer trade often leads to a greater demand for the harvested resource. If the resource is well managed and the enforcement of property rights is costless, then we would expect freer trade to increase welfare of the home country. However, when property rights are costly to enforce, then the outcome of freer trade is not so clear. Considering that resource management is costly, in some instances open access may be chosen instead. In such cases, free trade may not be welfare-increasing. International trade and management costs are considered in Chapter 5 of this dissertation.

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4 abstract from speculative attempts and thus better apply to non-storable goods such as meat and live exotic pets.

International trade in a world of second best has been studied by several authors. Well-known contributors to this literature are Bhagwati and Ramaswami (1963), who wrote about different possible types of distortions in an economy, and the policies that would lead to the first best outcome. They have shown that under such policies, free trade is necessarily welfare increasing, but without them, it may not be. Using their classification, the distortion we consider in this dissertation is an *endogenous* distortion, caused by a market imperfection under a *laissez-faire* policy. The first best policy for such a distortion is a tax-*cum*-subsidy on domestic production. Typically, resource management policy entails a tax-*cum*-subsidy scheme, a system of tradable quotas or a true change in property rights. The first best solution in our trade model with a renewable resource is therefore very similar to what these authors suggest – some resource management policy is applied directly to domestic production, in the sector where the distortion appears. Their work was later extended to include a ranking of different policies, in case the first best policy is, for some reason, unfeasible (Bhagwati, Ramaswami and Srinivasan, 1969). This is relevant to this dissertation since the management costs considered can render the usual policy (*i.e.*, resource management) too expensive to be worth undertaking. In such a case, Bhagwati, Ramaswami and Srinivasan (1969) find that free trade may not be welfare increasing. Candidate second-best policies are trade tariffs and a production factor tax-*cum*-subsidy. Which is the second best and the third best policy is case-dependent; they cannot be ranked analytically, as one would expect. In an oft-cited article, Bhagwati (1971) summarized and generalized the theory of distortions and welfare with international trade. The model considered in Chapter 5 is clearly related to the literature on distortions with international trade, but our model is more complex. Indeed, Bhagwati and Ramaswami (1963) and Bhagwati, Ramaswami and Srinivasan (1969) only considered static distortions, while the distortion that typically appears in renewable resource markets is a dynamic one.

A number of contributions, which include dynamic considerations, were made to the international trade literature. First, at a time where some believed that free trade was not inter-temporally Pareto-optimal, Samuelson (1978) offered a two-page verbal argument to the contrary. He insisted that the entire transitory path be considered for comparative welfare analysis, rather than just the steady states, as some authors had done before, especially in the immiserizing growth literature. Then, Smith (1979) wrote a model that confirmed Samuelson's assertions. Samuelson (1978) and Smith (1979) only considered first best economies however. Distortions with international trade in a dynamic setting were later considered by Bark (1987) in a growth model for a small open economy. In Bark's paper, a government tax on capital initially exists for lump-sum redistribution in the home country. Bark considers a tax increase at some point in time, which implies a greater distortion in the economy. Without any constraint on capital mobility, a new steady state is attained instantly. With some constraints on capital mobility, another steady state is attained in the long-run, where consumption, and therefore welfare, is lower than under the free trade instantaneous adjustment. However, when considering discounted inter-temporal welfare loss, Bark shows that the loss is always smaller with constraints on capital mobility than without. This is therefore an illustration of Samuelson's (1978) argument, but with a tax distortion in the economy. Bark then discusses first, second and third best policies and relates his findings, which include dynamic considerations, to Bhagwati's (1971) now classic summary of distortions and static welfare with international trade.

Chapter 5 of this dissertation is a contribution to the literature on distortions and welfare, only the distortion considered here is a dynamic one. We analyze welfare changes between autarkic and free trade steady states, and also between trajectories from the time the home country opens to free trade. Our goal is to delineate, in the second best world where resource management is costly, the cases where trade restrictions might lead to greater welfare than free trade.

To address environmental issues with international trade, recent efforts have concentrated on general equilibrium models, some with resource dynamics. Recent papers include Brander and Taylor (1997a, 1997b, 1998) on renewable resources, Chichilnisky (1993, 1994, 1996) on renewable resources and on the environment, Copeland and Taylor (1994) on the environment, Emami and Johnston (2000) on renewable resources and Hannesson (2000) on renewable resources as well. Most of these papers that dealt with a renewable resource analyzed either the open access management regime (infinite discount rate: the future does not matter) or the maximization of steady state utility (zero discount rate: the future is as important as the present). However, dynamic optimization normally makes use of a discount rate, δ, such that $0 < \delta < \infty$, which is assumed in Chapter 5. Also, in some recent renewable resource models of trade, specific functional forms prevented extinction from occurring with free trade but not in autarky, which seems counterintuitive (*e.g.*, Brander and Taylor, 1997a). In contrast, in Chapter 5 of this dissertation, functional forms are as general as possible and do not eliminate the possibility of extinction under free trade.

Also, all trade papers with environmental concerns mentioned thus far assume that the resource management regime is exogenous and constant over trade regimes. These papers provide interesting results, but we wish to go one step further and make the resource management regime endogenous.

One previous trade paper does just that (Hotte *et al.*, 2000). Our model in Chapter 5 is close in spirit to that of Hotte *et al.* (2000), except our renewable resource is managed by a benevolent resource planner, rather than being exploited by agents who maximize their profit and choose to enforce their own property rights accordingly. Hotte *et al.* (2000) found that freer trade may not be welfare-increasing, which is not surprising, given that in general equilibrium, private agents' decisions about property right enforcement are generally sub-optimal. This result goes back to de Meza and Gould (1992), who showed that in a perfectly competitive economy, private property right enforcement efforts, which use resources from the economy, may be smaller or greater than is socially optimal. Long (1994) showed the same regarding the timing of land enclosure.

In Chapter 5 of this dissertation, the social planner's objective is to maximize the inter-temporal total economic surplus, while taking management cost into account. He takes the whole economy into account rather than only maximizing his own profit, as was done in Hotte *et al*. (2000) and de Meza and Gould (1992). In Chapter 5, departures from the usual result that freer trade is welfare-increasing therefore do not depend on the fact that property rights are privately enforced, but rather because they are costly.

CHAPTER 3. PARTIAL EQUILIBRIUM MODEL WITH COSTLY RESOURCE MANAGEMENT

3.1. Introduction

The illegal trade in wildlife, worth about five billion dollars annually, is the second most important cause of species extinction, the first cause being land use conversion that leads to the loss of natural habitat (Anderson, 1997; Le Duc, 1990). Since 1989, the US has been the most active player in illegal wildlife trade with estimated annual imports of $773 million and exports of $256 million (Anderson, 1997). Paradoxically, there is also high demand for conservation in the US and this country plays a significant role in international enforcement efforts. The black market in endangered species has attracted substantial public attention as newspapers and magazines have featured articles on the problem, making it an issue known by most North Americans nowadays (Anonymous, 1996; Broussard, 1997; Brower, 1994; Glenn and Fino, 1998; Lavigne, 1998; Marston, 1997; Sabourin, 1998; Webster, 1997; to name only a few). Currently, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) regulates the trade of 33 659 species, 113 sub-species and 46 wildlife populations worldwide [2,3].

The main objective of this chapter is to propose a model especially suited to the case of endangered, hence scarce, harvested species. Another objective is to offer some

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[2] CITES Secretariat: http://www.cites.org/eng/disc/species.shtml (July 28, 2004).

[3] Some details are provided in Appendix I.

policy insight for a resource that is legally managed and where poaching is a fact or at least a threat.

In this chapter, we assume that the resource price is endogenous. In the *social planner*'s problem, where we assume he maximizes the discounted flow of total-economic-surplus, price is endogenous to his actions. The social planner's potential actions are his own legal harvest and his resource management enforcement efforts. His behavior leads to the welfare benchmark.

In contrast, a private owner of the resource would maximize his discounted flow of profit. If the resource is scarce, due to its endangerment for example, then the private owner could have market power, and in such a case, price is endogenous in his problem as well. Indeed, a scarce resource is likely to be managed by a limited number of managers. For simplicity, the limiting case of a monopolist or a unique cartel of resource managers is compared to the social planner's model. In the case where the resource is not endangered, then an endogenous price could be observed because the resource is found in a limited geographic area, so it is owned by only one resource manager. Given that the profit-maximizing monopolist faces potential or actual poachers, he will be called *pseudo-monopolist* from now on. The pseudo-monopolist's potential actions are also his own legal harvest and his property rights enforcement efforts.

In this chapter, the *legal harvest* is provided either by the social planner or by the pseudo-monopolist, depending on the problem considered, and the *illegal harvest* is provided by poachers.

Throughout Chapters 3, 4 and 5, s(t) is the resource stock at time t, and its growth function, $g\left(s\left(t\right)\right)\geq 0$, is assumed to be compensatory. That is, $g\left(0\right)=g\left(\bar{s}\right)=0$, g'(0) > 0 and g''(s(t)) < 0 for all s such that $0\leq s\left(t\right)\leq \bar{s}$, where $\bar{s}$ is the wildlife population's natural carrying capacity.

In Chapter 3, we analyze the social planner's problem as the welfare benchmark. In section 3.2 we present the poachers' problem, whose solution then constrains the social planner's and the pseudo-monopolist's problems. In sections 3.3 and 3.4, the social planner's problem and the pseudo-monopolist's problems are analyzed, and corrective policies are suggested in order to make their solution coincide. Finally, we conclude this chapter in section 3.5.

3.2. Poachers' problem

Individual poachers do not own the renewable resource, and there are no barriers to their entry. Consequently, they are assumed to harvest under an open access regime. This means that they maximize their static profit and that there is entry of poachers until all rents are dissipated, *i.e.*, profit is equal to zero for all poachers. They are also assumed to be risk-neutral, so they maximize their expected static profit.

There is a probability, $\lambda(t)$, that any poacher will get caught by an enforcer, which would lead to the poacher having to pay a per-unit harvest fine, ϕ. At any point in time, t, a poacher takes the resource market price, P(t), and the expected per-unit harvest fine, $\lambda(t)\phi$, as given. An individual poacher's harvest cost is represented by a C^2 function, $K(q_I\left(t\right),s\left(t\right))$, where $q_I\left(t\right)$ is the amount of the resource an individual illegally harvests.[4] Assume $K_1(q_I(t),s(t))>0$, $K_{11}(q_I(t),s(t))>0$, $K_2(q_I(t),s(t))\le 0$, $K_{22}(q_I(t),s(t))\ge 0$, and $\left[K_{11}(q_I(t),s(t))K_{22}(q_I(t),s(t))-\left(K_{12}(q_I(t),s(t))\right)^2\right]\ge 0$. The fixed cost of poaching is $F\left(s(t)\right)>0$. The fixed cost may depend on the resource stock, for example if it includes search costs for the stock. Consequently, we assume that $F'\left(s(t)\right)\le 0$ and $F''\left(s(t)\right)\ge 0$. Assuming poachers are identical and risk-neutral, and following Becker's approach to crime and punishment with null opportunity cost to the illegal activity, the poacher's problem is to maximize his expected profit, $E\left(\pi(t)\right)$:

$$\begin{aligned}\underset{q_I(t)}{\text{Max}}\,E\left(\pi(t)\right)&=\lambda(t)\left(P(t)-\phi\right)q_I(t)+\left(1-\lambda(t)\right)P(t)q_I(t)-K\left(q_I(t),s(t)\right)-F\left(s(t)\right)\\&=P(t)q_I(t)-\lambda(t)\phi q_I(t)-K\left(q_I(t),s(t)\right)-F\left(s(t)\right)\end{aligned}$$

Assuming a positive illegal harvest, the individual's first order condition is:

$$P(t)-\lambda(t)\phi-K_1\left(q_I(t),s(t)\right)=0. \tag{3.1}$$

The open access regime will lead to entry until all expected rents are dissipated, so that, in market equilibrium, we obtain for each poacher:

$$E\left(\pi(t)\right)=P(t)q_I(t)-\lambda(t)\phi q_I(t)-K\left(q_I(t),s(t)\right)-F\left(s(t)\right)=0. \tag{3.2}$$

Equating (3.1) to (3.2) leads to the conclusion that in open access, the marginal cost is equated to the minimum average cost for each identical poacher:

$$K_1\left(q_I(t),s(t)\right)=\frac{K\left(q_I(t),s(t)\right)+F\left(s(t)\right)}{q_I(t)}. \tag{3.3}$$

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[4] A C^2 function is a twice continuously differentiable function.

By the implicit function theorem, let $q_I^*\left(s(t)\right)$ be the value of q_I that solves equation (3.3). We can simplify the notation for the problems to come in the rest of the chapter, and define the poachers' minimum average cost as:

$$k\left(s(t)\right)=\frac{K\left(q_I^*\left(s(t)\right),s(t)\right)+F\left(s(t)\right)}{q_I^*\left(s(t)\right)}. \tag{3.4}$$

We find that $k'\left(s(t)\right)=\dfrac{K_2+F'}{q_I\left(s(t)\right)}<0$,[5] the stock effect on the minimum average cost is negative.

Notice that in the special case where instantaneous gains are not stock-dependent, *i.e.*, $K_2\left(q_I,s(t)\right)=0$, then the poachers' minimum average cost is constant at all times and equal to:

$$k=\frac{K(q_I^*)+F}{q_I^*}. \tag{3.5}$$

In the general case, combining (3.1), (3.3) and (3.4), one can infer the market equilibrium price, constrained by poachers' behavior, to be

$$P(t)=k\left(s(t)\right)+\lambda(t)\phi. \tag{3.6}$$

Given the downward-sloping inverse demand curve $P\left(Q(t)\right)$, the instantaneous market equilibrium total harvest is

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[5] Using (3.3), we find

$$k'(s)=\frac{K_1q'_Iq_I+K_2q_I+F'q_I-Kq'_I-Fq'_I}{(q_I)^2}=\frac{\left(K_1-\left((K+F)/q_I\right)\right)q'_I+K_2+F'}{q_I}=\frac{K_2+F'}{q_I}<0.$$

$$Q(t) = D\left(k\left(s(t)\right) + \lambda(t)\phi\right), \tag{3.7}$$

where $D\left(k\left(s(t)\right)+\lambda(t)\phi\right) = P^{-1}\left(k\left(s(t)\right)+\lambda(t)\phi\right)$.

If the resource is exploited in open access only, without any probability of paying a fine, then the number of harvesters, $N^{OA}\left(s(t)\right)$, is $N^{OA}\left(s(t)\right) = \dfrac{D\left(k\left(s(t)\right)\right)}{q^*_I\left(s(t)\right)}$.

In the special case where instantaneous gains do not depend on the resource stock, then the number of open access harvesters is constant and equal to $N^{OA}(t) = \dfrac{D(k)}{q^*_I}$.

3.2.1. Equilibrium paths

As long as there is no enforcement, $\lambda(t)\phi = 0$ and open access results. In the special case where instantaneous gains do not depend directly on the resource stock, *i.e.*, $K_2\left(q_I, s(t)\right) = 0$, the open access instantaneous equilibrium harvest is $Q^{OA} = D(k)$. This indicates that the harvest level is invariant as the resource stock changes, Q(t) is thus constant and so $\dfrac{dQ(t)}{dt} = \dot{Q}(t) = 0$. The stock evolves according to the transition equation $\dfrac{ds(t)}{dt} = \dot{s}(t) = g\left(s(t)\right) - D(k)$. The three possible equilibrium paths for this special case are illustrated in Figure 3.1.

In the more general case where $K_2\left(q_I, s(t)\right) > 0$, the equilibrium harvest in open access depends on the resource stock: $Q^{OA}\left(s(t)\right) = D\left(k\left(s(t)\right)\right)$. As s(t) increases (decreases), the open access harvest increases (decreases):

$\frac{dQ^{OA}(s(t))}{ds(t)} = D'(\cdot)k'(\cdot) > 0$. In this case, $\dot{Q}(t) = D'(\cdot)k'(\cdot)\dot{s}(t)$, and

$\dot{s}(t) = g(s(t)) - D(k(s(t)))$. Sample equilibrium paths for this case are illustrated in

Figure 3.2.

Figure 3.1. Equilibrium paths and steady states in open access; $K_2(q_I, s(t)) = 0$

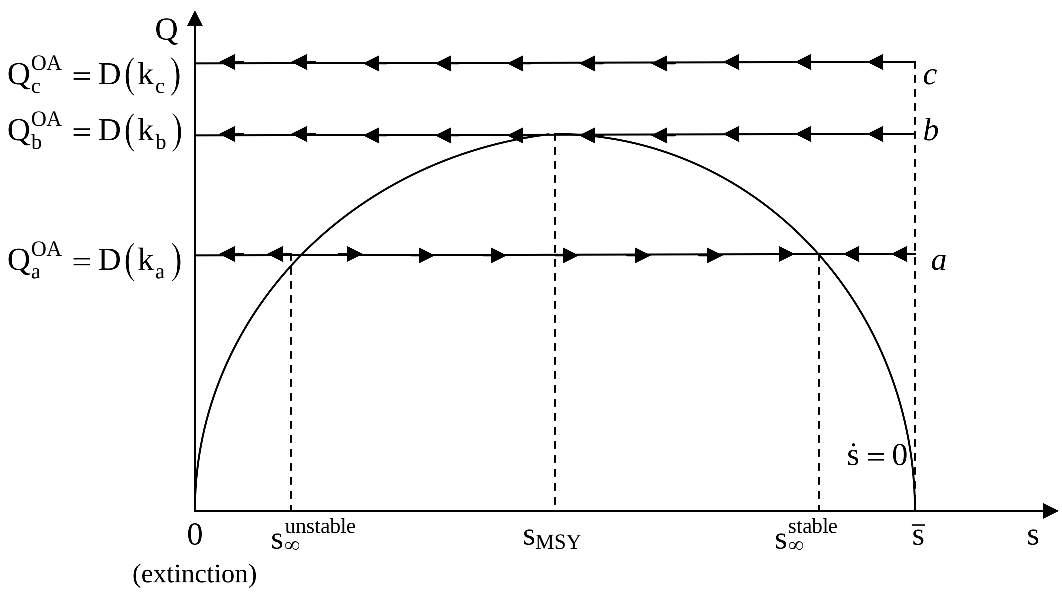
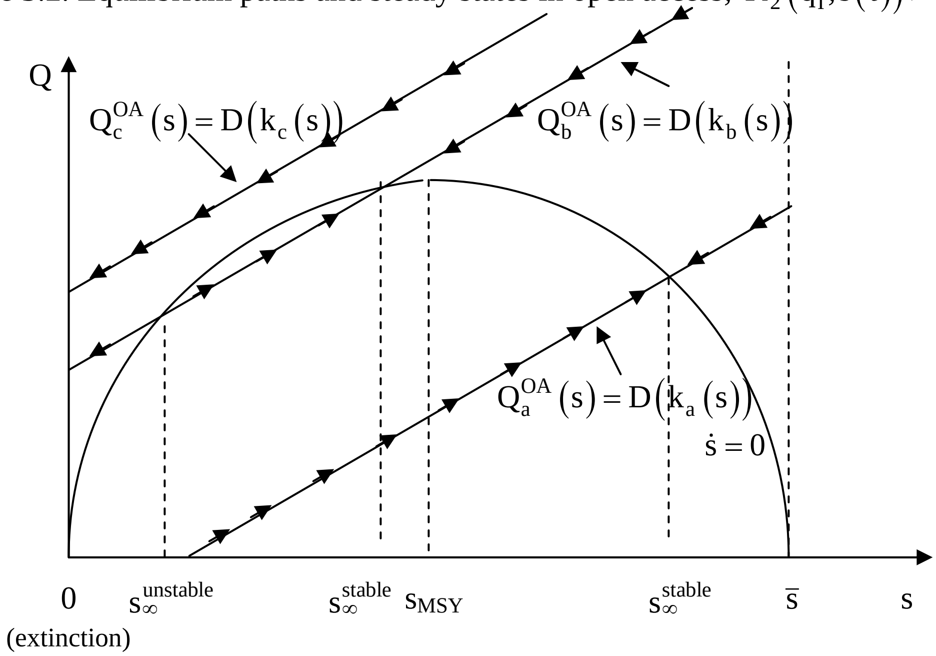


Figure 3.2. Equilibrium paths and steady states in open access; $K_2(q_I, s(t)) > 0$



3.2.2. Steady state *equilibria*

In the special case where instantaneous gains do not depend directly on the resource stock, *i.e.*, where $K_2(q_I, s(t)) = 0$, a positive steady state occurs where $\dot{s} = \dot{Q}^{OA} = 0$, in other words where $g(s) = D(k)$.

Definition 3.1.

Let s_{MSY} be the resource stock at which the harvest is at its maximum sustainable yield, *i.e.*, the resource stock at which the growth function, $g(s(t))$, is at its maximum, which also corresponds to the resource stock at which steady state harvest is at its maximum feasible level.

If $g(s_{MSY}) > D(k)$, then there are two potential steady states, and the steady state with the greatest stock is stable, while the other one is unstable. If the initial stock, s_0, is such that $s_0 < s_\infty^{unstable}$, then extinction occurs in finite time. Otherwise, one of the two steady states with a positive stock occurs. See path *a* in Figure 3.1.

If $g(s_{MSY}) = D(k)$, then the steady state at the MSY stock is unique and unstable. In that case, if $s_0 < s_{MSY}$, then extinction occurs in finite time. Otherwise, the steady state at s_{MSY} occurs. See path *b* in Figure 3.1.

If however, $g(s(t)) < D(k) \ \forall \ s(t)$, then in finite time, the resource will become extinct, whatever what the initial stock, s_0, may be. Species that are endangered due to their economic over-exploitation likely exhibit this characteristic. See path *c* in Figure 3.1.

Some level of property right enforcement, *i.e.*, $\lambda(t)\phi > 0$, would lower the harvest level at any point in time, and may prevent extinction. We consider such a possibility in the rest of this chapter.

In the more general case where $K_2(q_I, s(t)) > 0$, there can be multiple steady states, but one at most at stocks larger than s_{MSY}. Their stability is similar to that of the steady states described for the special case above. See Figure 3.2 for examples of steady states for the model when $K_2(q_I, s(t)) > 0$. In open access, extinction could be prevented if poaching costs are high enough, as for $k_a(s)$ in Figure 3.2. The possibility of extinction with open access exploitation could depend on the initial resource stock for lower poaching costs, as for $k_b(s)$. Finally, for low enough poaching costs such as

$k_c(s)$, extinction could be the ultimate outcome of open access exploitation, irrespective of the initial resource stock.

3.3. Social planner's problem: total economic surplus maximization

The social planner can use two instruments to decrease poachers' activities and thus steer away from the open access regime: legal harvest, $Q_L(t)$, and enforcement efforts, E(t). If the social planner harvests the resource himself, he decreases the poachers' market supply.

Let $Q_I(t)$ be the aggregate illegal harvest. Since poaching firms are assumed to be identical, $Q_I(t) = \sum_{n=1}^{N^*(t)} q_I{}^*(t) = N^*(t) q_I{}^*(t)$. Furthermore, since there may be simultaneous legal and illegal harvest, in market equilibrium, from (3.7), we can infer that $Q_I(E(t), Q_L(t), s(t)) = D(k(s(t)) + \lambda(E(t))\phi) - Q_L(t)$. The legal harvest cost is represented by a C^2 function, $h(Q_L(t),s(t))$, assuming $h_1(Q_L(t),s(t)) > 0$, $h_{11}(Q_L(t),s(t)) \geq 0$, $h_2(Q_L(t),s(t)) \leq 0$, $h_{22}(Q_L(t),s(t)) \geq 0$ and $\left[h_{11}(Q_L(t),s(t))h_{22}(Q_L(t),s(t)) - \left(h_{12}(Q_L(t),s(t))\right)^2\right] \geq 0$. Enforcement efforts, E(t), have a cost also represented by a C^2 function, $c(E(t))$, for which $c'(E(t)) > 0$ and $c''(E(t)) > 0$. The social planner can charge a per-unit harvest fine, ϕ, to poachers that he catches. We assume this fine is exogenous due to solvency constraints, which limit the fine that a poacher can actually pay. The exogenous fine could for example be equal to the confiscation of poaching equipment. The enforcement level, E(t), affects the probability of catching any and all poachers, which is represented by the C^2 function $\lambda(E(t))$, assuming $\lambda'(E(t)) > 0$ and $\lambda''(E(t)) < 0$. Also assume that $\lambda(0) = 0$ and $0 \le \lambda(E(t)) < 1$, for the domain $0 \le E(t) < \infty$. The social planner considers the reproductive capacity of the renewable resource in his problem, that is, the growth function of the resource stock, $g(s(t))$, as described in section 3.1. Finally, δ is the social discount rate, assuming that $0 < \delta < \infty$.

The social planner is assumed to maximize the discounted inter-temporal total economic surplus, in contrast with poachers' equilibrium actions, which do not take the future into account. The expected per-unit harvest fine paid by poachers to the social planner is a transfer in the economy, which does not affect the total economic surplus, so it cancels out in the objective function. Therefore, the social planner solves the following problem.

$$\underset{E(t),Q_L(t)}{\mathrm{Max}} \int_0^\infty \left\{ \int_0^{Q(t)} P(x)dx - h\left(Q_L(t),s(t)\right) - k\left(s(t)\right)Q_I\left(E(t),Q_L(t),s(t)\right) - c\left(E(t)\right) \right\} e^{-\delta t}dt \qquad (3.8)$$

subject to

$$\dot{s}(t) = g\left(s(t)\right) - D\left(k\left(s(t)\right) + \lambda\left(E(t)\right)\phi\right)$$
$$s(t=0) = s_0 \text{ given}$$
$$s(t), E(t), Q_L(t) \ge 0, \forall t,$$
$$\text{and } Q_I(t) \ge 0, \forall t,$$

where $Q(t)$ is defined in (3.7) and x is a placeholder.

Substituting $D\left(k\left(s(t)\right) + \lambda\left(E(t)\right)\phi\right) - Q_L(t)$ for $Q_I(t)$, the Lagrangean corresponding to problem (3.8), is:

$$\overline{L}(t) = \bar{\tilde{H}}(t) + \overline{\gamma}(t)\left[D\left(k\left(s(t)\right) + \lambda\left(E(t)\right)\phi\right) - Q_L(t)\right]$$

$$= \int_0^{D(k(s(t))+\lambda(E(t))\phi)} P(x)\,dx - h\left(Q_L(t), s(t)\right) - k\left[D\left(k\left(s(t)\right)+\lambda\left(E(t)\right)\phi\right) - Q_L(t)\right]$$
$$-c\left(E(t)\right) + \bar{\mu}(t)\left[g\left(s(t)\right) - D\left(k\left(s(t)\right)+\lambda\left(E(t)\right)\phi\right)\right] \qquad (3.9)$$
$$+\bar{\gamma}(t)\left[D\left(k\left(s(t)\right)+\lambda\left(E(t)\right)\phi\right) - Q_L(t)\right]$$

where $\bar{\tilde{H}}(t)$ is the current value Hamiltonian for problem (3.8), $\bar{\mu}(t)$ is the corresponding current value co-state variable and $\bar{\gamma}(t)$ is the Lagrange multiplier on the inequality constraint $Q_I\left(E(t), Q_L(t), s(t)\right) \geq 0$.

Using Leibnitz' rule of differentiation of integrals where appropriate, the necessary conditions for this problem are given by (3.10)-(3.15).

$\bar{L}_{Q_L(t)} = k\left(s(t)\right) - h_1\left(Q_L(t), s(t)\right) - \bar{\gamma}(t) \leq 0$, $Q_L(t) \geq 0$, and

$$\left[k\left(s(t)\right) - h_1\left(Q_L(t), s(t)\right) - \bar{\gamma}(t)\right] Q_L(t) = 0; \qquad (3.10)$$

$\bar{L}_{E(t)} = \left(\lambda\left(E(t)\right)\phi - \bar{\mu}(t) + \bar{\gamma}(t)\right) D'(\cdot)\lambda'\left(E(t)\right)\phi - c'\left(E(t)\right) \leq 0, E(t) \geq 0,$

and $\left[\left(\lambda\left(E(t)\right)\phi - \bar{\mu}(t) + \bar{\gamma}(t)\right) D'(\cdot)\lambda'\left(E(t)\right)\phi - c'\left(E(t)\right)\right] E(t) = 0;$ (3.11)

$$\begin{aligned} -\bar{L}_{s(t)} &= \dot{\bar{\mu}}(t) - \delta\mu(t) \\ &= h_2\left(Q_L(t), s(t)\right) - k'\left(s(t)\right) Q_L(t) \\ &\quad - D'(\cdot) k'\left(s(t)\right)\left(\lambda\left(E(t)\right)\phi - \bar{\mu}(t) + \bar{\gamma}(t)\right) \\ &\quad - \bar{\mu}(t) g'\left(s(t)\right) + k'\left(s(t)\right) D(\cdot) \end{aligned} \qquad (3.12)$$

$$\bar{L}_{\mu(t)} = \dot{s}(t) = g\left(s(t)\right) - D(\cdot); \qquad (3.13)$$

$$\bar{L}_{\bar{\gamma}(t)} = D(\cdot) - Q_L(t) \geq 0,\ \bar{\gamma}(t) \geq 0,\ \left[D(\cdot) - Q_L(t)\right]\bar{\gamma}(t) = 0; \qquad (3.14)$$

$$\lim_{t\to\infty} \bar{\mu}(t) e^{-\delta t} \geq 0,\ \lim_{t\to\infty} \bar{\mu}(t) s(t) e^{-\delta t} = 0. \qquad (3.15)$$

The necessary Legendre condition is verified:

$\bar{L}_{Q_L(t)Q_L(t)} = -h_{11}\left(Q_L(t), s(t)\right) \leq 0$. We assume that the necessary Legendre condition on E(t) also holds,[6] as well as sufficient conditions for the concavity of the Hamiltonian. That way, first order conditions (3.10)-(3.15) are necessary and sufficient, which ensures a solution.

Conditions (3.10), (3.11) and (3.14) are Kuhn-Tucker conditions allowing $Q_L(t)$, $Q_I(t)$ and E(t) to be greater than or equal to zero, leading to a total of eight possible cases along the optimal path, depending on the resource stock and the parameters of the model. It is interesting to note that dynamic optimization in this model occurs through enforcement only. Indeed, condition (3.10) is static and, in conjunction with (3.14), ensures that the total optimal harvest is provided cost-efficiently at all times. As we will characterize in some details below, depending on the relative legal and illegal harvest cost structures, either the social planner or the poachers may provide the entire harvest, or they might share the market. In addition, the composition of suppliers may change over time, as the resource stock and the corresponding optimal enforcement effort change. For example, if it is optimal for legal and illegal harvest to occur simultaneously, then $\bar{\gamma}(t) = 0$. As the stock level increases, the legal harvests could increase or decrease, depending on the relative changes between illegal minimum

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[6]
$$\begin{aligned}\bar{L}_{E(t)E(t)} &= D'(\cdot)\left[\lambda'\left(E(t)\right)\phi\right]^2 \\ &+\left(\lambda\left(E(t)\right)\phi - \bar{\mu}(t) + \bar{\gamma}(t)\right)\left[D''(\cdot)\left[\lambda'\left(E(t)\right)\phi\right]^2 + D'(\cdot)\lambda''\left(E(t)\right)\phi\right] \\ &-c''\left(E(t)\right) \\ &\leq 0.\end{aligned}$$

average harvest cost and legal marginal harvest cost; from (3.10),

$$\frac{dQ_L(t)}{ds(t)} = \frac{\left(k'\left(s(t)\right) - h_{12}\left(Q_L(t), s(t)\right)\right)}{h_{11}\left(Q_L(t), s(t)\right)}.$$

We will say that *complete deterrence* occurs if poaching activities are eliminated altogether, *i.e.*, if $Q_I\left(t\right) = 0$. In contrast, *partial deterrence* occurs if poaching activities are reduced as compared to the open access scenario but are not completely eliminated, *i.e.*, if $0 < Q_I\left(t\right) < Q^{OA}\left(t\right)$.

Equation (3.11) provides the condition for inter-temporally optimal enforcement. At any point in time, there will be positive enforcement only if it is not too costly, *i.e.*, if $c'\left(0\right) < \left(\lambda(t)\phi D'\lambda'\phi - \overline{\mu}(t)D'\lambda'\phi + \overline{\gamma}(t)D'\lambda'\phi\right)\Big|_{E(t)=0}$. But there will be no enforcement at all if it is prohibitively costly: *i.e.*, if $c'\left(0\right) \geq \left(\lambda(t)\phi D'\lambda'\phi - \overline{\mu}(t)D'\lambda'\phi + \overline{\gamma}(t)D'\lambda'\phi\right)\Big|_{E(t)=0}$. In that case, enforcing the property right over the resource would be inefficient. This illustrates Demsetz' (1967) assertion that if the costs of internalization of externalities are too high, then effective property rights cannot be efficient. If enforcement is prohibitively costly, the social planner may harvest if his harvest cost is low enough relative to market inverse demand, but the shadow value of the resource has vanished to zero. In that case, the total harvest is the same as in open access regime since $\lambda(E(t))\phi = 0$. The illegal harvesters could also harvest under open access conditions. Overall, if enforcement cost is prohibitively costly, demand is satisfied by either or both the social planner's and the illegal harvesters' supply, at the open access level: $D\left(k\left(s\left(t\right)\right)\right) = Q_L\left(s\left(t\right)\right) + Q_I\left(s\left(t\right)\right)$ $= Q^{OA}\left(s\left(t\right)\right)$, $Q_L\left(s\left(t\right)\right) \geq 0$, $Q_I\left(s\left(t\right)\right) \geq 0$ and $Q^{OA}\left(s\left(t\right)\right) \geq 0$

Equation (3.12) gives the optimality condition with respect to the resource stock that drives $\dot{\bar{\mu}}(t)$, the change in the shadow price of the resource. Equation (3.13) gives back the resource transition equation. The non-negativity constraint on illegal harvest along with its complementary slackness conditions are found in (3.14). We note that by writing the upper boundary of the integral in (3.9) as $D\left(k\left(s\left(t\right)\right)+\lambda\left(E\left(t\right)\right)\phi\right)$, we implicitly assume that even if $Q_I\left(s\left(t\right)\right)=0$ (if there is no illegal harvest), $P\left(s\left(t\right)\right)>k\left(s\left(t\right)\right)$ for all feasible stocks. This means that positive enforcement is necessary to prevent the entry of poachers into open access harvest. Finally, equation (3.15) is the transversality condition for the problem.

Cases 1-3 below describe the different supply eventualities emerging from the relative harvest cost structures of the social planner relative to that of poachers. For all three cases, we assume that $D^{-1}\left(0\right)=P\left(0\right)>k\left(s(t)\right)$. This means that poachers' minimum average harvest cost is lower than the choke price. Therefore, if there is no enforcement effort, poachers will harvest and their supply will find demanders on the market. We assume that the resource rent is always positive, $\bar{\mu}^*\left(t\right)>0$. This implies that $c'\left(0\right)<\left(\lambda(t)\phi D'\lambda'\phi-\bar{\mu}(t)D'\lambda'\phi+\bar{\gamma}(t)D'\lambda'\phi\right)\Big|_{E(t)=0}$, *i.e.*, enforcement is cheap enough to be optimally positive. With positive optimal enforcement, the four possible cases arising from Kuhn-Tucker conditions (3.10) and (3.14) are included within Cases 1-3. Whether partial or complete deterrence of poaching should be achieved depends on the marginal cost of the social planner being constant or convex and on it being greater, equal to or smaller than the minimum average cost of the poachers, k(s(t)). In Proposition 3.1, complete deterrence occurs, while in Proposition 3.2 and Proposition

3.4 we only find partial deterrence. The situation depicted in Proposition 3.3 could lead to either complete or partial deterrence. Proofs of these propositions rely on Kuhn-Tucker conditions (3.10) and (3.14).

Case 1.

In this case, assume that $D\left(k\left(s(t)\right)+\lambda\left(E*(t)\right)\phi\right)=$ $Q_L\left(s(t)\right)*+Q_I\left(E*(t),Q_L\left(s(t)\right)*,s(t)\right)>0$, *i.e.*, the equilibrium resource supply is positive. Such a case implies that the market price is lower than the choke price, even though enforcement is positive: $D^{-1}\left(0\right)=P\left(0\right)>k\left(s(t)\right)+\lambda\left(s(t)\right)\phi>k\left(s(t)\right)$. Propositions 3.1-3.3 refer to this case.

Proposition 3.1.

If $k\left(s(t)\right)>h_1\left(D\left(k\left(s(t)\right),s(t)\right)\right)$, then the entire market supply is provided by the social planner and poachers are completely deterred.

Proof.

Suppose $\overline{\gamma}(t)=0$. Since $k\left(s(t)\right)>h_1\left(D\left(k\left(s(t)\right),s(t)\right)\right)$, then $\overline{L}(t)_{Q_L(t)}>0$, but this violates Kuhn-Tucker condition (3.10). Hence, $\overline{\gamma}(t)>0$, which in turn means that $Q*_I(t)=0$ from condition (3.14). This implies $Q_L*(t)=D\left(k\left(s(t)\right)+\lambda\left(s(t)\right)\phi\right)$.□

Hence, whenever the minimum average harvest cost of poachers is greater than the marginal harvest cost of the social planner evaluated at the market equilibrium quantity, the social planner prefers to supply this entire quantity because it is cost-efficient, which serves to maximize total economic surplus. We note that, since we assumed $P(0) > k(s(t)) + \lambda(s(t))\phi$, and in this case, $k(s(t)) > h_1(D(k(s(t)), s(t)))$, then $P(0) > P(Q) = k(s(t)) + \lambda(s(t)) > h_1(D(k(s(t)), s(t)))$. At price $P(Q)$, demand is positive and $P(Q)$ is greater than the legal marginal cost of harvesting. This is intuitive since at least part of the resource rent must be used to pay for the enforcement effort.

Proposition 3.2.

If $k(s(t)) < h_1(D(k(s(t)), s(t)))$, then the entire market supply is provided by the poachers and poaching can at best be partially deterred.

Proof.

Since $\overline{\gamma}(t) \geq 0$ and $k(s(t)) < h_1(D(k(s(t)), s(t)))$, then $\overline{L}(t)_{Q_L(t)} < 0$ and hence $Q*_L(t) = 0$. Since $D(k(s(t)), s(t)) = Q_L(t) + Q_I(Q_L(t), s(t)) > 0$, then it must be that $Q*_I(s(t)) = D(k(s(t)), s(t))$. If E(s(t)) = 0, then D = D(k(s(t))) and open access results, *i.e.*, poaching is not deterred at all. But if E(s(t)) > 0, we know that $D(k(s(t)), s(t)) < D(k(s(t)))$ and partial deterrence occurs, that is, poachers are still active, but less than they would be under open access. □

Proposition 3.2 says that whenever the minimum average harvest cost of the poachers is less than the marginal cost of the social planner evaluated at the market equilibrium quantity, it is optimal to let poachers provide the entire quantity supplied to the market.

Proposition 3.3.

Suppose a constant legal harvest marginal cost, $h_1\left(Q_L\left(s(t)\right), s(t)\right) = h\left(s(t)\right)$ for all $Q_L\left(s(t)\right)$. If $k\left(s(t)\right) = h\left(s(t)\right)$, then Q_I*(s(t)) and Q_L*(s(t)) are indeterminate but satisfy $D\left(k\left(s(t)\right), s(t)\right) = Q^*_L\left(s(t)\right) + Q^*_I\left(s(t)\right)$.

Proof.

Suppose $\bar{\gamma}(t) > 0$. Since $k\left(s(t)\right) = h_1\left(Q_L(t), s(t)\right)$, then $\bar{L}_{Q_L(t)} < 0$ and $Q_L(t) = 0$, in order to satisfy condition (3.10). Also, $Q_I(t) = 0$ to satisfy condition (3.14). This leads to $D\left(k\left(s(t)\right), s(t)\right) = Q_L(t) + Q_I\left(Q_L(t), s(t)\right) = 0$, which is contrary to our assumption. Hence, $\bar{\gamma}(t) = 0$. Then $\bar{L}_{Q_L(t)} = 0$ satisfies condition (3.10), which means that $Q^*_L\left(s(t)\right) \geq 0$. Since $\bar{\gamma}(t) = 0$, $Q^*_I\left(s(t)\right) \geq 0$ as well. The share of legal to illegal harvest is however indeterminate. □

Proposition 3.3 applies to the restrictive case where the social planner's marginal harvest cost is constant and equal to those of the poachers. Any distribution of the total harvest will be equally cost-efficient, and therefore the actual optimal distribution is indeterminate.

Assumption 3.1.

Assume that the social planner's harvest cost function is strictly convex in Q_L. Assume also that $h(0, s) < k(s)$, for all s, which means that the legal marginal harvest cost and the illegal minimum average harvest cost are equal at one harvest quantity only, *i.e.*, for all s(t), $k\left(s\left(t\right)\right)=h_1\left(Q_L\left(t\right),s\left(t\right)\right)$ has a unique implicit solution, which we now define.

Definition 3.2.

Under Assumption 3.1, let us define the harvest quantity at which the legal marginal harvest cost and the illegal minimum average harvest cost are equal as $\tilde{Q}\left(s\left(t\right)\right)$. Therefore $\tilde{Q}\left(s\left(t\right)\right)$ is defined by an implicit function, $f\left(\cdot\right)$, which depends on the resource stock and on the legal and illegal harvest technologies:

$\tilde{Q}\left(s\left(t\right)\right)=f\left(k\left(s\left(t\right)\right),h\left(Q_L\left(s\left(t\right)\right)\right),s\left(t\right)\right)$.

Assumption 3.2.

Under Assumption 3.1, further assume that $D\left(k\left(s(t)\right),s(t)\right)>\tilde{Q}\left(s\left(t\right)\right)$ so that $Q_L\left(s\left(t\right)\right)=\tilde{Q}\left(s\left(t\right)\right)$.

Under Assumption 3.2, there exists a legal harvest quantity, $Q_L(t)$ such that $k\left(s\left(t\right)\right)=h_1\left(Q_L\left(t\right),s\left(t\right)\right)$. This intersection of marginal costs implicitly defines the legal harvest quantity $Q_L\left(s\left(t\right)\right)=\tilde{Q}\left(s\left(t\right)\right)$, as long as $D\left(k\left(s(t)\right),s(t)\right)>\tilde{Q}\left(s\left(t\right)\right)$. This leads to Case 2.

Case 2.

Under Assumption 3.2, $Q^* = Q_L^*\left(s(t)\right) + Q_I\left(Q_L^*\left(s(t)\right)\right) =$ $D\left(k(s(t)), s(t)\right) > \tilde{Q}\left(s(t)\right) > 0$, *i.e.*, the equilibrium resource supply is positive and it is greater than $\tilde{Q}(s)$, the harvest quantity where the social planner's marginal harvest cost curve crosses the poachers' minimum average harvest cost level. Proposition 3.4 refers to this case. We suppose again that enforcement is positive, although this assumption could be relaxed for Proposition 3.4.

Proposition 3.4.

Under the assumptions of Case 2, the social planner will supply $\tilde{Q}\left(s(t)\right)$ to the market while the poachers will provide the rest of the total optimal supply: $Q_I\left(\tilde{Q}\left(s(t)\right), s(t)\right) = D\left(k\left(s(t)\right), s(t)\right) - \tilde{Q}\left(s(t)\right) > 0$.

Proof.

This proof proceeds in a piecewise fashion.

First, for $Q_L \in \left[0, \tilde{Q}(s)\right]$, we have that $k\left(s(t)\right) \geq h_1\left(Q_L(t), s(t)\right)$. Suppose $\overline{\gamma}(t) = 0$. Then $\overline{L}_{Q_L(t)} > 0$, which violates Kuhn-Tucker condition (3.10).

Hence, $\overline{\gamma}(t) > 0$, which in turn means that $Q_I(t) = 0$ from condition (3.14). Since it is assumed that $D\left(k\left(s(t)\right), s(t)\right) = Q_L(t) + Q_I\left(Q_L\left(s(t)\right), s(t)\right) > \tilde{Q}(s)$, then $Q_L^*\left(s(t)\right) = \tilde{Q}(s)$.

Second, for $Q_L \in \left(\tilde{Q}(s), D\left(k\left(s(t)\right), s(t)\right)\right]$, we have that $k\left(s(t)\right) < h_1\left(Q_L(t), s(t)\right)$. Since $\overline{\gamma}(t) \geq 0$, $\overline{L}_{Q_L(t)} < 0$ and hence it is not optimal for legal harvest to exceed $\tilde{Q}(s)$.

Finally, since $D\left(k\left(s(t)\right), s(t)\right) = Q_L\left(s(t)\right) + Q_I\left(Q_L(t), s(t)\right)$, we have that $Q_I{*}\left(s(t)\right) = D\left(k\left(s(t)\right), s(t)\right) - \tilde{Q}(s)$. □

Proposition 3.4 says that when the social planner's marginal harvest cost is strictly convex and therefore crosses poachers' minimum average harvest cost at one point, $\tilde{Q}\left(s(t)\right)$, then if $D\left(k\left(s(t)\right), s(t)\right) > \tilde{Q}\left(s(t)\right)$, the social planner's harvest is $Q_L^*\left(s(t)\right) = \tilde{Q}\left(s(t)\right)$ and the poachers' harvest is $Q_I^*\left(s(t)\right) = \left[D\left(k\left(s(t)\right), s(t)\right) - \tilde{Q}\left(s(t)\right)\right]$.

Let us remark that the case, still under Assumption 3.1, where $Q_L^*\left(s(t)\right) + Q_I\left(Q_L^*\left(s(t)\right), s(t)\right) = D\left(k\left(s(t)\right), s(t)\right) < \tilde{Q}\left(s(t)\right)$ is included in the more general Proposition 3.1.

It seems noteworthy that, in the absence of fully controlled access to the resource, it could be optimal for poachers to provide the entire market supply *ad infinitum* while the social planner only monitors and limits their activities through enforcement (it is the case in Proposition 3.2, and possibly 3.3 as well). Case 2 offers an example where it could be optimal for the supply to the market to be shared across legal and illegal harvesters. Hence this model shows clearly that the presence and possibly even the persistence of a black market[7] is not necessarily an indication that resource management policy is nonexistent or sub-optimal. With costly enforcement, this situation could be second best optimal and, in such a case, the existence of a black market would be justified by the relative marginal harvest costs across legal and illegal harvesters.

Indeed, when the poachers' minimum average harvest cost is lower than the social planner's marginal harvest cost, it is cost-efficient for the social planner to let the poachers harvest in his place. This is conceptually equivalent to the social planner delegating its harvest to poachers who can do it at a lower cost, which is welfare increasing for society.

Case 3.

$D\left(k\left(s\left(t\right)\right), s\left(t\right)\right) = Q_L^*\left(s\left(t\right)\right) + Q_I\left(Q_L^*\left(s\left(t\right)\right), s\left(t\right)\right) = 0$, *i.e.*, in equilibrium, there is no supply to the market. This case is limited neither by Assumption 3.1 nor by Assumption 3.2.

Since, from the beginning, we have assumed that $D^{-1}\left(0\right) = P\left(0\right) > k\left(s(t)\right)$, for this case to arise, enforcement is necessary so that price is raised up to the choke price: $k\left(s(t)\right) + \lambda\left(s\left(t\right)\right)\phi = P\left(0\right)$.

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[7] A market trading an illegally harvested resource.

Since enforcement is costly and in this case there is no instantaneous welfare due to harvest, then the social planner must be investing in the future by letting the resource stock replenish itself. This situation can only be transitory the instantaneous welfare effect is negative. Hence in Case 3, we know that resource harvest will resume at some later point in time.

Cases 1 and 2 referred to situations that could hold both in the short run, along the optimal path, or in the long-run, *i.e.*, in a steady state equilibrium, depending on the initial stock level, s_0, and on the parameters of the model. In contrast, Case 3 refers to clear-cut transitory situations because instantaneous welfare is negative.

3.3.1. Optimal steady states

An optimal steady state equilibrium exists, for a vector $\left(s_\infty^*, Q_{L,\infty}^*, Q_{I,\infty}^*, E_\infty^*, \overline{\mu}_\infty^*\right)$ such that necessary conditions (3.10) to (3.15) hold, as well as $\dot{s} = \dot{Q}_L = \dot{Q}_I = \dot{E} = \dot{\overline{\mu}} = 0$.

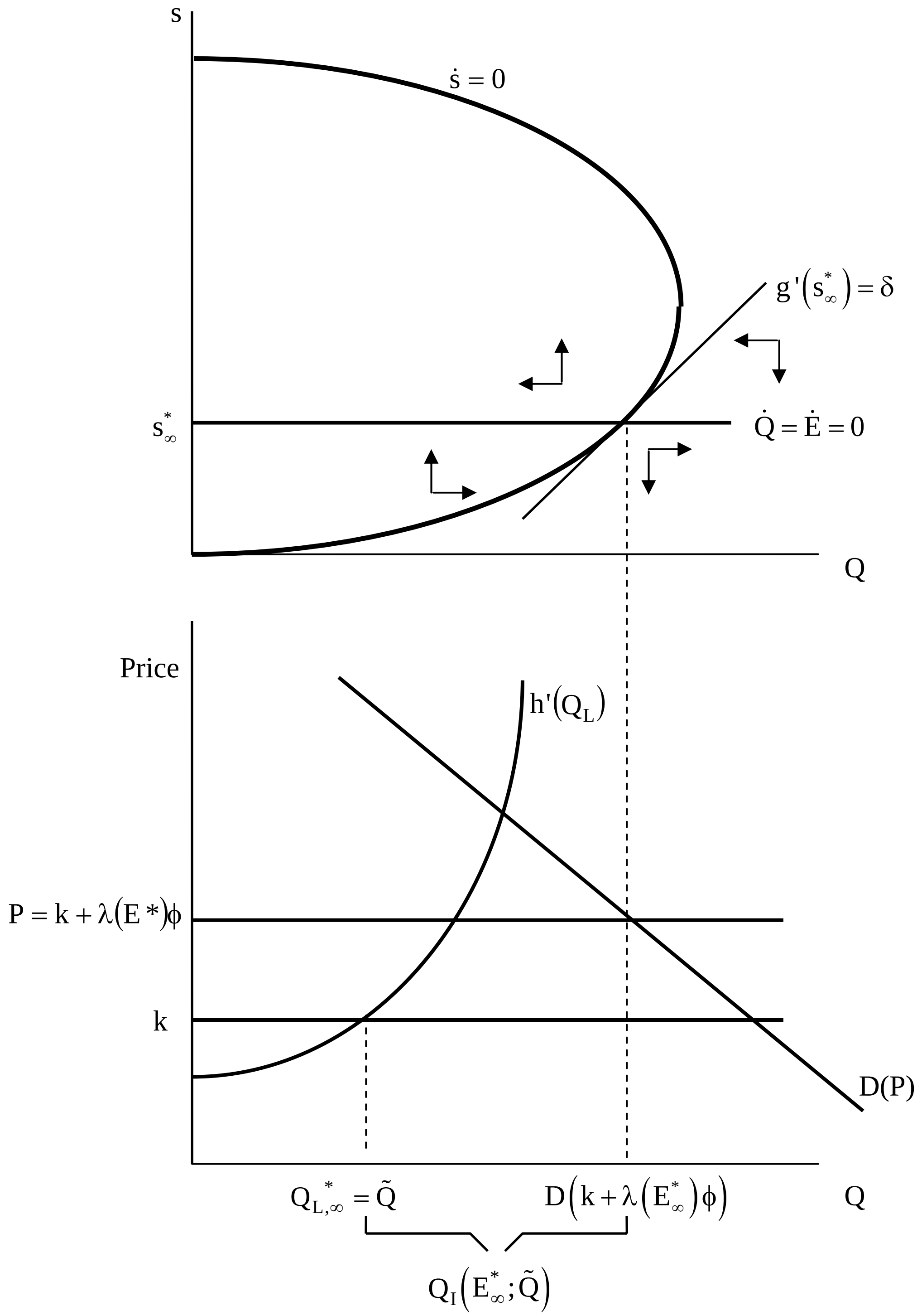
In the special case where instantaneous gains are not stock-dependent, *i.e.*, where $K_2\left(q_I, s(t)\right) = 0$, $h_2\left(Q_L, s(t)\right) = 0$ and $F'\left(s(t)\right) = 0$, there is only one possible optimal steady state. Indeed, from necessary condition (3.12), the unique steady state is such that $s_\infty^* = \inf\left\{s : g'(s) \le \delta\right\}$. Since s(t) ≥ 0, $s_\infty^* = \inf\left\{s : g'(s) \le \delta\right\}$ includes the possibility of extinction if $\delta \ge g'(0)$ and the possibility of long run conservation if $\delta < g'(0)$.

For the steady state analysis that follows, we assume that $\delta < g'(0)$, which means that the optimal steady state stock is positive. We also assume that the unique optimal steady state is consistent with Case 2. Still assuming that instantaneous gains are not stock-dependent, under Assumption 3.1 and Assumption 3.2, which lead to Case 2, there exists a steady state legal harvest quantity, $Q^*_{L,\infty}$ such that $k = h'\left(Q^*_{L,\infty}\right)$. This intersection of marginal costs implicitly defines the steady state legal harvest quantity $Q^*_{L,\infty} = \tilde{Q}$, as long as $D\left(k + \lambda\left(E^*_\infty\right)\phi\right) > \tilde{Q}$. This leads to a steady state equilibrium where both the social planner and poachers harvest the resource.

If a species that is harvested enough to be economically scarce in steady state, then $\bar{\mu}^*_\infty > 0$, which implies that $E^*_\infty > 0$.

A positive steady state stock and (3.13), imply that $g\left(s^*_\infty\right) = D\left(k + \lambda\left(E^*_\infty\right)\phi\right)$. In addition, from (3.12), the golden rule of economic growth applies: $g'\left(s^*_\infty\right) = \delta$. Hence, the only steady state variable that remains to be found is E^*_∞, the enforcement level, which in turn will determine $Q_I\left(E^*_\infty, Q^*_{L\infty}\right)$, or simply $Q_I\left(E^*_\infty\right)$ since in the case considered, $Q^*_{L,\infty} = \tilde{Q}$ is pegged. At the stock level where $\delta = g'\left(s^*_\infty\right)$, the enforcement level must be such that $Q_I\left(E^*_\infty; \tilde{Q}\right) + \tilde{Q} = D\left(k + \lambda\left(E^*_\infty\right)\phi\right) = g\left(s^*_\infty\right)$. Figure 3.3 illustrates this steady state. The top graph looks like the typical textbook optimum steady state when harvest costs are not stock-dependent, only with the Q- and s-axes flipped as compared to the usual presentation of a phase diagram. At the same time, the bottom graph is a modified version of the textbook graph of a static free entry dominant firm-competitive fringe model (*e.g.*, Carlton and Perloff (1994), p. 168).

Figure 3.3. Steady State Equilibrium; No Stock Dependence



In the more general case, where harvest costs are stock-dependent, assuming that $g\left(s_{\infty}^{*}\right) > \tilde{Q}\left(s_{\infty}^{*}\right)$, we find from necessary conditions (3.11) and (3.12) that

$g'\left(s_{\infty}^{*}\right) = \delta + \frac{D'\lambda'\phi\left(h_2 + k'\left(D - Q_L\right)\right) - D'k'c'}{D'\lambda'\lambda\phi^2 - c'}$, where arguments of functions have been left out for brevity. The second right hand side term has a negative denominator. The firs term of the numerator is negative, pushing towards a greater steady state stock, than where $g'\left(s_{\infty}^{*}\right) = \delta$, while the second term of the numerator is negative, pushing towards a smaller steady state stock than where $g'\left(s_{\infty}^{*}\right) = \delta$. Since the second right hand side term could be overall positive or negative, depending on the parameters of the model, we conclude that a positive steady state stock could be greater or smaller than when harvest costs are not stock dependent. This differs from the costless enforcement model where the steady state stock is always greater under stock-dependent harvest costs. The possibility of a lower steady state stock arises here because of the structure of the model where price is endogenous and depends on the stock level and the enforcement effort. Since $h_2(q_I(t), s(t)) \leq 0$ and $k'\left(s(t)\right) = \frac{K_2(t)}{q_I(t)} < 0$, a higher stock does not only lower harvest costs, it also lowers the market price since $P = k(s) + \lambda\phi$. Given that the demand is downward-sloping, this increases the equilibrium quantity harvested, which in turn lowers the resource stock. Hence, the overall effect of the stock-dependence of harvest costs on the steady state resource stock is unclear.

Furthermore in the more general model, multiple optimal steady states could exist. Whether the optimal long run equilibrium leads to conservation or extinction could depend on the parameters of the model and possibly also on the initial stock level, s_0. Without any specification of functions however, little can be said about long run outcomes. In Chapter 4, we present a model with some level of function specification which allows us to compare phase diagrams with and without a fixed flow of resource management costs.

3.3.2. Equilibrium paths

For the special case where instantaneous gains are not stock-dependent, *i.e.*, where $K_2\left(q_I, s(t)\right) = 0$ and $h_2\left(Q_L, s(t)\right) = 0$, we characterize the equilibrium paths with optimal positive enforcement. The more general case, where $K_2\left(q_I, s(t)\right) > 0$ and $h_2\left(Q_L, s(t)\right) > 0$, is substantially more complicated; paths are difficult to characterize, unless the functions are specified. Therefore, we concentrate on the simpler version of the model.

Resource stock.

From (3.12), we obtain $\dot{\bar{\mu}}(t) = \bar{\mu}(t)\left[\delta - g'\left(s(t)\right)\right]$. Therefore, as long as $\delta \leq g'(0)$, there can exist only one positive steady state stock, where g'(s) = δ. This problem is an autonomous infinite horizon problem with positive discount rate and a unique stock. This means that the resource stock path is monotonic over time (Long, 1979; Léonard and Long, 1992, Theorem 9.5.1). Therefore, if s(t) is such that

$\left(\delta - g'\left(s\left(t\right)\right)\right) < 0$, then by the strict concavity of g(s) and the monotonicity of the resource stock path, $\dot{s}\left(t\right) > 0$, and *vice versa*.

In what follows, we consider cases with s*trictly legal supply*, *i.e.*, cases where $Q_L\left(t\right) > 0$ but $Q_I\left(t\right) = 0$, and hence $Q_L\left(t\right) = D\left(k + \lambda\left(E\left(t\right)\right)\phi\right)$. From equations (3.10) and (3.14), a positive supply that is strictly legal implies $\overline{\gamma}\left(t\right) = k - h'\left(Q_L\left(t\right)\right) \geq 0$, which leads to $\dot{\overline{\gamma}}\left(t\right) = -h''\left(Q_L\left(t\right)\right)\dot{Q}_L\left(t\right) = -h''\left(Q_L\left(t\right)\right)D'\lambda'\phi\dot{E}\left(t\right)$.

Co-state variable, with strictly legal supply.

We find $\dot{\overline{\mu}}\left(t\right)$ directly in (3.12), where we substitute $\overline{\mu}$ from equation (3.11):

$$\dot{\overline{\mu}}\left(t\right) = \left[\lambda\left(E\left(t\right)\right)\phi + k - h' - \frac{c'}{D'\lambda'\phi}\right]\left(\delta - g'\left(s\left(t\right)\right)\right)$$

Since $\left[\lambda\left(E\left(t\right)\right)\phi + k - h' - \frac{c'}{D'\lambda'\phi}\right] = \overline{\mu}\left(t\right) > 0$, the sign of $\dot{\overline{\mu}}\left(t\right)$ is the same as the sign of $\left(\delta - g'\left(s\left(t\right)\right)\right)$, and therefore the opposite sign as $\dot{s}\left(t\right)$.

Enforcement, with strictly legal supply.

We totally differentiate (3.11) with respect to time. We then substitute $\dot{\bar{\mu}}(t)$ from (3.12) and $\dot{\bar{\gamma}}(t) = -h''(\cdot)\dot{Q}_L(t)$, as explained above, and we find the optimal enforcement path

$$\dot{E}(t) = \frac{\left[D'\lambda'\phi\left(\lambda\left(E(t)\right)\phi + \bar{\gamma}(t)\right) - c'\left(E(t)\right)\right]\left(\delta - g'\left(s(t)\right)\right)}{\bar{\tilde{H}}(t)_{E(t)E(t)} - \left(D'\lambda'\phi\right)^2 h''\left(Q_L(t)\right)},$$

where $\bar{\tilde{H}}(t)_{E(t)E(t)} \leq 0$ by assumption of concavity of the Hamiltonian. Since $\left[D'\lambda'\phi\left(\lambda\left(E(t)\right)\phi + \bar{\gamma}(t)\right) - c'\left(E(t)\right)\right] = \bar{\mu}(t)D'\lambda'\phi < 0$ and since the denominator is negative, then it follows that the sign of $\dot{E}(t)$ is the same as the sign of $\left(\delta - g'\left(s(t)\right)\right)$, and therefore the opposite sign as $\dot{s}(t)$. The enforcement path is therefore monotonic, like that of the resource stock.

In what follows, we now consider cases with *illegal supply*, *i.e.*, cases where $Q_I(t) > 0$ and $Q_L(t) \geq 0$. These cases encompass situations where supply is partially or completely illegal. With illegal supply, from equations (3.10) and (3.14), we know that $D\left(k + \lambda\left(E(t)\right)\phi\right) - Q_L(t) > 0$, $\bar{\gamma}(t) = 0$ and therefore $\dot{\bar{\gamma}}(t) = 0$.

Co-state variable, with illegal supply.

We find $\dot{\bar{\mu}}(t)$ directly in (3.12), where we substitute $\bar{\mu}(t)$ from equation (3.11):

$$\dot{\bar{\mu}}(t) = \left[\lambda\left(E(t)\right)\phi - \frac{c'}{D'\lambda'\phi}\right]\left(\delta - g'\left(s(t)\right)\right)$$

As in the case with strictly legal supply, because $\left[\lambda\left(E(t)\right)\phi - \frac{c'}{D'\lambda'\phi}\right] = \bar{\mu}(t) > 0$ here, the sign of $\dot{\bar{\mu}}(t)$ is the same as the sign of $\left(\delta - g'\left(s(t)\right)\right)$, and therefore the opposite sign as $\dot{s}(t)$.

Enforcement, with illegal supply.

Following the same steps as for the strictly legal supply, but using $\dot{\bar{\gamma}}(t) = 0$ instead, we obtain

$$\dot{E}(t) = \frac{\left[D'\lambda'\phi\lambda\left(E(t)\right)\phi - c'\right]\left(\delta - g'\left(s(t)\right)\right)}{\bar{\bar{\tilde{H}}}(t)_{E(t)E(t)}},$$

where again $\bar{\bar{\tilde{H}}}(t)_{E(t)E(t)} \leq 0$ by assumption of concavity of the Hamiltonian. Since the denominator and $\left[D'\lambda'\phi\lambda\left(E(t)\right)\phi - c'\right] = \bar{\mu}(t)D'\lambda'\phi$ are both negative, then the sign of $\dot{E}(t)$ is the same as the sign of $\left(\delta - g'\left(s(t)\right)\right)$ or the opposite sign as $\dot{s}(t)$. This is qualitatively similar to the case with strictly legal supply. Again, the enforcement path is monotonic. When the initial stock is below the optimal steady state, enforcement is high, but as the stock increases, enforcement declines. Likewise, if the initial stock is larger than the optimal steady state, then enforcement is small but it increases as harvesting reduces the stock size.

We note that the total harvest moves in the opposite direction as enforcement, due to the downward-sloping demand curve, and therefore, in the same direction as the resource stock.

We mentioned before that if the resource is exploited in open access only, without any probability of paying a fine, then the number of harvesters was constant independent of time and of the resource stock. However, with a social planner (or a pseudo-monopolist as in section 3.4), who can harvest legally while poachers could simultaneously harvest illegally, the total equilibrium harvest is equal to

$$Q\left(s(t)\right) = D\Big(k\left(s(t)\right) + \lambda\Big(E*\left(s(t)\right)\Big)\phi\Big) = Q_I\Big(E*\left(s(t)\right), Q_L^*\left(s(t)\right)\Big) + Q_L^*\left(s(t)\right), \qquad (3.16)$$

that is, the sum of illegal harvests aggregated over poachers, Q_I, and the legal harvest, Q_L. If there is some positive level of enforcement, so that $\lambda(t)\phi > 0$, then the number of poachers is reduced compared to the open access regime since

$Q\left(s(t)\right) = D\Big(k\left(s(t)\right) + \lambda\Big(E*\left(s(t)\right)\Big)\phi\Big) < D\Big(k\left(s(t)\right)\Big)$, whether $Q_L^*\left(s(t)\right) > 0$ or not.

Hence some positive level of deterrence occurs as long as $\lambda(t)\phi > 0$.

3.4. Pseudo-monopolist problem: profit maximization and corrective policies

In this section we examine the problem of a pseudo-monopolist, who legally exploits the resource and enforces his property rights in order to maximize inter-temporal profit without regard for the welfare of consumers and poachers. It is assumed that the pseudo-monopolist keeps the fines collected from poachers. From a global perspective, the pseudo-monopolist's behavior is consistent with an individual country's government that manages an exportable renewable resource without regard to domestic consumer and poachers' welfare. Alternatively, in a national context, the pseudo-monopolist's behavior is consistent with that of a private resource owner who is only interested in making discounted inter-temporal profits from the resource.

From the predicted poachers' behavior, we substitute P using market equilibrium condition (3.6), *i.e.*, $P(t)=k(s(t))+\lambda(t)\phi$ and Q using equation (3.7), *i.e.*, $Q(t)=D(k(s(t))+\lambda(t)\phi)$. We also make use of identity (3.16), *i.e.*, $D(k(s(t))+\lambda(E^*(s(t)))\phi)=$ $Q_I(E^*(s(t)),Q_L^*(s(t)))+Q_L^*(s(t))$, so the pseudo-monopolist's problem can be written as follows.

$$\underset{E(t),Q_L(t)}{\text{Max}}\int_0^\infty \left\{\begin{array}{l} k(s(t))Q_L(t)-h(Q_L(t),s(t)) \\ +\lambda(E(t))\phi D(k(s(t))+\lambda(E(t))\phi)-c(E(t)) \end{array}\right\} e^{-\delta t}dt \qquad (3.17)$$

subject to:

$$\begin{gathered} \dot{s}(t)=g(s(t))-D(k(s(t))+\lambda(E(t))\phi) \\ s(t=0)=s_0 \text{ is given} \\ s(t),E(t),Q_L(t)\geq 0,\forall t, \\ \text{and } Q_I(t)=D(k(s(t))+\lambda(E(t)\phi))-Q_L(t)\geq 0,\forall t, \end{gathered}$$

with variables defined as in (3.8).

The Lagrangean for problem (3.17) is as follows:

$$L(t)=\tilde{H}(t)+\gamma(t)\left[D(k(s(t))+\lambda(E(t))\phi)-Q_L(t)\right]$$

$$\begin{aligned} &=k(s(t))Q_L(t)-h(Q_L(t),s(t))+\lambda(E(t))\phi D(k(s(t))+\lambda(E(t))\phi) \\ &\quad -c(E(t))+\mu(t)\left[g(s(t))-D(k(s(t))+\lambda(E(t))\phi)\right] \qquad (3.18) \\ &\quad +\gamma(t)\left[D(k(s(t))+\lambda(E(t))\phi)-Q_L(t)\right] \end{aligned}$$

where $\tilde{H}(t)$ is the current value Hamiltonian corresponding to problem (3.17), $\mu(t)$ is the corresponding current value co-state variable and γ(t) the corresponding Lagrange multiplier on the constraint $Q_I(t) \geq 0$.

The necessary conditions for this problem are given by (3.19)-(3.24).

$$L_{Q_L(t)} = k(s(t)) - h_1(Q_L(t), s(t)) - \gamma(t) \leq 0,\ Q_L(t) \geq 0, \text{ and}$$

$$(k(s) - h_1(Q_L, s) - \gamma) Q_L = 0; \tag{3.19}$$

$$L_{E(t)} = \lambda'(E(t))\phi D(\cdot) + (\lambda(E(t))\phi - \mu(t) + \gamma(t)) D'(\cdot)\lambda'(E(t))\phi - c'(E(t)) \leq 0$$

$$E(t) \geq 0, \text{ and } \begin{pmatrix} \lambda'(E(t))\phi D(\cdot) \\ +(\lambda(E(t))\phi - \mu(t) + \gamma(t)) D'(\cdot)\lambda'(E(t))\phi \\ -c'(E(t)) \end{pmatrix} E(t) = 0; \tag{3.20}$$

$$\begin{aligned} -L_{s(t)} = \dot{\mu}(t) - \delta\mu(t) = h_2(Q_L(t), s(t)) - k'(s(t)) Q_L(t) \\ -D'(\cdot) k'(s(t)) (\lambda(E(t))\phi - \mu(t) + \gamma(t)) \text{ -}\mu(t) g'(s(t)) \end{aligned} \tag{3.21}$$

$$L_{\mu(t)} = \tilde{H}_{\mu(t)} = \dot{s}(t) = g(s(t)) - D(\cdot); \tag{3.22}$$

$$L_{\gamma(t)} = D(\cdot) - Q_L(t) \geq 0,\ \gamma(t) \geq 0,\ (D(\cdot) - Q_L(t))\gamma(t) = 0; \tag{3.23}$$

$$\lim_{t\to\infty} \mu(t) e^{-\delta t} \geq 0,\ \lim_{t\to\infty} \mu(t) s(t) e^{-\delta t} = 0. \tag{3.24}$$

The first Legendre condition holds: $L_{Q_L(t)Q_L(t)} = -h_{11}\left(Q_L(t), s(t)\right) \leq 0$. We assume that Legendre condition on E(t) holds as well,[8] and that all sufficient conditions are satisfied, so that the necessary conditions (3.19)-(3.24) are necessary and sufficient.

First we notice that the necessary conditions above are the same as those found for the social planner, except for (3.20), which differs from (3.11). Hence, for a given total supply to the market, the split between legal (here, the pseudo-monopolist's) and illegal (poachers') harvests is the same as it would be for the social planner. This least-cost provision of the resource good to the market is dependent on the fact that the pseudo-monopolist keeps the fines he collects. This way, the marginal harvest cost of poachers *vis-à-vis* that of the pseudo-monopolist dictates who supplies the resource to the market, just as they did in the social planner's problem. Therefore, cases 1-3 and Propositions 3.1-3.4 hold for the pseudo-monopolist's problem, with a slightly different notation (no upper-bars above variables and functions).

In a model with exogenous price, but endogenous legal harvest and enforcement, Milliman (1986) pointed out that "total gain maximization" is formally equivalent to the maximization of legal gains augmented by fine payments (p.379). He suggested that total economic surplus advocates (as opposed to legal surplus only) should consider allowing resource managers to keep the fines collected from illegal

---

[8] That is, $L_{E(t)E(t)} = \lambda''\left(E(t)\right)\phi D(\cdot) + 2\left[\lambda'\left(E(t)\right)\phi\right]^2 D'(\cdot)$

$$+\left[\lambda\left(E(t)\right)\phi - \mu(t) + \gamma(t)\right]\left[D''(\cdot)\left[\lambda'\left(E(t)\right)\phi\right]^2 + D'(\cdot)\lambda''\left(E(t)\right)\phi\right]$$
$$-c''\left(E(t)\right)$$
$$\leq 0.$$

fishermen in order to trigger optimal behavior. Here however, this is not sufficient to trigger optimality because price is endogenous and is a source of rent-seeking by the pseudo-monopolist who uses enforcement to his advantage. Indeed, the total supply (*i.e.*, legal plus illegal harvests) to the market for a given resource stock differs from that of the social planner, and therefore the pseudo-monopolist's behavior is sub-optimal. This occurs because the first term in (3.20) does not appear in (3.11), which means that the equilibrium enforcement level will differ from the social optimum. Since the resource price is in part determined by the enforcement level, it follows that the equilibrium supply to the market will be sub-optimal.

3.4.1. Corrective policies

A policy can be put in place to rectify the pseudo-monopolist's behavior. Indeed, the social planner can influence the pseudo-monopolist by subsidizing him by the amount of the consumer surplus.

Proposition 3.5.

The pseudo-monopolist could be subsidized at each point in time by the amount of the consumer surplus in order to make him behave optimally. This subsidy is:

$$\hat{S}(t) = \int_0^{D\left(k(s(t))+\lambda(E(t))\phi\right)} P(x)\,dx - \left(k\left(s(t)\right)+\lambda\left(E(t)\right)\phi\right)D(\cdot) \qquad (3.25)$$

Proof.

$\bar{L}(t)$ is the Lagrangian (3.9) for the inter-temporal economic surplus maximization problem and $L(t)$ is the Lagrangian (3.18) for the inter-temporal profit maximization problem. Since $\hat{S}(t)=\overline{L}(t)-L(t)$, the subsidy (3.25) makes the pseudo-monopolist behave optimally because it redefines his problem and renders it equivalent to that of the social planner: $\hat{L}(t)=L(t)+\hat{S}(t)=L(t)+\left(\overline{L}(t)-L(t)\right)=\overline{L}(t)$.□

Alternatively, the social planner can influence the pseudo-monopolist by requesting that a royalty on the resource be paid to the government.

Proposition 3.6.

The optimal royalty to be paid by the pseudo-monopolist at each point in time is

$$\Re(t)=\int_{0}^{k(s(t))+\lambda(E(t))\phi} D(x)\,dx\,. \tag{3.26}$$

Proof.

The redefined pseudo-monopolist's problem can be written as

$$\begin{aligned}\overline{\overline{L}}(t)&=L(t)-\Re(t)\\&=k(s(t))Q_L(t)-h(Q_L(t),s(t))+\lambda(E(t))\phi D\left(k(s(t))+\lambda(E(t))\phi\right)\\&\quad-c(E(t))+\mu(t)\left[g(s(t))-D\left(k(s(t))+\lambda(E(t))\phi\right)\right]\\&\quad+\gamma(t)\left[D\left(k(s(t))+\lambda(E(t))\phi\right)-Q_L(t)\right]-\Re(t).\end{aligned} \tag{3.27}$$

The necessary conditions for problem (3.27) are given by (3.28)-(3.33).

$\overline{\overline{L}}_{Q_L(t)}=k(s(t))-h_{Q_L(t)}(Q_L(t),s(t))-\gamma(t)\le 0$, $Q_L(t)\ge 0$, and

$$\left(k(s(t))-h_{Q_L(t)}(Q_L(t),s(t))-\gamma(t)\right)Q_L(t)=0; \tag{3.28}$$

$\overline{\overline{L}}_{E(t)}=\left(\lambda(E(t))\phi-\mu(t)+\gamma(t)\right)D'(\cdot)\lambda'(E(t))\phi-c'(E(t))\le 0$, $E(t)\ge 0$, and

$$\left(\left(\lambda(E(t))\phi-\mu(t)+\gamma(t)\right)D'(\cdot)\lambda'(E(t))\phi-c'(E(t))\right)E(t)=0; \tag{3.29}$$

$$
\begin{aligned}
-\overline{\overline{L}}_{s(t)} &= \dot{\mu}(t) - \delta\mu(t) \\
&= h_{s(t)}\left(Q_L(t), s(t)\right) - k'\left(s(t)\right)Q_L(t) \\
&\quad - D'(\cdot)k'\left(s(t)\right)\left(\lambda\left(E(t)\right)\phi - \mu(t) + \gamma(t)\right) - \mu(t)g'\left(s(t)\right) + k'\left(s(t)\right)D(\cdot)
\end{aligned} \tag{3.30}
$$

$$
\overline{\overline{L}}_{\mu(t)} = \dot{s}(t) = g\left(s(t)\right) - D(\cdot); \tag{3.31}
$$

$$
\overline{\overline{L}}_{\gamma(t)} = D(\cdot) - Q_L(t) \geq 0, \ \gamma(t) \geq 0, \ \left(D(\cdot) - Q_L(t)\right)\gamma(t) = 0; \tag{3.32}
$$

$$
\lim_{t \to \infty} \mu(t)e^{-\delta t} \geq 0, \ \lim_{t \to \infty} \mu(t)s(t)e^{-\delta t} = 0. \tag{3.33}
$$

Conditions (3.28)-(3.33) are the same as (3.10)-(3.15), and hence, the royalty suggested in (3.26) influences the pseudo-monopolist to behave optimally at the margin.□

Even though the policy suggested in Proposition 3.6 triggers the right behavior *at the margin* and may at first glance seem preferable to the policy suggested in Proposition 3.5, it would be difficult to implement. Indeed, the optimal royalty represents the area to the left of the inverse demand curve between zero and the equilibrium price level. The larger Q_I, the smaller the harvest net revenue for the pseudo-monopolist, but he still needs to pay the royalty over the entire equilibrium quantity, $D\left(k\left(s(t)\right) + \lambda\left(E(t)\right)\phi\right) = Q_L(t) + Q_I\left(E(t), Q_L(t), s(t)\right)$. Hence, the more likely will the pseudo-monopolist's equilibrium behavior result in a negative value for the Lagrangian. In such an instance the pseudo-monopolist would prefer to shut down unless the social planner pays a large lump-sum subsidy.

Note that, in the special case where the harvest costs are not stock-dependent, the pseudo-monopolist's enforcement level is sub-optimal in the short run but not in the long run. That is because the pseudo-monopolist's steady state is the same as the social planner's: $g'\left(s_{\infty}^{*}\right)=\delta$. Therefore, in that special case, once the steady state is reached, no more corrective policy is necessary for the pseudo-monopolist to behave optimally.

Another alternative when the legal harvester is a pseudo-monopolist is that the resource planner be responsible for enforcement. However, the fines collected would have to be given back to the pseudo-monopolist for him to harvest optimally. This way, the enforcement level can be optimal, and both legal and illegal harvesters would react cost-effectively to it. The disadvantage of this approach is that external budget, such as government spending, must be devoted to enforcement while the resource rents and profits do not accrue to a governmental agency. In countries where the government is relatively poor, this would not likely be feasible.

3.4.2. Equilibrium paths

If one of the above policies is put in place, then the equilibrium paths occur as those found for the social planners' problem. The analysis of section 3.2.1 therefore holds for the regulated pseudo-monopolist.

3.4.3. Steady state equilibrium

Similarly, if the above policies are put in place, then the same long run *equilibria* occur as those found in the social planners' problem. The analysis of section 3.2.2 therefore holds for the regulated pseudo-monopolist.

For the special case where the harvest cost is not stock-dependent, then at the unique steady state, a corrective policy is no longer necessary however. This is because the unique steady state of the social planner and the pseudo monopolist coincide, as long as the pseudo-monopolist discounts the future at the social discount rate, δ.

3.5. Conclusion

A model that is more general than previous models with costly enforcement of property rights over a renewable resource was presented in this chapter. Indeed, the price of the resource, the legal harvest level and the property right enforcement level were all endogenously determined in a dynamic version of the dominant-firm-competitive-fringe model of industrial organization. Moreover, different relative harvest cost structures across legal and illegal harvesters were allowed. We showed that, given the marginal harvest costs of the legal harvester relative to that of the poachers, it could be optimal to have a positive and persistent black market. Hence, the presence of a black market does not necessarily indicate that resource management policy is inexistent or sub-optimal; it could simply be better to have some illegal harvest than none when enforcement is costly.

Furthermore, with a resource that has market value only, we've shown that if the pseudo-monopolist is allowed to keep the fines collected from poachers, he will insure that the total harvest is provided cost-effectively. His level of enforcement will in general be sub-optimal however, and if it is, a corrective policy is required to trigger overall optimal behavior.

CHAPTER 4. THE OPTIMAL EXTINCTION OF A RENEWABLE NATURAL RESOURCE WITH COSTLY MANAGEMENT

4.1. Introduction

In this chapter, we make use of a model developed by Cropper *et al*. (1979) for the problem of a benevolent social planner who chooses the optimal harvest level of a renewable resource over the infinite horizon. We do this for two reasons: 1) in order to gain more insight into the model with costly management and stock-dependent harvest cost, we must specify some functions as compared to the more general model in Chapter 3; 2) in order to compare the phase diagrams of the social planner's management decisions with and without costly management so we can see the impact of costly management on long run equilibrium.

Cropper *et al*. (1979) have specified a harvest cost function that depends on the resource stock but is linear in harvest quantity. We make the same assumption, but instead of considering variable enforcement cost, as in Chapter 3, here we assume an instantaneous flow of fixed cost of resource management, M > 0. This simplification is necessary in order to analyze phase diagrams. Indeed, the model with variable enforcement costs does not allow for steady states when instantaneous gains are stock-dependent as in Cropper *et al.* (1979).[9] Thus we still have positive transaction costs of resource management, but here it is not explicitly related to illegal behavior. Instead, we can think of the planner charging a per-unit harvest tax, $\tau(t)$, to the harvesters, while collecting and redistributing the tax incurs a fixed cost, M, at each point in time, which is independent of the tax level and time. If however the planner decided not to collect the tax, then M = 0, and the resulting exploitation regime of the resource would be open access.

When resource management is costly, open access may be preferred to effective management if the cost of management is too high for a given stock level. In fact, there could be resource management regime switches between open access and effective costly management as the resource stock changes over time. In order to consider management regime switches, let us define the overall resource manager's problem in two simultaneous stages.

The second stage, which must be solved before the first one, includes two M*anagement problems:* the harvesters' problem under open access exploitation, and the social planner's costly management problem. Under open access, harvesters choose their equilibrium harvest assuming entry until they reach zero profit. Under costly

---

[9] Assuming a well behaved model with costly enforcement of property rights and Cropper *et al*.'s other model specifications, steady states do not exist in the positive quadrant. Conversely, assuming steady states in the positive quadrant, that model is not well-behaved. This is why the costly management specification is simplified to an instantaneous flow of fixed cost.

management, the manager chooses the tax, τ, that will trigger second best optimal harvest behavior. These two management problems are solved in sections 4.2 and 4.3.

The first stage is the social planner's *Timing Problem* for management regime switches across open access and costly management (or *vice versa*). Once the planner knows his second best optimal choice of tax, $\tau(t)$, and the equilibrium choice of harvest by the harvesters under either regime, he must choose the best management regime as well as the timing of management regime switches. The *Timing Problem* is solved in section 4.4. Then in section 4.5, we characterize the phase diagrams for the problem with fixed flow cost of management with the possibility of management regime switches. In section 4.6, we conclude.

4.2. Harvesters' problem

In this model, we suppose that harvesters are homogeneous, and they all have a right to harvest. Individual harvesters do not own the resource, so they are static optimizers who operate in open access. At any point in time, t, a harvester takes the resource market price, P, and the per-unit tax, $\tau(t)$, as given. An individual harvester's continuous and twice differentiable harvest cost function is $K(s(t))q(t)$, where q is the amount of the resource an individual harvests, s is the resource stock and K(s(t)) is the marginal cost of harvesting. Here we assume that $K'(s(t)) < 0$ and $K''(s(t)) \geq 0$. There is no fixed cost of harvest. A harvester's problem is to maximize his profit, $\pi(t)$:

$$\begin{aligned} \underset{q(t)}{\text{Max}}\,\pi(t) &= P(t)q(t) - K(s(t))q(t) - \tau(t)q(t) \\ &= \left[P(t) - K(s(t)) - \tau(t)\right]q(t) \end{aligned}$$

The individual's first order condition is:

$$\pi_{q(t)} = P(t) - K(s(t)) - \tau(t) = 0 . \tag{4.1}$$

The open access regime will lead to entry until all expected rents are dissipated, so that, in equilibrium, we obtain for each harvester:

$$\pi(t) = \left[P(t) - K(s(t)) - \tau(t)\right]q(t) = 0 . \tag{4.2}$$

Equating (4.1) to (4.2) leads to the conclusion that in open access, the number of harvesters is indeterminate, as well as the quantity harvested by each one of them, due to the perfect competition among them and their constant per-unit harvest cost, for a given stock level, K(s). The total quantity harvested, $Q(t) = \sum q(t)$, is determinate however as it occurs at the equilibrium between supply and demand. On the supply side, the market price is affected by the resource stock level, s(t), and the resource planner's tax, $\tau(t)$. Indeed, by combining (4.1) and (4.2), one can infer the price level, given the harvester's behavior, to be

$$P = K(s(t)) + \tau(t) . \tag{4.3}$$

Given the downward-sloping inverse demand curve $P(Q(t))$, the market equilibrium for the total quantity harvested and consumed is

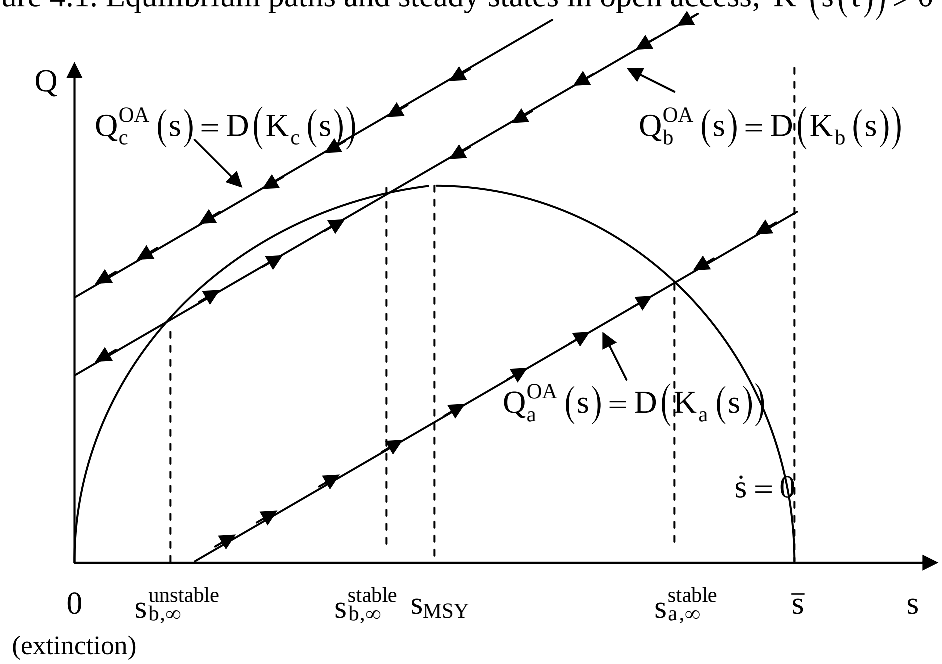
$$Q(t) = P^{-1}\left(K(s(t)) + \tau(t)\right) = D\left(K(s(t)) + \tau(t)\right). \tag{4.4}$$

A positive tax will lead to a smaller total harvest, since D'(t) < 0:
$Q(s(t),\tau(t)) = D\left(K(s(t)) + \tau(t)\right) < D\left(K(s(t))\right) = Q^{OA}(s(t))$, where $Q^{OA}(s(t))$ is the open access total harvest at stock level s. Hence some positive level of resource management will occur, *i.e.*, harvest will be lower than under open access, as long as $\tau(t) > 0$.

4.2.1. Equilibrium paths and steady states under open access exploitation

The phase diagram of open access exploitaiton in (Q,s)-space is relatively simple. First, the equation of motion for the resource is $\dot{s}(t) = g(s(t)) - Q(s(t))$ and we assume g(s) to be a compensatory biological growth function. The steady state locus $\dot{s}(t) = 0$ is plotted as $g(s(t)) = Q(s(t))$. We need to understand harvesting behaviour as the resource stock varies. Assuming open access, $\tau(t) = 0$, and from (4.4) harvest is equal to $Q(s(t)) = D(K(s(t)))$. As s increases, harvest increases as well because the inverse demand is downward-sloping and the harvest cost decreases with stock: $Q'(s(t)) = D'(K(s(t)))K'(s(t)) > 0$. Sample equilibrium paths with three different harvest costs, $K_a(s) > K_b(s) > K_c(s)$, are illustrated in Figure 4.1.

Figure 4.1. Equilibrium paths and steady states in open access; $K'(s(t)) > 0$



In Figure 4.1, we see that there can be multiple steady states, but one at most at stocks larger than s_{MSY}, for which g'(s) < 0. In open access, extinction can be prevented if harvesting costs are high enough, such as for $K_a(s)$ in Figure 4.1. The possibility of extinction with open access exploitation could depend on the initial resource stock for lower harvesting costs, as for $K_b(s)$, where if $s_0 < s_{b,\infty}^{unstable}$ extinction eventually occurs but not otherwise. Finally, for low enough harvesting costs, such as $K_c(s)$, extinction is the ultimate outcome of open access exploitation, irrespective of the initial resource stock.

4.3. Social planner's costly management problem

The resource planner's problem is to find the optimal total harvest over time, Q(t), given s(t), that will maximize the flow of discounted social welfare as measured by the instantaneous total economic surplus. The resource planner's problem is

$$\underset{Q(t)}{\text{Max}} \int_0^T \left[\int_0^{Q(t)} p(x)\,dx - K(s(t))Q(t) - M \right] e^{-\delta t} dt \tag{4.5}$$

subject to

$$\begin{gathered} \dot{s}(t) = g(s(t)) - Q, \\ s(t=0) = s_0 \text{ given}, \\ s(t) \geq, Q(t) \geq 0, \forall t, \end{gathered}$$

where M is the instantaneous fixed cost due to resource management, and x is a placeholder.

The current value Hamiltonian corresponding to the resource planner's problem is

$$\tilde{H} = \int_0^{Q(t)} P(x)dx - K(s(t))Q(t) - M + \mu(t)(g(s(t)) - Q(t)) \qquad (4.6)$$

where μ is the current value co-state variable or shadow value of the resource. Using Leibnitz' rule of differentiation of integrals where appropriate and assuming an interior solution, the necessary conditions for this problem are as follow.

$$\tilde{H}_{Q(t)} = P(Q(t)) - K(s(t)) - \mu(t) = 0 \qquad (4.7)$$

$$-\tilde{H}_{s(t)} = \dot{\mu}(t) - \mu(t)\delta = K'(s(t))Q(t) - \mu(t)g'(s(t)) \qquad (4.8)$$

$$\tilde{H}_{\mu(t)} = \dot{s}(t) = g(s(t)) - Q(t) \qquad (4.9)$$

$$\lim_{t\to T} \mu(t)e^{-\delta t} \geq 0,\ \lim_{t\to T} \mu(t)s(t)e^{-\delta t} = 0. \qquad (4.10)$$

For an interior solution, the necessary Legendre condition holds: $\tilde{H}_{Q(t)Q(t)} = P'(Q(t)) < 0$. Further, we have $\tilde{H}_{s(t)s(t)} = -K''(s(t)) + \mu(t)g''(s(t)) < 0$, $\tilde{H}_{Q(t)s(t)} = -K'(s(t)) > 0$, and we assume that $\tilde{H}_{Q(t)Q(t)}\tilde{H}_{s(t)s(t)} - \left(\tilde{H}_{Q(t)s(t)}\right)^2 \geq 0$, which implies the concavity of the Hamiltonian and guarantees a solution to this problem.

4.3.1. Phase diagrams for the costly management problem

Assuming T= ∞, the phase diagrams with costless resource management are analyzed in Cropper *et al*. (1979). A summary is presented in Appendix II.

We want to plot the phase diagram in (s,Q)-space for problem (4.5), *i.e.*, for the Cropper *et al.* (1979) model only a fixed flow cost of resource management, M. We therefore need two *loci*: $\dot{s}(s(t), Q(t)) = 0$ and $\dot{Q}(s(t), Q(t)) = 0$. The first one is already expressed in the proper space (4.9): $\dot{s}(t) = g(s(t)) - Q(t) = 0$. For the second one, we use the first two necessary conditions, (4.7) and (4.8). First we differentiate (4.7) with respect to time and we obtain $\dot{Q}(t) = \frac{K'(s(t))\dot{s}(t) + \dot{\mu}(t)}{P'(Q(t))}$. From (4.9), we can substitute $\left[g(s(t)) - Q(t)\right]$ for $\dot{s}$. From (4.7) and (4.8), we can substitute $\dot{\mu}(t) = \left[P(Q(t)) - K(s(t))\right]\left[\delta - g'(s(t))\right] + K'(s(t))Q(t)$ for $\dot{\mu}(t)$. We then have the locus in the appropriate space:

$$\dot{Q}(t) = \frac{\left[P(Q(t)) - K(s(t))\right]\left[\delta - g'(s(t))\right] + K'(s(t))g(s(t))}{P'(Q(t))} = 0. \qquad (4.11)$$

We realize that (4.11) is similar to equation (A1) in Cropper *et al.* (1979), where the planner's objective function was the same as (4.5), except that management was considered to be costless, which means that M = 0 in their model. Therefore, we conclude that the *locus* $\dot{Q}(t) = 0$ is exactly the same, whether M is positive or not. Intuitively, a flow of fixed management cost should not influence the harvest level if management is chosen. The impact it will have on the solution to the problem is in the choice of managing the resource or not. Hence, as M varies, the *locus* $\dot{Q}(t) = 0$ will not move. Of course, the *locus* $\dot{s}(t) = 0$ is the same as in Cropper *et al*. (1979) as well, regardless of M.

Let us introduce the phase diagrams for this problem under costless resource management, which are characterized in Cropper *et al*. (1979). See Figures 4.2 and 4.3, where we have drawn possible *loci* for $\dot{Q}(t) = 0$ that are similar to theirs, assuming costless management.[10]

In Figure 4.2, we have the case where $\delta < g'(0)$. Thick arrowed lines represent the optimal paths under costless management. In this case, it is always best to manage the resource, no matter its stock size. This is so because it is assumed that the zero average profit line, $P(Q(t)) - K(s(t)) = 0$, is above the optimal paths under management along the entire range of feasible stock sizes. From this phase diagram, we see that extinction is impossible, so the resource is necessarily conserved in the long run. Depending on s_0, the steady state stock is either at s_1^* or at s_3^*. There is also the special case where $s_0 = s_2^*$, which is the only way to reach and stay at the unstable steady state, s_2^*.

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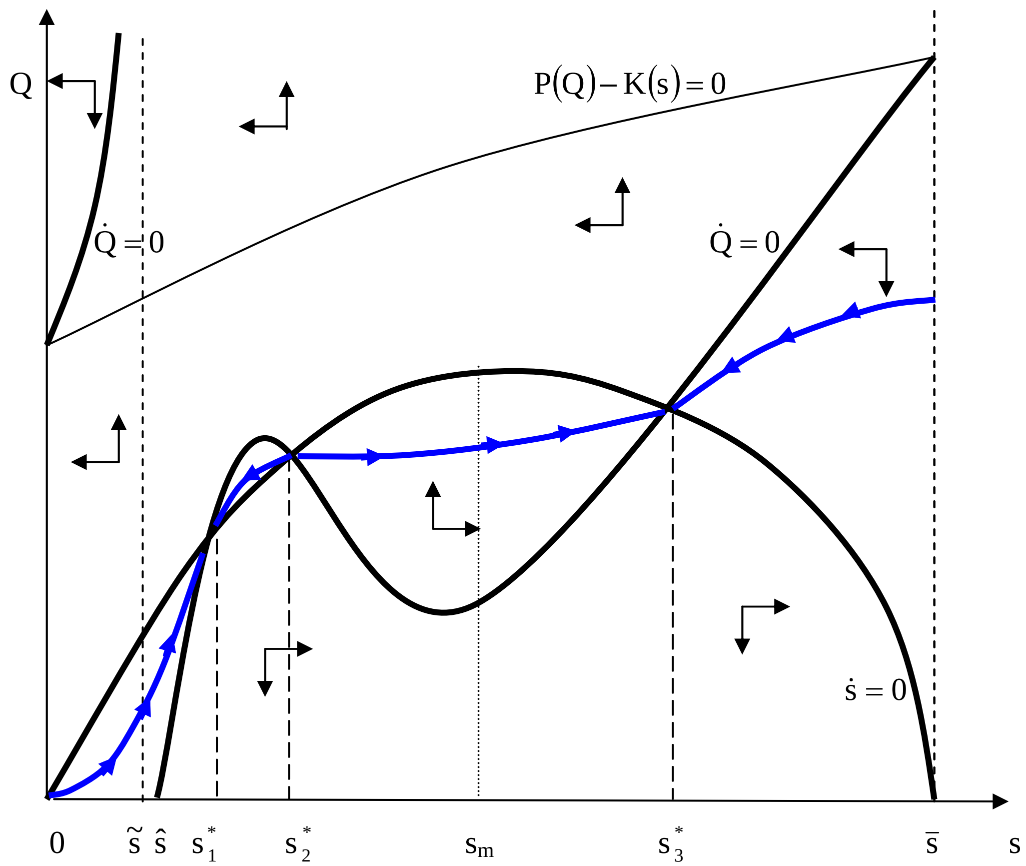
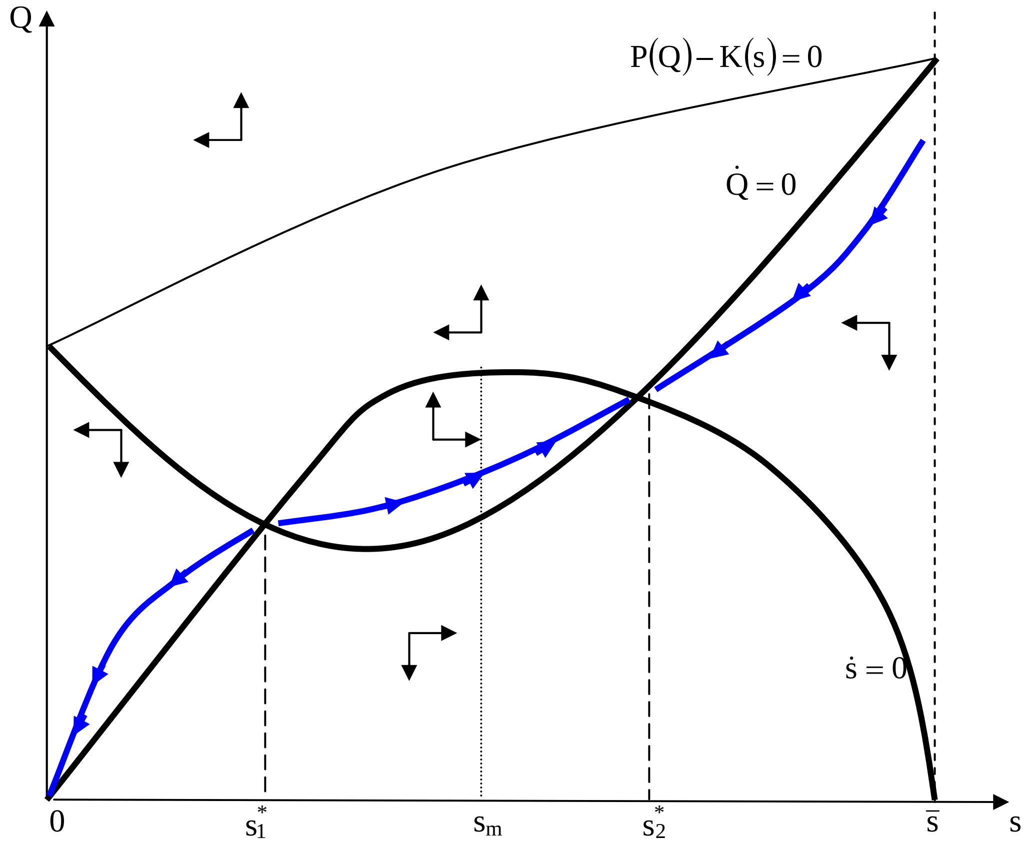
[10] See APPENDIX II for explanations on Figure 4.1 and 4.2, which were analyzed by Cropper *et al.* (1979).

Figure 4.2. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Costless Enforcement; $\delta < g'(0)$.



In Figure 4.3, the case where $\delta > g'(0)$ with costless management is presented. The optimal paths under costless management are presented as thick arrowed lines. Again, it is always best to manage the resource, no matter its stock size for the same reason as in Figure 4.1. In this phase diagram however, extinction is optimal if $s_0 < s_1^*$. But if $s_0 > s_1^*$, then the optimal steady state stock is positive and it is s_3^*. In the special case where $s_0 = s_1^*$, then the system remains at that steady state forever.

Figure 4.3. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Costless Enforcement, $\delta > g'(0)$



Of interest to us is when management is worth doing at a fixed flow cost of M. In Cropper *et al.* (1979), the resource was worth managing because for all possible s, the authors assumed that $\mu^* > 0$, which is implicit in the fact that in Figures 4.2 and 4.3 the zero average profit line, $P\left(Q\left(t\right)\right) - K\left(s\left(t\right)\right) = 0$, is above the optimal paths under management along the entire range of feasible stock sizes. With M > 0 in problem (4.5) however, the locus of management regime switch differs from $P\left(Q\left(t\right)\right) - K\left(s\left(t\right)\right) = 0$. Let us characterize it by solving what we call the social planner's timing problem.

4.4. Social planner's timing problem

The social planner's problem of choosing between costly management and open access is a timing problem since switches can occur across management regimes as the resource stock varies. The timing of resource management regime switch(es) is a problem that includes the resource management sub-problems in open access (presented in section 4.2) and with costly management (problem (4.5) presented in section 4.3). In this section, we define the timing problem and we characterize its necessary conditions.

In order to find the second-best timing of management regime switch(es), we therefore assume that the current value Hamiltonian for problem (4.5) is optimized, and we denote it as $\tilde{H}^*(t)$. Assuming that $T_0 = 0$, the resource planner's timing problem is as follows:

$$\begin{aligned}\underset{\{T_{i+1},T_{i+2}\}}{\text{Max}}\, J(T_{i+1},T_{i+2}) &= \sum_i \left[\int_{T_i^+}^{T_{i+1}^-} \tilde{H}^*(t)e^{-rt}dt\right] \\ &= \sum_i \left[\int_{T_i^+}^{T_{i+1}^-}\left[\int_0^{Q^*} p(x)dx - K(s^*)Q^* - M + \mu^*\big(g(s^*)-Q^*\big)\right]e^{-rt}dt\right]\end{aligned}, \quad (4.12)$$

where i = 0, 2, 4, …∞.

Using Leibnitz' rule of differentiation of integrals, the Kuhn-Tucker conditions that let us peg T_{i+1}, the time(s) when open access is chosen over costly management, are

$$\frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+1}} = \tilde{H}^*\left(T_{i+1}^-\right)e^{-rT_{i+1}^-} \le 0,$$

$$T_{i+1} \ge 0 \text{ and } \frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+1}}T_{i+1} = 0, \quad i = 0, 2, 4, \ldots, \infty. \qquad (4.13)$$

We can rewrite these conditions in terms of the current value Hamiltonian instead:

$$\frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+1}} e^{rT_{i+1}} = \tilde{H}^*\left(T_{i+1}^-\right) \leq 0,$$

$$T_{i+1} \geq 0 \text{ and } T_{i+1}\left[\frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+1}}\right] e^{rT_{i+1}} = 0, \quad i = 0, ,2, 4, \ldots, \infty. \tag{4.14}$$

Note however that in such a case, the resource management problem no longer has an infinite horizon. Therefore in that case, the transversality condition (4.10) is replaced by the following condition:

$$\mu\left(T_{i+1}\right) \geq 0, \; \mu\left(T_{i+1}\right) s\left(T_{i+1}\right) = 0, \; T_{i+1} < \infty. \tag{4.10'}$$

The Kuhn-Tucker conditions that let us peg T_{i+2}, the time(s) when costly management is chosen over open access, are

$$\frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+2}} = -\tilde{H}^*\left(T_{i+2}^+\right) e^{-rT_{i+2}^+} \leq 0,$$

$$T_{i+2} \geq 0 \text{ and } \frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+2}} T_{i+2} = 0, \quad i = 0, ,2, 4, \ldots, \infty. \tag{4.15}$$

We can rewrite these conditions in terms of the current value Hamiltonian instead:

$$\frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+2}} e^{rT_{i+2}} = -\tilde{H}^*\left(T_{i+2}^+\right) \leq 0,$$

$$T_{i+2} \geq 0 \text{ and } T_{i+2}\left[\frac{\partial J\left(T_{i+1}, T_{i+2}\right)}{\partial T_{i+2}}\right] e^{rT_{i+2}} = 0, \quad i = 0, 2, 4, \ldots, \infty. \tag{4.16}$$

First order conditions (4.14) and (4.16) reveal that a switch occurs precisely when $\tilde{H}^*\left(t\right) = 0$. Indeed, the fixed flow cost of management can lead $\tilde{H}^*\left(t\right)$ to be negative even though the open access locus (or zero profit locus) is above the infinite horizon solution paths for all feasible s (this is possible only because M is not incurred in open access).

4.5. Steady states with costly resource management

We already mentioned that for the problem with fixed flow of management cost, the loci $\dot{s}(t)=0$ and $\dot{Q}(t)=0$ are entirely similar to Figures 4.2 and 4.3 (from Cropper *et al.* (1979)). The difference in the phase diagrams lies in whether it is worth managing the resource or not, given that M must be paid at each instant for resource management, but not in open access. In section 4.4, we found that the condition for a management regime switch is $\tilde{H}^* = \int_0^{Q^*} p(x)dx - K(s^*)Q^* - M + \mu^*\left(g(s^*) - Q^*\right) = 0$. Let us characterize this locus. We use first order condition (4.7) in the optimized Hamiltonian, leading to

$$\begin{aligned}\tilde{H}(Q,s,\mu^*) &= \int_0^{Q} P(x)dx - K(s)Q + \left[P(Q) - K(s)\right]\left(g(s) - Q\right) - M \\ &= \int_0^{Q} P(x)dx - P(Q)Q + \left[P(Q) - K(s)\right]g(s) - M \\ &= U(Q) - P(Q)Q + \left[P(Q) - K(s)\right]g(s) - M\end{aligned} \tag{4.17}$$

Note that with this notation, $U'(Q) = P(Q) > 0$ and $U''(Q) = P'(Q) < 0$.

The following analysis is divided into three cases, depending on whether the locus $\tilde{H}(Q,s,\mu^*) = 0$ intersects the zero profit line or not.

Assumption 4.1

The zero profit line is above the growth function for all feasible stock, as in Cropper *et al*. (1979) and as depicted in Figure 4.2 and Figure 4.3

Assumption 4.1 holds in all cases considered below.

The first case is when the locus $\tilde{H}(Q,s,\mu^*)=0$ intersects the zero profit line. The second case is when $\tilde{H}(Q,s,\mu^*)=0$ is below the zero profit line for all feasible s (this implies a relatively small M). Finally, the third case is when $\tilde{H}(Q,s,\mu^*)=0$ is above the zero profit line for all feasible s (this implies a large enough M that management is prohibitively costly for all feasible s).

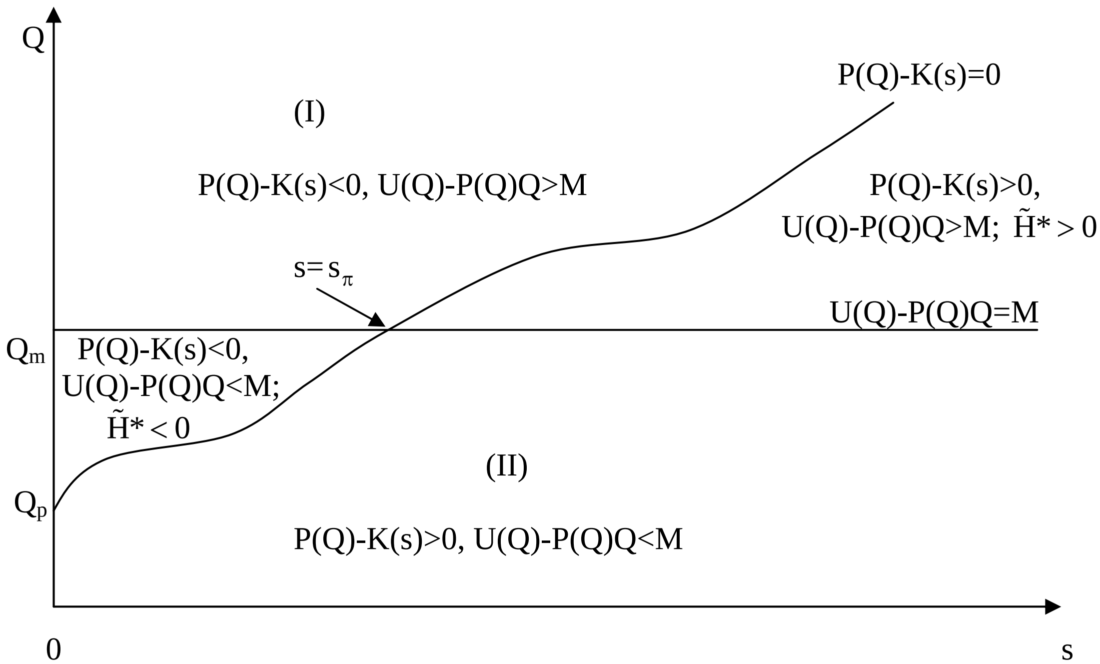
Case 1 : The locus $\tilde{H}(Q,s,\mu^*)=0$ intersects the zero profit line, $\left[P(Q)-K(s)\right]=0$ at stock s_π.

First consider points where the locus $\tilde{H}(Q,s,\mu^*)=0$ intersects the vertical axis, where $s=0$. At $s=0$, the locus $\tilde{H}(Q,s,\mu^*)=0$ implies $U(Q)-P(Q)Q=M$: the instantaneous consumer surplus generated by costly resource management is equal to the instantaneous cost of management, M. Let Q_m be the quantity that satisfies $U(Q)-P(Q)Q=M$ at $s=0$.

Second, consider the point(s) where the locus $\tilde{H}(Q,s,\mu^*)=0$ intersects the zero profit line (or open access locus) defined by $\left[P(Q)-K(s)\right]=0$, or equivalently, with no restriction on g(s), $\left[P(Q)-K(s)\right]g(s)=0$. If an intersection exists, it occurs at (Q,s) that satisfies $\tilde{H}(Q,s,\mu^*)=U(Q)-P(Q)Q+\left[P(Q)-K(s)\right]g(s)-M$ $=\left[P(Q)-K(s)\right]g(s)=0$, which means that $U(Q)-P(Q)Q=M$, the instantaneous consumer surplus generated by management is equal to M (for shortness, CS = M).

Figure 4.4 illustrates the open access locus and the CS = M line, as well as the different regions defined by them.

Figure 4.4. Regions delimited by the intersection of loci $\tilde{H}(Q,s,\mu^*)=0$ and $[P(Q)-K(s)]=0$



From the regions defined in Figure 4.4, the $\tilde{H}(Q,s,\mu^*)=0$ locus must lie in regions (I) and (II) exclusively since in the other two regions, $\tilde{H}(Q,s,\mu^*)>0$ or $\tilde{H}(Q,s,\mu^*)<0$, unequivocally.

The slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus is

$$\left.\frac{dQ}{ds}\right|_{\tilde{H}(Q,s,\mu^*)=0}=\frac{[P(Q)-K(s)]g'(s)-K'(s)g(s)}{P'(Q)[Q-g(s)]}. \tag{4.18}$$

The slope of $[P(Q)-K(s)]g(s)=0$, assuming $[P(Q)-K(s)]=0$, is

$$\left.\frac{dQ}{ds}\right|_{[P(Q)-K(s)]=0} = \frac{K'(s)}{P'(Q)}. \tag{4.19}$$

At $s=0$, the slope of $\tilde{H}(Q,s,\mu^*)=0$ is

$$\left.\frac{dQ}{ds}\right|_{\substack{\tilde{H}(Q,s,\mu^*)=0 \\ s=0}} = \frac{\left[P(Q_m)-K(0)\right]g'(0)}{P'(Q_m)Q_m}. \tag{4.20}$$

Let us define Q_p as the point where the zero profit line intersects the Q axis. Since Q_m is above Q_p, then at $s=0$, $\left[P(Q_m)-K(0)\right]<0$, and the slope of $\tilde{H}(Q,s,\mu^*)=0$ is positive. If Q_m were below Q_p, then at $s=0$, we would find $\left[P(Q_m)-K(0)\right]<0$, and thus the slope of $\tilde{H}(Q,s,\mu^*)=0$ would be negative. If Q_m = Q_p then at $s=0$, we would have $\left[P(Q_m)-K(0)\right]=0$, and the slope of $\tilde{H}(Q,s,\mu^*)=0$ would be zero. In Case 1, where the locus $\tilde{H}(Q,s,\mu^*)=0$ and the zero profit line intersect, $Q_m > Q_p$ and therefore, the slope of $\tilde{H}(Q,s,\mu^*)=0$ at $s=0$ is positive.

If the zero profit line intersects the $\tilde{H}(Q,s,\mu^*)=0$ locus at $s=s_\pi>0$, the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus at that intersection is

$$\left.\frac{dQ}{ds}\right|_{\substack{\tilde{H}(Q,s,\mu^*)=0 \\ [P(Q)-K(s)]=0}} = \frac{K'(s)}{P'(Q)\left[1-\dfrac{Q}{g(s)}\right]} \quad \begin{cases} >0, \text{ if } Q<g(s) \\ <0, \text{ if } Q>g(s) \\ =\infty, \text{ if } Q=g(s). \end{cases} \tag{4.21}$$

(This is also the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus where g'(s)=0)

Under Assumption 4.1, the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus is negative at its intersection with the zero profit line at $s=s_\pi>0$. By continuity of the locus

$\tilde{H}(Q, s, \mu^*) = 0$, we conclude that there must be a stock in the interval 0 < s < s_π where the slope of the locus is zero. From (4.18), this implies $[P(Q) - K(s)]g'(s) = K'(s)g(s)$. The right hand side of that equation is negative and since in the interval 0 < s < s_π the locus $\tilde{H}(Q, s, \mu^*) = 0$ is above the zero profit line, $[P(Q) - K(s)] < 0$. Therefore $\tilde{H}(Q, s, \mu^*) = 0$ has a zero slope at some s such that g'(s)>0, or in the interval 0 < s < s_{MSY}, where s_{MSY} is the resource stock that allows the maximum sustainable yield (g'(s_{MSY})=0).

If the $\tilde{H}(Q, s, \mu^*) = 0$ locus intersects the growth function, then where this happens Q = g(s) and we can rewrite (4.17) as $\tilde{H}(g(s), s, \mu^*) = 0$ as $U(g(s)) - K(s)g(s) - M = 0$: the instantaneous total economic surplus of harvesting is equal to the flow fixed cost of management. The slope of $\tilde{H}(g(s), s, \mu^*) = 0$ is infinite:

$$\left.\frac{dQ}{ds}\right|_{\substack{\tilde{H}^*=0\\ Q=g(s)}} = \frac{[P(Q) - K(s)]g'(s) - K'(s)g(s)}{P'(Q)[Q - g(s)]} = \frac{[P(Q) - K(s)]g'(s) - K'(s)g(s)}{0} = \infty \tag{4.21}$$

If the intersection is at a stock smaller or equal to the maximum sustainable yield, g'(s)≥0, and from (4.18), the slope of $\tilde{H}(Q, s, \mu^*) = 0$ is negative above the growth function and positive below it.

Alternatively, if the intersection between $\tilde{H}(Q, s, \mu^*) = 0$ and the growth function occurs at a stock greater than the maximum sustainable yield, g'(s)<0. From (4.18), this implies that the slope of $\tilde{H}(Q, s, \mu^*) = 0$ is positive above the growth function and negative below it. Since at the intersection between $\tilde{H}(Q,s,\mu^*)=0$ and the zero profit line the slope of $\tilde{H}(Q,s,\mu^*)=0$ is negative, the alternative case implies that the slope is infinite somewhere above the growth function. However, from (4.18), we see that the slope of $\tilde{H}(Q,s,\mu^*)=0$ is infinite only as it crosses the growth function. The alternative case where $\tilde{H}(Q,s,\mu^*)=0$ crosses the growth function at a stock greater than the maximum sustainable yield (where g'(s)<0) is impossible.

Let us now characterize the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus where it intersects the $\dot{Q}=0$ isocline. As shown in (4.11), $\dot{Q}=0$ satisfies

$\left[P(Q(t))-K(s(t))\right]\left[\delta-g'(s(t))\right]+K'(s(t))g(s(t))=0$, or

$\left[P(Q(t))-K(s(t))\right]\left[g'(s(t))\right]-K'(s(t))g(s(t))=\delta\left[P(Q(t))-K(s(t))\right]>0$

because $\left[P(Q(t))-K(s(t))\right]=\mu>0$ by Assumption 4.1. Since the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus is $\left.\frac{dQ}{ds}\right|_{\tilde{H}(Q,s,\mu^*)=0}=\frac{\left[P(Q)-K(s)\right]g'(s)-K'(s)g(s)}{P'(Q)\left[Q-g(s)\right]}$, at an intersection with $\dot{Q}=0$, the numerator of the slope is positive. Hence, at $\dot{Q}=0$, $\left.\frac{dQ}{ds}\right|_{\tilde{H}(Q,s,\mu^*)=0}>0$ if $\left[Q-g(s)\right]<0$ and $\left.\frac{dQ}{ds}\right|_{\tilde{H}(Q,s,\mu^*)=0}<0$ if $\left[Q-g(s)\right]>0$. This means that at an intersection with $\dot{Q}=0$, the slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus is positive if it occurs below the growth function; it is negative if the intersection occurs above the growth function.

For the Case 1, where $\tilde{H}(Q,s,\mu^*)=0$ and the zero profit line intersect, we have characterized the shape of the $\tilde{H}(Q,s,\mu^*)=0$ locus. We must now prove the existence of cases where $\tilde{H}(Q,s,\mu^*)=0$ intersects the growth function.

Assumption 4.2

$\left[P(0)-K(s)\right]>0$ for all feasible s.

We found that at $s=0$, $\tilde{H}(Q,s,\mu^*)=0$ implies $U(Q)-P(Q)Q=M$, which is illustrated at point (Q_m,0) in Figure 4.4. Under Assumption 4.1., if the locus $\tilde{H}(Q,s,\mu^*)=0$ and the zero profit line intersect at s_π, then the slope of $\tilde{H}(Q,s,\mu^*)=0$ is positive at $s=0$ and negative at $s=s_\pi$. That slope is then infinite when $\tilde{H}(Q,s,\mu^*)=0$ intersects the growth function below the maximum sustainable yield, and it is positive below the growth function. Given the continuity of $\tilde{H}(Q,s,\mu^*)=0$, the locus must either intersect the vertical axis again or it must intersect the horizontal axis. The only Q for which $\tilde{H}(Q,s,\mu^*)=0$ at $s=0$ is Q_m. If the locus $\tilde{H}(Q,s,\mu^*)=0$ went back to it from below, it would have to pass through the region in Figure 4.4 where $\tilde{H}^*<0$. Therefore this is not possible and $\tilde{H}(Q,s,\mu^*)=0$ must instead reach the horizontal axis where Q=0.

Consider points where the locus $\tilde{H}(Q,s,\mu^*)=0$ intersects the horizontal axis. At Q=0, $\tilde{H}(Q,s,\mu^*)=0$ implies $\left[P(0)-K(s)\right]g(s)-M=0$. Under Assumption 4.2

and since M > 0, if $\tilde{H}(Q, s, \mu^*) = 0$ intersects the horizontal axis, it must do so at some stock s_h > 0. The slope of $\tilde{H}(Q, s, \mu^*) = 0$ at Q=0 is

$$\left.\frac{dQ}{ds}\right|_{\substack{\tilde{H}(Q,s,\mu^*)=0 \\ Q=0}} = \frac{\left[P(0) - K(s)\right] g'(s) - K'(s) g(s)}{-P'(0) g(s)} > 0$$ since it occurs on the left of the maximum sustainable yield. Therefore in Case 1, as long as Assumption 4.2 holds, $\tilde{H}(Q, s, \mu^*) = 0$ intersects the horizontal axis.

Proposition 4.1

In Case 1, where the locus $\tilde{H}(Q, s, \mu^*) = 0$ intersects the zero profit line $\left[P(Q) - K(s)\right] = 0$ at stock s_π >0, under Assumptions 4.1 and 4.2, the locus $\tilde{H}(Q, s, \mu^*) = 0$ intersects the growth function.

Proof

As demonstration above, the locus $\tilde{H}(Q, s, \mu^*) = 0$ is defined at (Q_m,0), (Q_m, s_π) and at (0,s_h). By continuity, this implies that $\tilde{H}(Q, s, \mu^*) = 0$ must cross the growth function. □

(Examples of Case 1 are illustrated in Figures 4.5.A-C and 4.6.A-B.)

Let us now characterize how the consumer surplus line, $U(Q) - P(Q)Q = M$, and locus $\tilde{H}(Q, s, \mu^*) = 0$ move on the phase diagram as M increases. First note that if M = 0, then $U(Q) - P(Q)Q = M$ is verified at Q_m = 0. This is the case for the Cropper et al. (1979) model depicted in Figures 4.2 and 4.3, where $\tilde{H}(Q, s, \mu^*) > 0$ for all feasible s. As M increases, Q_m increases and the $U(Q) - P(Q)Q = M$ line moves up on the graph: $\frac{dQ_m}{dM} = \frac{-1}{P'(Q_m)Q_m} > 0$. Since the open access locus (or zero profit line) is invariant with M, if M is large enough, $U(Q) - P(Q)Q = M$ intersects it, as is assumed in Case 1. If M is relatively small however, $Q_m < Q_p$ and $U(Q) - P(Q)Q = M$ is below the open access locus for all feasible s; this is depicted in Case 2 below. If M is relatively large, then $U(Q) - P(Q)Q = M$ is above the open access locus for all feasible s; this is Case 3 below.

In Case 1, the locus $\tilde{H}(Q, s, \mu^*) = 0$ intersects the vertical axis at Q_m, the horizontal axis at s_h, and the open access locus at s_π. How does $\tilde{H}(Q, s, \mu^*) = 0$ vary as M increases? From (4.17), we find $\left.\frac{dQ}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0} = \frac{1}{P'(Q)\left[g(s) - Q\right]}$. Therefore, as M increases, the locus $\tilde{H}(Q, s, \mu^*) = 0$ above the growth function moves up on the phase diagram, and it moves down below the growth function. From (4.17) we also find $\left.\frac{ds}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0} = \frac{1}{\left[P(Q) - K(s)\right]g'(s) - K'(s)g(s)}$. Hence, for stocks below the maximum sustainable yield and quantities on or below the open access locus, $\left.\frac{ds}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0} > 0$, which is consistent with $\frac{dQ_m}{dM} = \frac{-1}{P'(Q_m)Q_m} > 0$ found above. Thus as M increases, the area where $\tilde{H}(Q, s, \mu^*) < 0$ increases (this is delimited by the vertical axis and the horizontal axis around the origin and by the locus $\tilde{H}(Q, s, \mu^*) = 0$).

In summary, in Case 1, where the zero profit locus and the surplus line (CS=M) cross at $s = s_\pi > 0$, in (Q,s)-space, the locus $\tilde{H}(Q, s, \mu^*) = 0$ starts at $(Q_m,0)$ and has a positive slope. It reaches a maximum in Q, and then slopes downward, more and more. It crosses both the zero profit locus and the surplus line at (Q_m,s_π). It then crosses the growth function ($\dot{s} = 0$ locus) with an infinite slope. Under the growth function, it has a negative slope and ultimately reaches the horizontal axis at $(0,s_h)$. The locus $\tilde{H}(Q, s, \mu^*) = 0$ crosses the growth function at the maximum sustainable yield or at a smaller stock, *i.e.*, at a stock such that $g'(s) \geq 0$.

Given the characterization of $\tilde{H}(Q, s, \mu^*) = 0$ for Case 1, let us now analyze long term *equilibria* for the phase diagrams introduced in Cropper *et al*. (1979). In a similar but more general model, Lewis and Schmalensee (1977) showed that a necessary condition for not following the infinite horizon optimal path is that the steady state that would be realized starting at initial stock s_0 lead to a negative steady state Hamiltonian.[11] In section 4.4, we found the necessary condition $\tilde{H}(Q, s, \mu^*) = 0$ for the locus that delimits the stock range where the infinite horizon optimal path (costly management) and open access are chosen. These conditions will be instrumental to the following phase diagram analysis.

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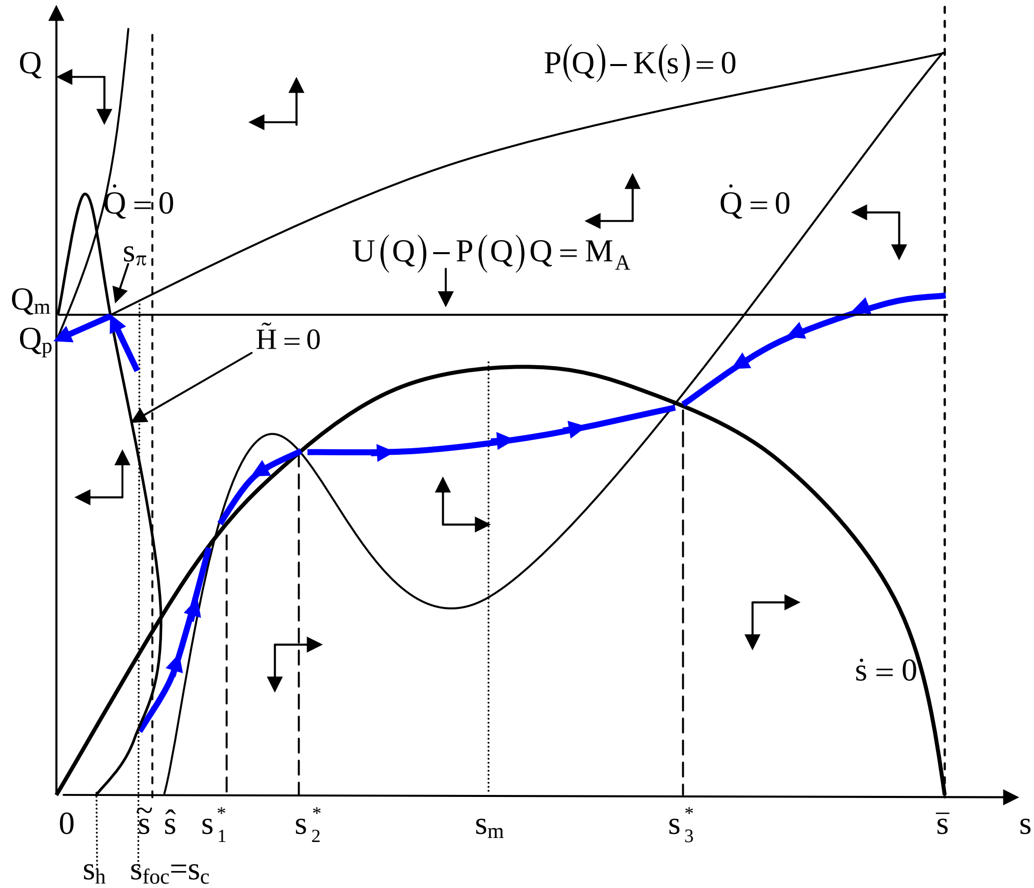
[11] See Proposition 10 on page 546. In their article, Lewis and Schmalensee assume a fixed flow of harvest cost and no open access harvest. Hence in their model, if the fixed flow of harvest cost is too high, no harvest occurs at all and the resource stock grows to $\bar{s}$.

Figures 4.5A-C relate to Cropper et al.'s case where $\delta < g'(0)$, while Figures 4.6B-C relate to Cropper et al.'s case where $\delta > g'(0)$. In all these figures, s_c is the critical stock below which the initial stock, s_0, leads to a path other than the infinite horizon optimal path in the costly management problem and ultimately, to extinction.

In Figure 4.5.A, the fixed flow cost of management, $M=M_A$, is smaller than in Figure 4.5.B where $M=M_B$. Figure 4.5.C has the highest cost of all three figures, $M=M_C$. Hence $M_A<M_B<M_C$. This is illustrated by the surplus line moving up, s_π moving right and the area where $\tilde{H}(Q, s, \mu^*) < 0$ increasing from Figure 4.5.A to 4.5.B to 4.5.C. The same goes for Figures 4.6.A and 4.6.B: $M_{AA}<M_{BB}$.

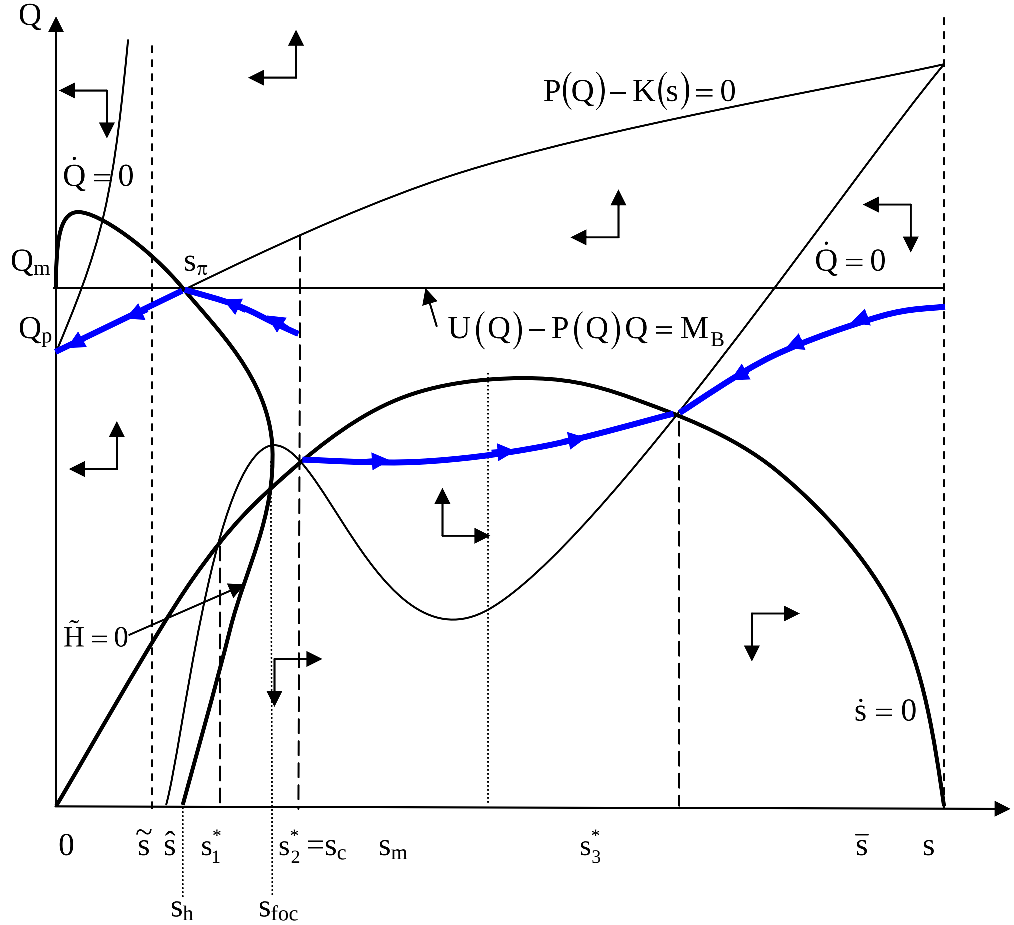
Figure 4.5.A. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement; $\delta < g'(0)$.



In Figure 4.5.A, since M_A is relatively small, the intersection between $\tilde{H}(Q, s, \mu^*) = 0$ and the infinite horizon optimal path (s_{foc}) is at a rather low stock. Since at that intersection, $\dot{s} > 0$ on the optimal path, s_c=s_{foc}: the critical initial stock under which the infinite horizon optimal path is sub-optimal is s_{foc}. For stocks such that $s_{foc} \leq s_0 \leq \bar{s}$, the infinite horizon optimal path is followed as if M=0. This is because at such higher stocks where harvest cost is smaller and harvest is greater, management cost is worth incurring. If $s_0 < s_{foc}$, there is costly management and harvest until (Q_m,s_π) is reached, after which open access prevails until extinction occurs. One possible path is illustrated on Figure 4.5.A between s_{foc} and s_π. The path chosen between those two stocks must follow first order conditions (4.7)-(4.10). Specifically in finite horizon, (4.10) implies that when costly management is no longer incurred, since s(T)>0 at s_π, then we must have μ(T)=0: the resource manager's finite horizon path must reach the zero profit line, as depicted above. The second best optimal path illustrated between s_{foc} and s_π leads to $\tilde{H}(Q,s,\mu^*)>0$ for that range of resource stock. There are several paths that reach the zero profit line, but the most inter-temporal welfare inducing one is chosen. From section 4.4, we know that a switch in management regime will occur at $\tilde{H}(Q,s,\mu^*)=0$ and transversality condition (4.10) tells us that the management path must reach the zero profit line. Hence, the end of the costly management regime must occur at (Q_m,s_π). The exact shape of the path is unknown; it could be upward-sloping, downward-sloping or it could even be non-monotonic in Q. What we know for sure is that it starts at s_{foc} and ends at (Q_m,s_π).

If $s_0 \le s_\pi$, then we immediately have open access until extinction is reached.

Figure 4.5.B. Steady State Equilibria with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement; $\delta < g'(0)$.



In Figure 4.5.B, the flow of fixed management cost, M_B is greater than M_A in Figure 4.5.A. Here the intersection between $\tilde{H}(Q, s, \mu^*) = 0$ and the infinite horizon optimal path (s_{foc}) is at a stock greater than s_1^*, the lowest stable steady state in the phase diagram. The intersection occurs where $\dot{s} < 0$ on the optimal path, and therefore, $s_c = s_2^*$: the critical initial stock under which the infinite horizon optimal path is sub-optimal is the unstable steady state s_2^*.

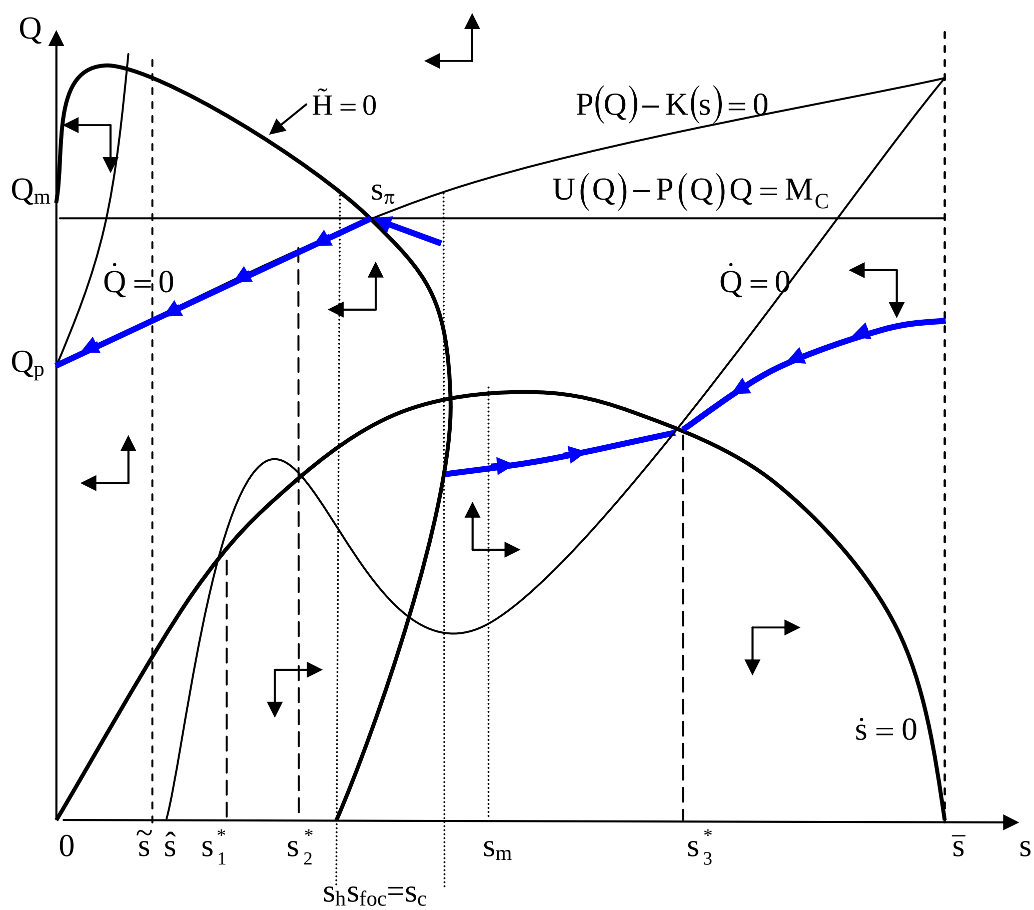
For small initial stocks, *i.e.*, $s_0 < s_2^*$, the second best optimal finite horizon management path is chosen between s_2^* and (Q_m, s_π), for which $\tilde{H}(Q, s, \mu^*) > 0$. Once ($Q_m$, s_π) is reached, no management occurs and open access prevails until extinction occurs. The finite horizon path between s_2^* and (Q_m, s_π) must follow first order conditions (4.7)-(4.10) and the necessary condition $\tilde{H}(Q, s, \mu^*) = 0$ when there is a switch from costly management to open access exploitation. Similarly to Figure 4.5.A, the exact shape of that path depends on the parameters of the problem and cannot be known in this general model.

If $s_0 \leq s_\pi$, then we immediately have open access until extinction is reached. If $s_0 \geq s_2^*$, the infinite horizon optimal path is followed as if M=0. As in Figure 4.5.A, this is because at such higher stocks where harvest cost is smaller and harvest is greater, management is worth paying for.

In Figure 4.5.C, the fixed flow of management cost, M_C, is even greater than in Figure 4.5.B. As in Figure 4.5.A, the intersection between $\tilde{H}(Q, s, \mu^*) = 0$ and the infinite horizon optimal path (s_{foc}) occurs where $\dot{s} > 0$ on the optimal path. Hence, $s_c = s_{foc}$: the critical initial stock under which the infinite horizon optimal path is sub-optimal is s_{foc}. For stocks such that $s_{foc} \leq s_0 \leq \bar{s}$, the infinite horizon optimal path is followed as if M=0. However, for smaller initial stocks, $s_0 < s_{foc}$, open access exploitation will eventually prevail, which will lead to extinction. If $s_0 \leq s_\pi$, we immediately have open access until extinction is reached. If however $s_\pi < s_0 < s_{foc}$, then the path between s_{foc} and (Q_m, s_π) is in finite horizon and must respect first order and transversality conditions (4.7)-(4.10) as well as the necessary condition for a management regime switch: $\tilde{H}(Q,s,\mu^*)=0$. As before, the shape of the finite horizon path between s_{foc} and (Q_m,s_π) could vary depending on the parameters of the problem. One possible path is illustrated on Figure 4.5.C between s_{foc} and s_π.

As we go from Figure 4.5.A to B to C, we note that as the fixed flow cost of management increases, the interval for s_0 that leads to optimal infinite horizon paths contracts.

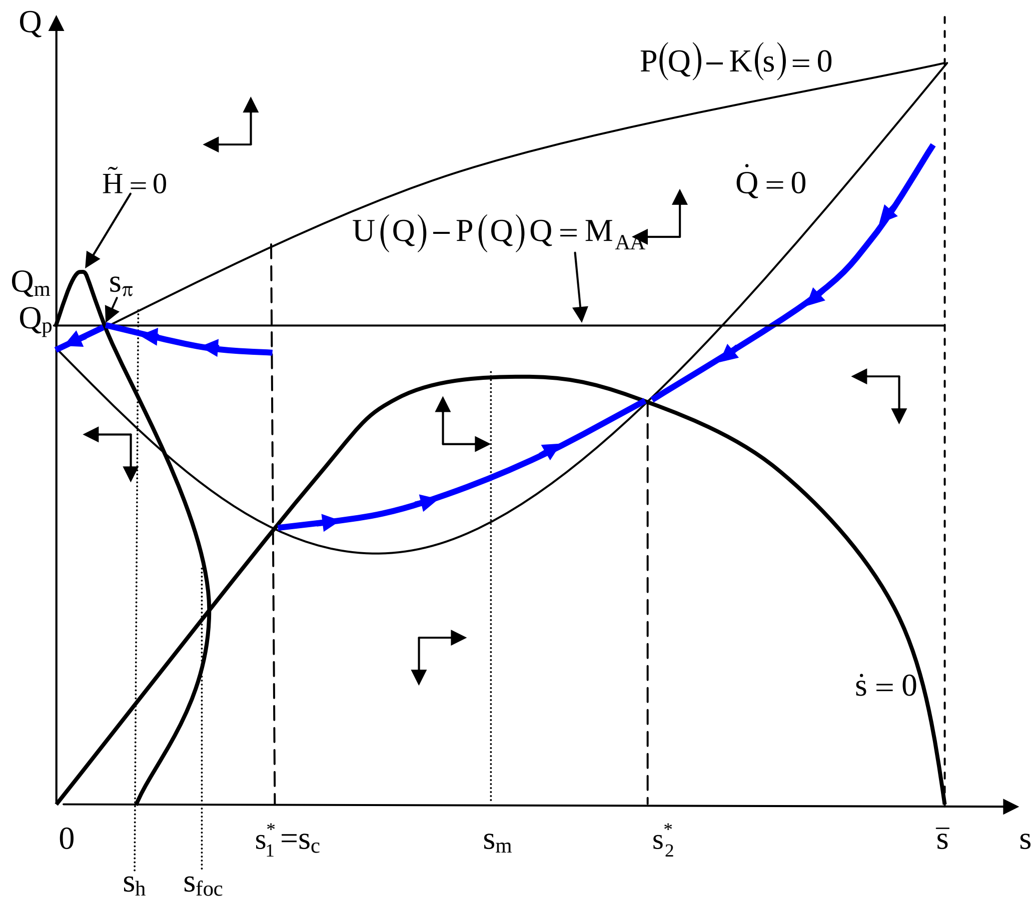
Figure 4.5.C. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement; $\delta < g'(0)$.



In Figures 4.5.A-C, we assumed that $\delta < g'(0)$: the discount rate is small compared to the marginal biological growth close to extinction. In Cropper *et al*. (1979) extinction was never optimal in that case (see Figure 4.2). However, when the resource manager must pay a fixed flow of management cost M, despite the fact that $\delta < g'(0)$, there exists a critical stock s_c, under which the second best optimal management will lead to extinction. This is what happens if $s_0 < s_c$.

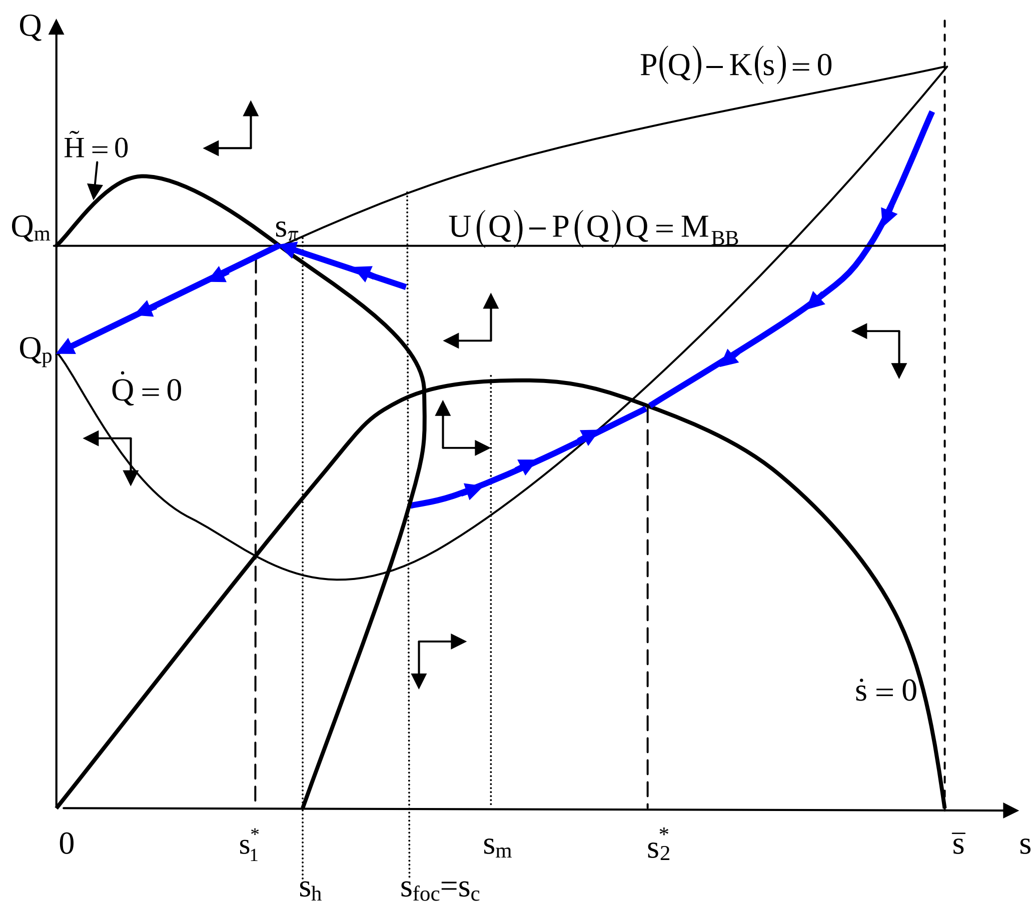
In the next two figures (4.6.A-B), we assume that $\delta > g'(0)$: the discount rate is large compared to the marginal biological growth close to extinction. In that case, as shown by Cropper *et al*. (1979), at relatively small initial stocks, extinction is optimal even when resource management is costless (see Figure 4.3).

Figure 4.6.A. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement, $\delta > g'(0)$



In Figure 4.6.A, the critical stock leading to extinction, s_c, is s_1^*, the same as if M=0. Indeed in the case where $\delta > g'(0)$, extinction is first best optimal for $s_0 < s_1^*$. Here however, if $s_0 < s_1^*$, then a second best optimal path is chosen because of the area where $\tilde{H}(Q, s, \mu^*) < 0$. A second best optimal path between s_1^* and (Q_m, s_π) is chosen so that $\tilde{H}(Q, s, \mu^*) > 0$. Then open access management prevails until extinction is reached. The finite horizon path between s_1^* and (Q_m, s_π) can be upward or downward sloping and it can even be non-monotonic in Q, as long as it follows necessary conditions (4.7)-(4.10) and $\tilde{H}(Q,s,\mu^*)=0$ when costly management is abandoned for open access exploitation. If $s_0 < s_\pi$, then open access exploitation happens immediately until extinction of the resource is reached. For $s_0 \geq s_1^*$, the infinite horizon optimal path is followed towards s_2^* as if M=0.

Figure 4.6.B. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement, $\delta > g'(0)$



In Figure 4.6.B, the fixed flow of management cost, M_{BB}, is greater than M_{AA} in Figure 4.6.A. Also, in Figure 4.6.B, since the locus $\tilde{H}(Q,s,\mu^*)=0$ and the infinite horizon path cross where $\dot{s} > 0$, then the critical stock, s_c, is equal to s_{foc}. For stocks such that $s_{foc} \le s_0 \le \bar{s}$, the infinite horizon optimal path is followed as if M=0. At such larger stocks, per-unit harvest cost is smaller and instantaneous harvest is greater, which leads to management cost being worth incurring.

However, for smaller initial stocks, $s_0<s_{foc}$, open access exploitation will eventually prevail, which will lead to extinction. If $s_0 \le s_\pi$, then we immediately have open access until extinction is reached. If $s_\pi < s_0 < s_{foc}$, then the path between s_{foc} and (Q_m,s_π) is in finite horizon and must respect first order and transversality conditions (4.7)-(4.10) as well as the necessary condition for a management regime switch: $\tilde{H}(Q,s,\mu^*)=0$. As before, the shape of the finite horizon path between s_{foc} and (Q_m,s_π) could vary depending on the parameters of the problem. One possible path is illustrated on Figure 4.6.B between s_{foc} and (Q_m,s_π).

Going from Figure 4.6.A to Figure 4.6.B, we note once more that as the fixed flow cost of management increases, the interval for s_0 that leads to the optimal infinite horizon path contracts.

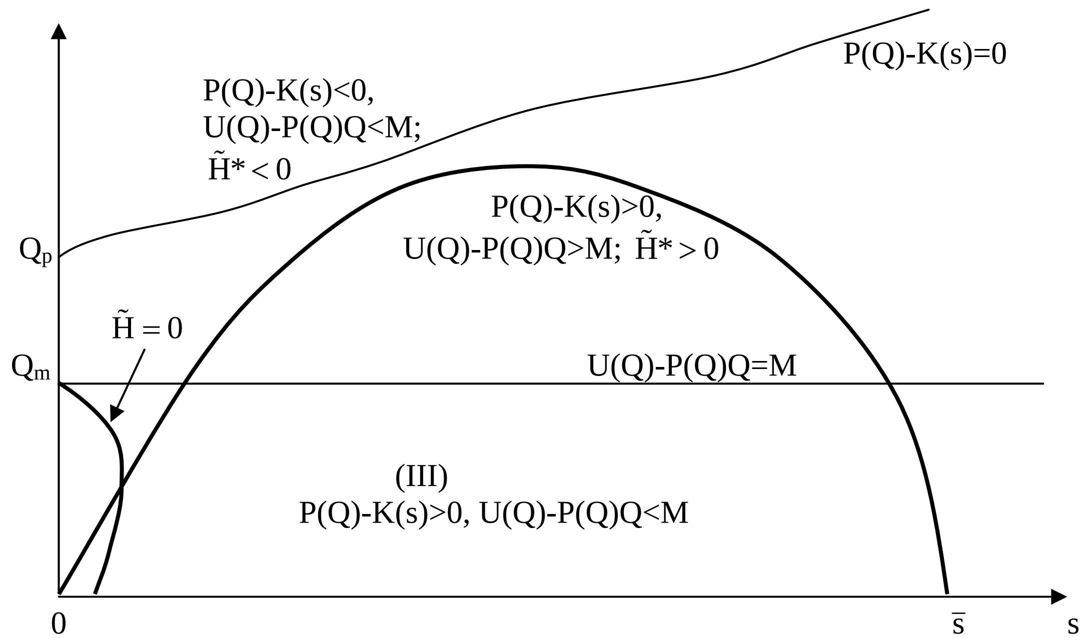
We now present Case 2.

Case 2: The surplus line $\left[U(Q)-P(Q)Q\right]=M$ lies below the zero profit locus, $\left[P(Q)-K(s)\right]=0$.

Consequently, Q_m is below zero profit line, and $\tilde{H}(Q,s,\mu^*)=0$ does not intersect the zero profit line. Let us illustrate the regions delimited by $\left[P(Q)-K(s)\right]=0$, and $\left[U(Q)-P(Q)Q\right]=M$ when $Q_m < Q_p$ (see Figure 4.7).

Figure 4.7. Regions delimited by U(Q)-P(Q)Q=M, $\left[P(Q)-K(s)\right]=0$ and

$\tilde{H}(Q,s,\mu^*)=0$ when $Q_m < Q_p$.



In this case, a locus $\tilde{H}(Q,s,\mu^*)=0$ can only be found in region (III). Indeed, above the zero profit line $\tilde{H}^*<0$ and between the zero profit line and the locus $U(Q)-P(Q)Q=M$, $\tilde{H}^*>0$. We illustrate an example of locus $\tilde{H}(Q,s,\mu^*)=0$ in Figure 4.7 for Case 2. The locus $\tilde{H}(Q,s,\mu^*)=0$ has the following characteristics: from equation (4.20), it has a negative slope at (Q_m, $s=0$), it has an infinite slope where it crosses the growth function and it crosses the horizontal axis at some $s_h > 0$. Also, if it crosses the $\dot{Q}=0$ locus, its slope is positive if the intersection below the growth function; it is negative if the intersection occurs above the growth function.

The same exercise can be done with Case 2 as we did in Case 1 in Figures 4.5.A-C and 4.6.A-B. Around the growth function and the infinite horizon optimal paths, the characteristics of the $\tilde{H}(Q,s,\mu^*)=0$ locus are the same as in Case 1. Results are therefore similar to those explained above, except that for smaller stocks, extinction can be reached under costly management. This is because in Case 2, the area where $\tilde{H}(Q,s,\mu^*)<0$ does not encompass any part of the zero profit (or open access management) locus. Costly management leading to extinction thus respects finite horizon transversality condition (4.10) since this implies that $\mu(T)>0$ but $s(T)=0$ and hence $\mu(T)s(T)=0$.

As in Case 1, the surplus line moves up as the fixed flow of management cost increases, and consequently, the area for which $\tilde{H}(Q,s,\mu^*)<0$ increases. As we found before, the critical stock, s_c, increases as M increases, *i.e.*, the interval of initial stocks for which second best optimal management leads to extinction increases as M increases. Also, as in Case 1, even when $\delta<g'(0)$,[12] for a high enough fixed flow of management cost, M, and a small enough initial stock s_0, extinction can be second best optimal even though it would never be first best optimal, *i.e.*, never optimal under M=0.

In Cropper *et al.*(1979), M=0, which in our analysis means that $U(Q)-P(Q)Q=M$ lies on the horizontal axis. Therefore $\tilde{H}^*>0$ everywhere between the zero profit line and the horizontal axis and the infinite horizon optimal path is followed. In Case 2, as in Case 1, as M increases, Q_m increases and the

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[12] The discount rate is small compared to the marginal biological growth close to extinction (see Figure 4.2).

$U(Q)-P(Q)Q=M$ locus moves up on the phase diagram: $\frac{dQ}{dM}=\frac{-1}{P'(Q)Q}>0$. Also,

as M increases, the locus $\tilde{H}(Q,s,\mu^*)=0$ moves as follows:

$\left.\frac{dQ}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0}=\frac{1}{P'(Q)\left[g(s)-Q\right]}$. Therefore, as M increases, the locus $\tilde{H}(Q,s,\mu^*)=0$

above the growth function moves up on the phase diagram, and it moves down below

the growth function. Also, $\left.\frac{ds}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0}=\frac{1}{\left[P(Q)-K(s)\right]g'(s)-K'(s)g(s)}$. Hence,

for stocks below the maximum sustainable yield and quantities on or below the open

access locus, $\left.\frac{ds}{dM}\right|_{\tilde{H}(Q,s,\mu^*)=0}>0$, which is consistent with $\frac{dQ_m}{dM}=\frac{-1}{P'(Q_m)Q_m}>0$ found

above.

The change in the area delimited by $\tilde{H}(Q,s,\mu^*)=0$ leads to the fact that as M

increases, the stocks at which $\tilde{H}(Q,s,\mu^*)=0$ intersects the growth function as well as

the infinite horizon path increase. If M is large enough, we have the polar case where

open access is preferred for all feasible stocks and extinction occurs no matter what s_0

may be; see Case 3 below and Figures 4.8-4.10.

Case 3: The surplus line $\left[U(Q)-P(Q)Q\right]=M$ lies above the zero profit locus,

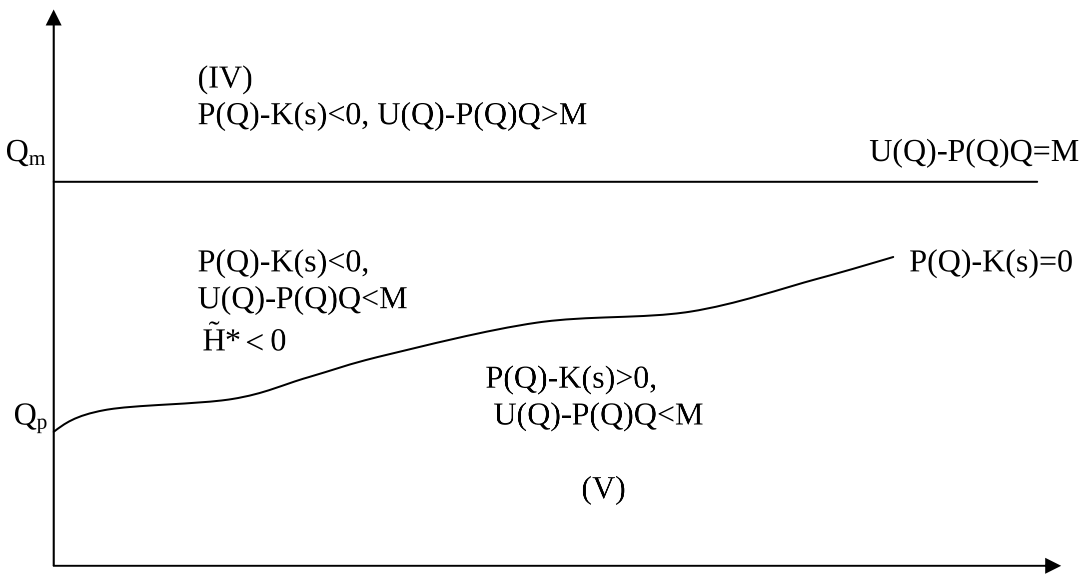
$\left[P(Q)-K(s)\right]=0$, for all feasible stocks.

This implies that Q_m is above Q_p. As a consequence, the locus $\tilde{H}(Q,s,\mu^*)=0$

does not intersect the zero profit line. Let us illustrate the regions delimited by

$\left[P(Q)-K(s)\right]=0$, and $\left[U(Q)-P(Q)Q\right]=M$ when $Q_m > Q_p$ and the *loci* do not cross.

Figure 4.8. Regions delimited by the intersection of loci $\tilde{H}(Q,s,\mu^*)=0$ and $\left[P(Q)-K(s)\right]=0$ with $Q_m>Q_p$ and the lines do not cross.



In Figure 4.8, there are two regions where we could have $\tilde{H}(Q,s,\mu^*)=0$: regions (IV) and (V). However, we must rule out region (V) because at $s=0$, $\tilde{H}(Q,s,\mu^*)=0$ holds at Q_m only and at that point, the slope of $\tilde{H}(Q,s,\mu^*)=0$ is positive. In addition, at $s=\bar{s}$, since $g(\bar{s})=0$ we find

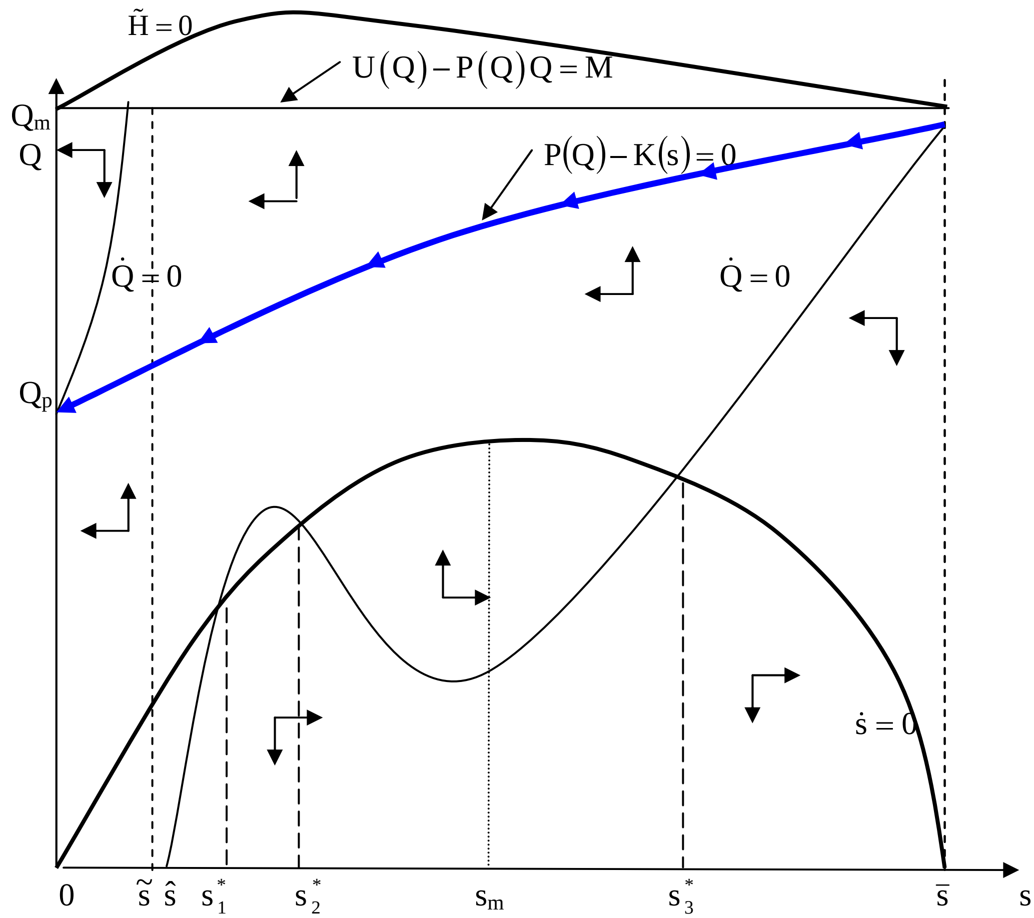
$\tilde{H}(Q,s,\mu^*)=U(Q)-P(Q)Q-M=0$ (from equation 4.17), so $\tilde{H}(Q_m,\bar{s},\mu^*)=0$. Also at $s=\bar{s}$, the slope of $\tilde{H}(Q,s,\mu^*)=0$ is negative since $g(\bar{s})=0$, $\left[P(Q_m)-K(0)\right]<0$ and $g'(\bar{s})<0$ (see equation 4.18). The fact that the locus $\tilde{H}(Q,s,\mu^*)=0$ and the zero profit line do not intersect implies that $\tilde{H}(Q,s,\mu^*)=0$ does not intersect the line U(Q)-P(Q)Q=M and therefore, $\tilde{H}(Q,s,\mu^*)=0$ is above the line U(Q)-P(Q)Q=M for all feasible s. This is consistent with $\tilde{H}^*<0$ below Q_m. Since the $\tilde{H}(Q,s,\mu^*)=0$ locus does not reach $Q<Q_m$, we must rule out region (V) for $\tilde{H}(Q,s,\mu^*)=0$.

Proposition 4.2

In Case 3, any initial stock s_0 will lead to extinction. Management problem (4.12) is a finite horizon problem with $T_{i+1}=0$, which means that open access is chosen from the beginning until the resource stock is extinct.

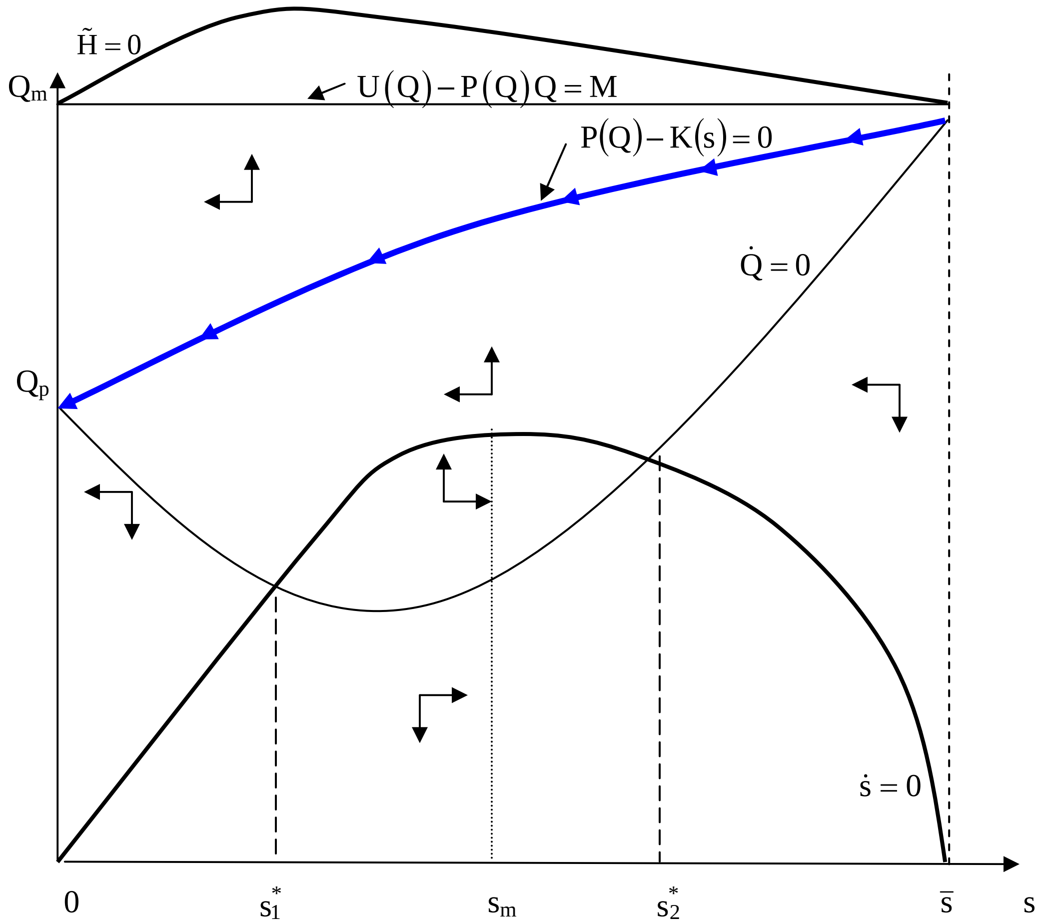
Let us characterize the slope of $\tilde{H}(Q,s,\mu^*)=0$ for $0<s<\bar{s}$ (not necessary to know which path is chosen however). The slope of the $\tilde{H}(Q,s,\mu^*)=0$ locus is given by equation (4.18). First, at the maximum sustainable yield stock, $g'(s_{MSY})=0$, which implies a negative slope: $\left.\frac{dQ}{ds}\right|_{\substack{\tilde{H}(Q,s,\mu^*)=0\\ s=s_{MSY}}}=\frac{-K'(s)g(s)}{P'(Q)\left[Q-g(s)\right]}<0$. Second, for $0<s<s_{MSY}$, we have $g'(s)>0$ and $g(s)>0$, meaning that the slope of $\tilde{H}(Q,s,\mu^*)=0$ could be positive or negative. Third, for $s_{MSY}<s<\bar{s}$, we have $g'(s)<0$ and $g(s)>0$, which implies that $\tilde{H}(Q,s,\mu^*)=0$ has a negative slope. Finally from (4.18), $\tilde{H}(Q,s,\mu^*)=0$ has a zero slope where $\left[P(Q)-K(s)\right]g'(s)-K'(s)g(s)=0$. This can only occur at a stock where $g'(s)>0$, or s such that $0 < s < s_{MSY}$ because $\left[P(Q) - K(s)\right] < 0$. We illustrate possible cases in Figures 4.9 and 4.10.

Figure 4.9. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement; $\delta < g'(0)$.



In Figures 4.9 and 4.10, the fixed flow of management cost is so high that open access is the second best optimal management regime for all feasible resource stocks. Hence, irrespective of the magnitude of s_0, open access is chosen and extinction is the ultimate outcome.

Figure 4.10. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Fixed Flow Cost of Enforcement, $\delta > g'(0)$



4.6 Conclusion

In this chapter, a fixed flow of management cost, M, was added to Cropper *et al.*'s 1979 model of optimal resource management.

Since the flow of management cost is fixed, if the infinite horizon trajectory is second best optimal, it is the exact same as the first best optimal trajectory. However, for some resource stocks, the first best optimal path may not be second best optimal. In the limit, for very large M, it may be second best optimal to let the resource be exploited in open access to extinction for any feasible initial resource stock. For smaller M, the first best optimal path is not second best optimal for smaller resource stocks only. In those cases, a finite horizon second best optimal costly management path can be chosen that leads to positive returns until resource management switches to open access leading to extinction (Case 1) or costly management can be second best optimal until extinction occurs (Case 2). Either way, a second best finite horizon path decreases the resource stock and extinction is the ultimate outcome.

The greater the fixed flow of management cost, the greater is the area (and the greater is the interval of initial stock, s_0) for which the first best optimal trajectory is not second best. Even in cases where $\delta < g'(0)$, *i.e.*, the discount rate is small compared to the marginal biological growth close to extinction, extinction can be the best option for a resource manager who must pay a fixed flow of management cost.

CHAPTER 5. TRADE MODEL WITH COSTLY RESOURCE MANAGEMENT

5.1. Introduction

International trade is welfare increasing in the simplest theoretical models, but it may not always be so in reality. Over the past decade, popular beliefs against free trade have developed such that nowadays, anti-globalization demonstrations often make headline news. For example, in Seattle in 1999, anti-globalization protestors were effective in getting media attention and even in disrupting high-level international meetings dealing, among other things, with international trade. Anti-globalization activists fear that free trade may not be good for the environment, for different labor interests and for the economic welfare of the poorest (Powell and White, 2002; Colitt, 2002). Some fear a generalized "race to the bottom," towards a world where national regulations would disappear due to global competition, and therefore, where the quality of life would be overall diminished. Members of *academia* are part of the debate as well. For example, in 1993, economists Bhagwati and Daly presented arguments for and against free trade in the popular magazine *Scientific American*.

Contrary to anti-globalization groups' contentions, economists Dollar and Kraay (2002) have shown that freer trade in the past has decreased the economic inequality between the richest and poorest, both across and within nations. However, these authors insist on the importance of changing institutions and policies along with increased international integration in order for the economic growth to benefit the entire economy. They also insist that free trade *per se* does not increase inequality.

Anti-globalization groups also tend to think that trade is detrimental to the environment. Many economists believe that freer trade can help protect the environment. Their point of view is that, if trade promotes economic development, and if the environmental Kuznets' curve (EKC) hypothesis turns out to be true, then free trade would necessarily promote a better environment, at least in the long run. However, the economic incentives through which the EKC could occur are little known so far, and so more theoretical and empirical work is needed to study trade with negative externalities or natural resource issues. No clear-cut theoretical result exists, so we cannot say if trade is altogether good or bad for the environment. From what we know, trade is likely good for the environment and the conservation of natural resources in some cases, and bad in others. What characterizes each case is the question.

Not surprisingly, anti-globalization groups are not keen on the World Trade Organization (WTO), whose political mandate is to promote international free trade. In recent years however, the WTO and other international institutions have publicly discussed environmental and social issues more than ever before. In 1994, the Marrakhesh Agreement Establishing the World Trade Organization (the WTO's founding charter) was signed following the Uruguay Round, and its preamble refers to the importance of sustainable development, including the protection of the environment (WTO, 2002c). With this Agreement, the WTO was created (formerly "GATT members"), as well as, namely, the Committee on Environment and Trade (CET), whose mandate is to study the impact of international trade on the environment. The WTO has been interested in environmental policies for a long time. Historically however, the question it asked was whether environmental policies hindered free trade.

Indeed, the 1971 GATT study entitled "Industrial Pollution Control and International Trade" was more concerned about the impact of environmental policy on free trade than the potential opposite effect (WTO, 2002b). Now however, through the CET, the WTO does discuss free trade potentially hindering the environment.

Chapter 5 provides a partial answer to the contemporary debate over free trade of a renewable resource. An important finding is that resource management institutions (or management regimes), are crucial to our results about welfare changes following a move from autarky to free trade. Hence we concur with Dollar and Kraay (2002) on the fact that institutions matter a great deal in the process towards free trade.

The objectives of this chapter are

i. characterize the impact of free trade on social welfare and on the conservation of the resource under open access exploitation of the resource;

ii. characterize the impact of free trade on social welfare and on the conservation of the resource under costless management of the resource, *i.e.*, under the first best policy;

iii. characterize the impact of free trade on social welfare and on the conservation of the resource under costly management of the resource, *i.e.*, under a second best policy;

iv. characterize the cases where the resource management regime could change due to free trade following autarky (open access *versus* costly management); and finally,

v. characterize the cases where the move from autarky to free trade can be welfare decreasing, and by extension, where some level of barrier to trade would be better; and finally,

vi. characterize the cases where the move from autarky to free trade can cause the extinction of the renewable resource.

We address these objectives through a trade model with a renewable resource input. In the next section, we introduce the general assumptions underlying all the models in this chapter. In section 5.3 to 5.6, a model is analyzed under different resource management regimes. Potential welfare and conservation impacts of moving from autarky to free trade are characterized for each management regime. In section 5.3, we assume an open access management regime for the resource sector, which is the worst-case scenario in terms of discounted inter-temporal welfare maximization. In section 5.4, we analyze the first best scenario, that is, the textbook costless resource management and welfare benchmark. In section 5.5 we analyze the second best model of resource management with a fixed cost of management. In section 5.6 we analyze empirically relevant resource management regimes and potential switches. In section 5.7, we discuss the policy implications of our results. We then conclude.

5.2. General assumptions about the home country

The trade model includes two final goods, a resource good, H(t), and a manufactured good, M(t), as well as two variable inputs, a renewable resource stock, s(t), and labor, L, the supply of which is assumed to be constant. The manufactures sector also uses a specific factor, $\overline{K}$.

In the sections that follow, we analyze welfare and conservation issues of the home country, which we assume is a small country. For the home country, A as a superscript stands for equilibrium values in autarky and T as a subscript for free trade equilibrium values; a subscript ∞ indicates long-run equilibrium as opposed to a transitory path equilibrium. Under different resource management regimes, we characterize short run and long run general *equilibria* in autarky and, in free trade, under small country assumptions, *i.e.*, taking world relative prices as given. The discount rate, δ, is given and constant in time; it represents individual's inter-temporal preferences. We assume that $0 < \delta < \infty$, which represents some level of impatience for consumption since $\delta > 0$, but also some care for future utility, since $\delta < \infty$. We do not allow for saving and borrowing, so the economy's budget must be balanced at each point in time.

5.2.1. Endowment

The home country is endowed with total fixed labor, L. For simplicity and without loss of generality, we normalize total labor to one unit per individual, for a total of L individuals in the economy. Furthermore, the home country is endowed with $\overline{K}$ fixed units of a specific factor.

The home country is endowed with a renewable resource with stock s(t), which can vary over time. We denote the initial resource stock as s_0. The resource growth function, $g\left(s\left(t\right)\right) \geq 0$, is assumed to be compensatory: $g(0) = g(\overline{s}) = 0$, $g'(0) > 0$ and g''(s(t)) < 0 for all s such that $0 \le s(t) \le \bar{s}$, where $\bar{s}$ is the wildlife population's natural carrying capacity and s(t) = 0 implies the irreversible extinction of the stock considered. The rate of change of the resource stock, when there is no harvest, is written as

$$\frac{ds(t)}{dt} = \dot{s}(t) = g(s(t)).$$

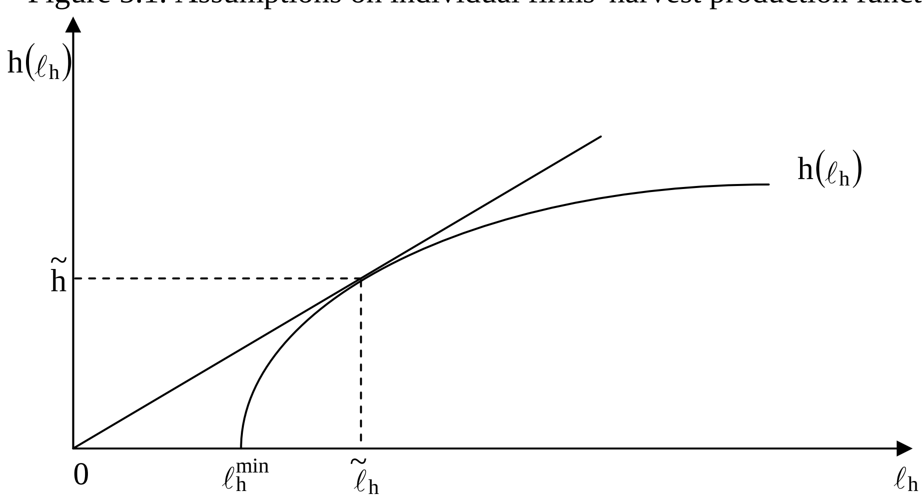
We note that even if a resource stock is unique in the world, an endemic species for example, or a rarified species dwindling on the brink of extinction, then an exogenous world price exists that represents the price of a substitute to the resource good. A famous example is rhinoceros horn powder, which is used in traditional Asian medicine, and which can be substituted by, among other medicines, the much cheaper and more effective aspirin for its proven anti-fever effect (Brower, 1994, p.124). Therefore, our analysis can be applied to an endangered *specie* found only in the home country, as long as some substitute exists for it on the world market. Our analysis also applies to other renewable resources that exist in the rest of the world as well as in the home country. In such cases, the world relative price applies to the exact same goods as the ones produced in the home country.

5.2.2. Production

A P-superscript refers to production, a cursive variable is for individual firms, and variables in capital letters represent aggregate quantities. Two goods are produced: a resource-based good $H^P(L_H(t))$, and a manufactured good, $M^P(L_M(t))$, which we assume is produced with labor and capital. The production function $\gamma^P(L_M(t), \bar{K})$ is characterized by constant returns to scale and a diminishing marginal rate of substitution between inputs, leading to strict concavity in labor since $\bar{K}$ is fixed in the economy. Therefore, capital, being a fixed factor in manufacturing, can be normalized to 1, so that $\gamma^P(L_M(t), \bar{K}) = \gamma^P(L_M(t), 1) = M^P(L_M(t))$ where $M^{P\prime}(L_M(t)) > 0$ and $M^{P\prime\prime}(L_M(t)) < 0$. The net gain that arises from the concavity of M^P is the fixed factor rent.

In this chapter, we assume that productivity in the resource good depends only on labor, as long as the resource stock is positive: if s(t) > 0, then $H^P(L_H(t)) = H^P(N(t)\ell_h(t)) = N(t)h^P(\ell_h(t))$, where $h^P(\ell_h(t))$ is an individual firm's output, and N(t) is the number of harvesting firms. We assume that $h^P(\ell_h(t)) = 0$ if $0 \le \ell_h(t) \le \ell_h^{min}$ and that $h^P(\ell_h(t)) > 0$ if $\ell_h(t) > \ell_h^{min}$. This means that there is a minimum labor requirement for a firm's harvest to be positive: $\ell_h^{min} = \{\min \ell_h(t) : h^P(\ell_h(t)) > 0\} > 0$; this is the production function equivalent of a fixed cost of harvest. For $\ell_h(t) > \ell_h^{min}$, we assume a strictly concave production function, that is, $h^{P\prime}(\ell_h(t)) > 0$, $h^{P\prime\prime}(\ell_h(t)) < 0$. See Figure 5.1 for clarification.

Figure 5.1. Assumptions on individual firms' harvest production function



We note that there is no dependence of the harvest production function on the resource stock, and that the only input paid for is labor, with wage rate $\omega(t)$. Therefore, in this model, instantaneous net gains do not depend on the resource stock. This means that the resource stock can only have inter-temporal value, depending on the discount rate, when the future is taken into account in an objective function.

The renewable resource stock is affected by harvesting as depicted by the stock transition equation: $\dot{s}(t) = g(s(t)) - H^P(L_H(t))$.

5.2.3. Numéraire good

The manufactured good is the numéraire: $p_M(t) = p_M = 1$, for all t, and the relative price is $p(t) = \frac{p_H(t)}{p_M} = p_H(t)$, where $p_H(t)$ is the resource good price relative to the manufactured good price.

5.2.4. Consumption

A C-superscript refers to consumption; a lowercase variable is for individuals, while capital letters are reserved for aggregate quantities. We assume that individual preferences can be represented by a neoclassical utility function $u\left(h^C(t), m^C(t)\right)$, which is homothetic. A homothetic utility function is a special case of the Gorman form utility function, which implies that an individual's utility function is representative of the aggregate, if we assume that individuals have identical preferences and that they all count equally in the social welfare function.[13] This way, social welfare depends on GDP, irrespective of distributional issues. We will thus be able to infer aggregate consumption easily, as well as aggregate welfare.

Aggregate income is $Y(t) = p(t)H^P(t) + M^P(t)$. Since utility is homothetic for all individuals in the economy, we can write individual *i*'s consumption of the resource good as $h(t) = h^C(p(t))y_i(t)$ and the aggregate consumption as $H^C(t) = \sum_{i=1}^{L} h^C(p(t))y_i(t) = h^C(p(t))\sum_{i=1}^{L} y_i(t) = h^C(p(t))Y(t)$. In the same manner, individual *i*'s consumption of the manufactured good is $m(t) = m^C(p(t))y_i(t)$, and its aggregate consumption is $M^C(t) = \sum_{i=1}^{L} m^C(p(t))y_i(t) = m^C(p(t))\sum_{i=1}^{L} y_i(t)$ $= m^C(p(t))Y(t)$.[14] A homothetic utility function also implies that the indirect utility function takes the form $v(p(t), Y(t)) = \nu(p(t))Y(t)$, such that $v_1 < 0$, $v_{11} > 0$, $v_2 > 0$, $v_{22} = 0$ and $v_{12} < 0$. This will be helpful in analyzing welfare changes.

Furthermore, we assume an interior solution to the consumer problem, whenever production and trade allow for it. This means that, at any point in time, if it is impossible to consume both goods (in autarky, because of the extinction of the renewable resource, for example), then individuals are worse off than they would have been if they could have consumed some of the resource good. Therefore, if it is possible

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[13] For details, see Varian (1992), p.152-154.

[14] Homothetic utility functions can be written as linearly homogeneous in income without loss of generality; see Varian (1992), p.146-147 for details.

to consume some of both goods, then that will always be the chosen over corner solutions.

5.3. Open access: complete rent dissipation

If property rights over the renewable resource are not defined or not effective, then exploitation occurs in open access. Profit maximizing harvesters, who hire labor, enter the resource sector until their respective profit is equal to zero, which means that all resource rents are dissipated. The intuition behind this is that if one does not exhaust all the rents he can extract at any point in time, then someone else will. Thus aggregate and individual harvesting behavior does not take the future into account.

5.3.1. Production of the resource good

Each harvesting firm takes the resource price and the wage rate as given, and it hires labor to maximize its profit. The objective is:

$$\underset{\ell_h(t)}{\mathrm{Max}}\left[p(t)h\left(\ell_h(t)\right)-\omega(t)\ell_h(t)\right] \tag{5.1}$$

Assuming harvesting takes place, the first order condition is

$$p(t)h'\left(\ell_h(t)\right)-\omega(t)=0\,. \tag{5.2}$$

Under perfect competition between harvesting firms, entry occurs until profit opportunities are dissipated:

$$\frac{p(t)h\left(\ell_h(t)\right)}{\ell_h(t)}-\omega(t)=0\,. \tag{5.3}$$

Therefore, we know each firm harvests at its maximum average productivity of labor, or where

$$\frac{h(\ell_h(t))}{\ell_h(t)} = h'(\ell_h(t)) = \tilde{h} \text{ = constant.} \tag{5.4}$$

Hence, from (5.2) and (5.4), when the resource good is produced in the economy, it must be that

$$\frac{\omega(t)}{p(t)} = \tilde{h}\,, \tag{5.5}$$

which is a constant ratio.

Let us write the unique corresponding level of hired labor per firm as

$\tilde{\ell}_h = \left\{ \ell_h(t) : \frac{h(\ell_h(t))}{\ell_h(t)} = h'(\ell_h(t)) = \tilde{h} \right\}$. Aggregate harvest is

$H^P(t) = H^P(L_H(t)) = H^P(N(t)\tilde{\ell}_h) = N(t)h^P(\tilde{\ell}_h) = N(t)\tilde{h}\tilde{\ell}_h$. Since $\tilde{h}$ and $\tilde{\ell}_h$ are constant, it is through the number of firms, N(t), that the production equilibrium occurs. We assume that entry is such that (5.3) occurs instantaneously.

5.3.2. Production of the manufactured good

As stated in section 5.2.2. the manufacturing sector has decreasing marginal returns, and it takes the resource price and the wage rate as given. Labor is hired to maximize aggregate profits:

$$\underset{L_M(t)}{\text{Max}}\left[M(L_M(t)) - \omega(t)L_M(t)\right] \tag{5.6}$$

Assuming an interior solution, the first order condition is

$$M'(L_M(t)) - \omega(t) = 0\,. \tag{5.7}$$

Using this first order condition and the results from the resource sector, we obtain that in general equilibrium, if both goods are produced, then the marginal value product of labor in both sectors is equated to the wage rate:

$$M'\left(L_M(t)\right) = p(t)\tilde{h} = \omega(t). \tag{5.8}$$

5.3.3. Consumption

A representative individual maximizes his utility under his budget constraint:

$$\underset{h^C(t),m^C(t)}{\mathrm{Max}} \left\{ u\left(h^C(t), m^C(t)\right) + \lambda(t)\left(y_i(t) - p(t)h^C(t) - m^C(t)\right) \right\}. \tag{5.9}$$

First order conditions lead to the equilibrium price being

$$p(t) = \frac{u_{h^C}(t)}{u_{m^C}(t)}. \tag{5.10}$$

As stated before, since individuals all have the same preferences, aggregate demands are as follows:

$$H^C(t) = h^C\left(p(t)\right)Y(t) \text{ and } M^C(t) = m^C\left(p(t)\right)Y(t) \tag{5.11}$$

5.3.4. Walrasian equilibrium

The necessary condition of consumption problem (5.9) determines the relative price of the resource good, $p(t)$ as specified in (5.10). Since $\tilde{h}$ is constant and $p(t)$ is given by the consumption equilibrium, the necessary and entry conditions on production of the resource good leading to (5.5) peg the wage rate, $\omega(t) = p(t)\tilde{h}$. The necessary condition on production of the manufactured good (5.7) then determines the division of labor across production sectors. The conditions for this general equilibrium do not depend on the resource stock and therefore, the division of labor remains the same as long as the resource stock is positive. Hence the harvest level does not change as long as the resource stock is positive.

At all times t, the labor and budget constraints of the home country translate into:

$$\begin{aligned} L &= L_H(t) + L_M(t) \\ &= N(t)\tilde{\ell}_h + L_M(t) \end{aligned} \tag{5.12}$$

$$\text{and } Y(t) = p(t)H^P(t) + M^P(t) \tag{5.13}$$

5.3.5. Autarky: temporary and long-run *equilibria*

By assumption, as long as the resource is not extinct, then both goods are produced and consumed in autarky. The economy's instantaneous Walrasian equilibrium requires that production and consumption of the resource good be equal:

$$H^C(p(t), Y(t)) = h^C(p(t))Y(t) = H^P(L_H(t); s(t) > 0) = N(t)\tilde{h}\tilde{\ell}_h. \tag{5.14}$$

So when the resource good is produced in open access, we find that

$$N(t) = \frac{h^C(p(t))Y(t)}{\tilde{h}\tilde{\ell}_h}. \tag{5.15}$$

Hence, the number of harvesting firms, N, is a function of p, which in general equilibrium implies a function of individuals' preferences, since $p(t) = \frac{u_{h^C}(t)}{u_{m^C}(t)}$. It is also a function of income, Y(t), which is determined by the parameters of the economy such as individual preferences, harvest and manufacturing technology, resource stock and quantity of labor. N(t) is also directly a function of the harvest technology through its denominator, $\tilde{h}\tilde{\ell}_h$.

Given that instantaneous net gains are not affected by the resource stock, and given that in open access, the change of the resource stock is not taken into account in the harvesters' optimization problem, then N(t) = N; it is fixed over time. Hence, as long as the resource stock is positive, the aggregate harvest and harvest labor also are fixed. Assuming preferences do not change over time, this implies that prices are also constant.

In autarky, supply and demand of the manufactured good must also be equal:

$$M^C\left(p(t),Y(t)\right)=m^C\left(p(t)\right)Y(t)=M^P\left(L_M(t)\right)=M^P\left(L-N(t)\tilde{\ell}_h\right). \quad (5.16)$$

Since harvest labor is fixed over time, given the total labor constraint, then the resource good and the manufactures are produced and consumed in fixed quantities over time, until a steady state stock is reached. Assuming that the initial resource stock is the natural carrying capacity, $s_0 = \bar{s}$, then conservation occurs as long as the equilibrium harvest is no greater than the biological growth at the maximum sustainable yield stock level, s_{MSY}, as defined in Definition 3.1:

$$\text{given that } s_0 = \bar{s},\ s_\infty^A > 0 \text{ iff } H^P\left(L_H\right) \le g\left(s_{MSY}\right). \quad (5.17)$$

If $H^P\left(L_H\right) < g\left(s_{MSY}\right)$, the optimal steady state is stable. In contrast, if $H^P\left(L_H\right) = g\left(s_{MSY}\right)$, then the optimal steady state is the MSY, and it is unstable.

If $H^P\left(L_H\right) > g\left(s_{MSY}\right)$, then extinction occurs in finite time. Given that an interior solution is optimal in the consumption of both goods, then, in autarky, individuals are worse off after extinction occurs.

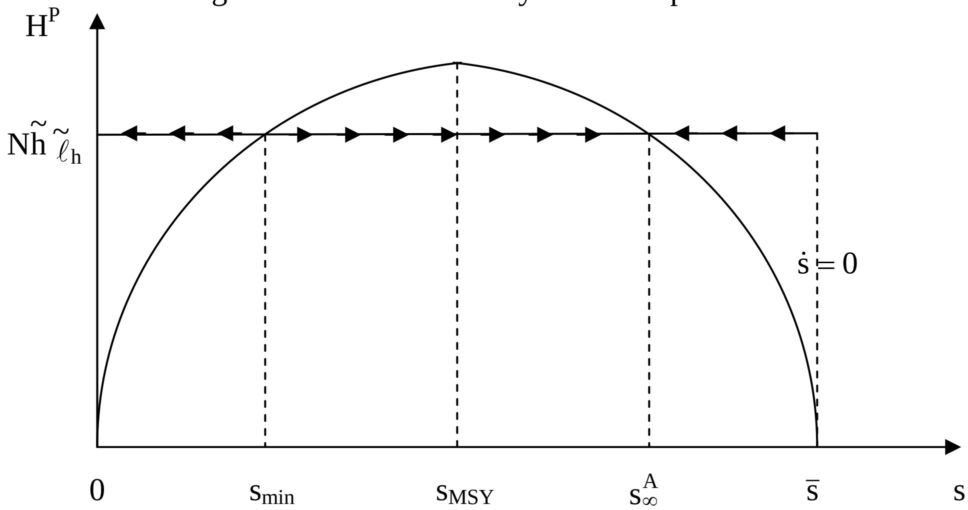
In the case where the initial resource stock is smaller than the natural carrying capacity, then even if condition (5.17) holds with inequality, we could have extinction.

To show this, let us define the unique resource stock

$$s_{min} = \{\min(s(t)) : H^P(L_H) = g(s(t))\} = \{s(t) : H^P(L_H) = g(s(t)), g'(s(t)) \geq 0\}, \textit{ i.e.},$$

s_{min} is the unique lower, unstable, steady state stock, out of one or two possible steady states. There is one possible steady state if $s_{min} = s_{MSY}$; there are two otherwise. Then under (5.17), if $s_0 < s_{min}$, extinction will occur. This is illustrated in Figure 5.2.

Figure 5.2. Autarkic steady states in open access



Let us assume that the initial resource stock in autarky is the natural carrying capacity, $s_0 = \bar{s}$, and that $H^P(L_H) < g(s_{MSY})$. This means that in autarky, the resource eventually reaches an autarkic stable steady state, s_∞^A such that $g'(s_\infty^A) < 0$. For the following free trade analysis, we assume that s_∞^A has been reached in autarky when the country is opened to free trade.

5.3.6. Free trade: temporary and long-run *equilibria*

By assumption, in free trade, the resource stock is initially s_{∞}^{A} such that $g'\left(s_{\infty}^{A}\right) < 0$. The equilibrium autarky price just before trade opens is denoted p_{∞}^{A}. Since the home country takes world prices as given, we need to analyze two possible cases: $p^{W} > p_{\infty}^{A}$, and $p^{W} < p_{\infty}^{A}$. The special case where $p^{W} = p_{\infty}^{A}$ would lead to an undetermined initial and long run pattern of production, although welfare would be the same as in autarky.

Case 1. $p^{W} > p_{\infty}^{A}$

Proposition 5.1.

As the home country opens to free trade, it produces more resource good and may or may not specialize in it. Welfare is higher initially. The resource good is exported, and the manufactured good is imported. If, in free trade, harvest is smaller or equal to the resource maximum sustainable yield, *i.e.*, $N\tilde{\ell}_{h}\tilde{h} \leq g\left(s_{MSY}\right)$, then this equilibrium is sustainable in the long run; in such a case, utility is higher than in autarky forever, and therefore discounted utility is greater. Otherwise, extinction occurs in finite time, and afterwards, the home country must export some M^{P}(t) in order to import some H^{C}(t). Utility is lower thereafter, although utility discounted to the time when trade opens could be higher or lower than it would have been in autarky.

Proof.

Specialization vs. diversification

Because the manufacturing sector production function is strictly concave in labor, we may have a positive level of $L_M^T = L - N^T\tilde{\ell}_h$ such that $p^W\tilde{h} = M'\left(L_M^T\right)$, in which case there would be diversification with trade. However, if $p^W\tilde{h} \geq M'(0)$, then the home country specializes in the resource good.

Welfare

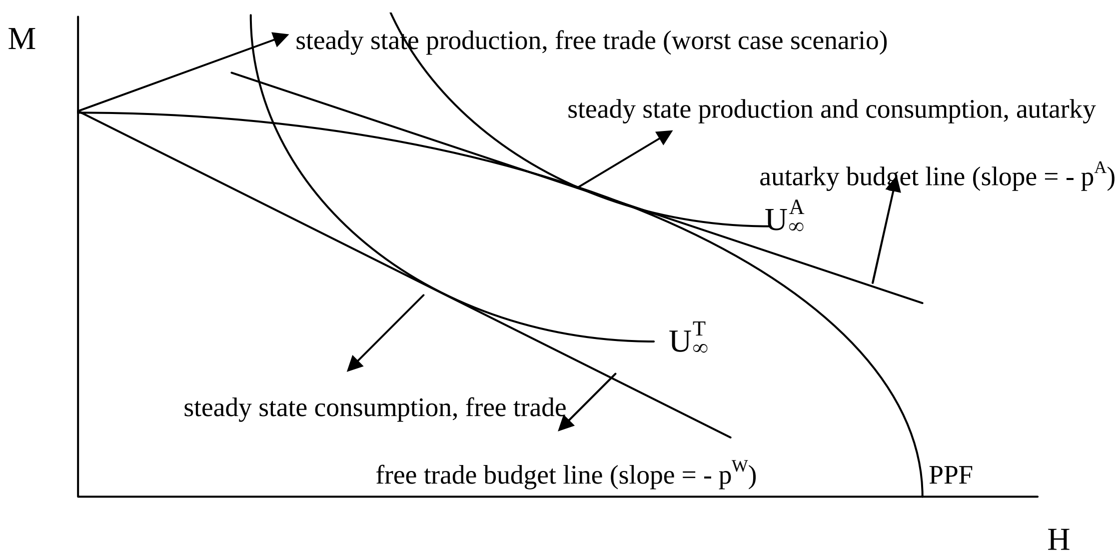
Initially, instantaneous welfare necessarily increases. Indeed, we find that $dv = \frac{\partial v(p,Y)}{\partial Y}\left[H^P - H^C\right]dp > 0$ with the new terms and pattern of trade.

If $N^T\tilde{\ell}_h\tilde{h} \leq g\left(s_{MSY}\right)$ in free trade, then the resource is conserved. In that case, a positive steady state stock is reached, and the new production pattern continues forever. Therefore steady state welfare is higher than in autarky as well as instantaneous welfare. The discounted welfare change due to the opening of the home country to free trade is therefore positive.

However, if $N^T\tilde{\ell}_h\tilde{h} > g\left(s_{MSY}\right)$, then the resource becomes extinct in finite time. Steady state welfare is lower than in autarky since $dv = \frac{\partial v(p,Y)}{\partial Y}\left[H^P - H^C\right]dp$ < 0. Indeed, with extinction, the trade pattern is reversed, but the terms of trade are fixed. In this case, the discounted welfare change due to free trade could be positive or negative, depending on the parameters of the economy, namely the discount rate, and other parameters which influence the time it takes for the resource stick to reach extinction. □

When $p^W > p_\infty^A$, trade can be immiserizing if it causes the extinction of the resource in the home country. Such possibility is due to the lack of effective property rights over the resource: gains from trade are mitigated by the dynamic inefficiency, and they can even be entirely dissipated. Case 1 of the open access model with trade is illustrated in Figure 5.3, for the case where extinction occurs. We note that the production possibilities frontier (PPF) does not depend on the magnitude of the resource stock, which implies that it remains the same even as the resource stock changes, as long as s(t) > 0.

Figure 5.3. Open access resource exploitation and trade, Case 1: $p^W > p^A_\infty$



Case 2. $p^W < p^A_\infty$

Proposition 5.2.

If $p^W < p^A_\infty$, the home country produces more manufactures than in autarky, and it may or may not specialize in it. In either the diversified case or the specialized case, the long run equilibrium stock with free trade, s^T_∞, is such that $H^P\left(L - L^T_M\right) = g\left(s^T_\infty\right)$

and $s_\infty^T > s_\infty^A$. Therefore extinction cannot occur in this case due to trade. Also, manufactures are exported and the resource good is imported. Furthermore, utility is higher forever. Hence overall, welfare is unambiguously improved, both inter-temporally and in steady state.

Proof.

Specialization vs. diversification

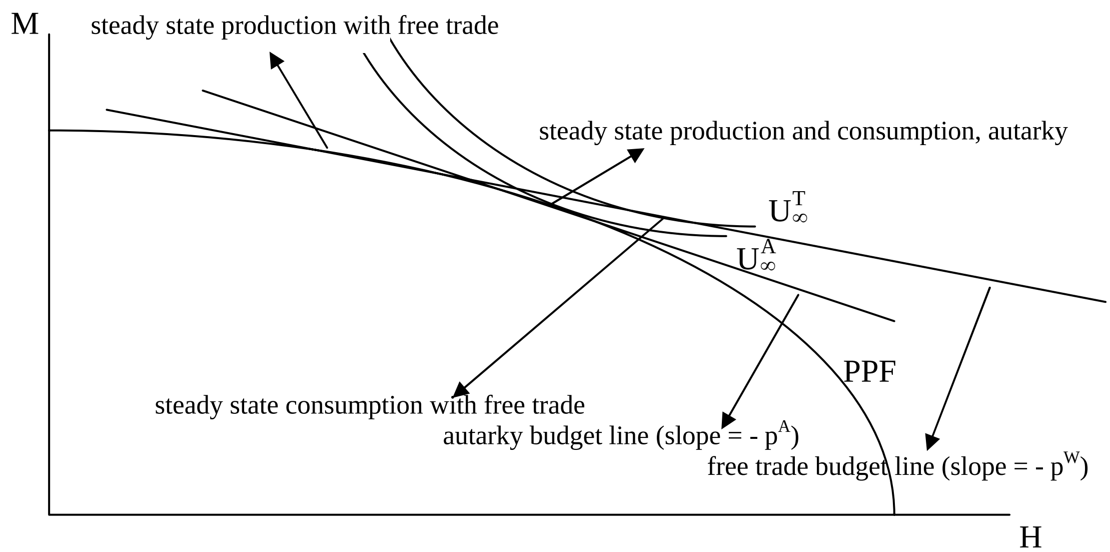
Since with diversified production, $\omega = p^W \tilde{h}$, then specialization occurs only if $M'(L) \geq p^W \tilde{h}$. However, if $M'(L) < p^W \tilde{h}$, then labor is hired in the manufactures sector up to a level such that $M'(L_M^T) = p^W \tilde{h}$ is satisfied, and the home country's harvest is $H^P(L_H^T) = H^P(L - L_M^T)$.

Welfare

In this case, instantaneous welfare necessarily increases forever. Indeed, we find that $dv = \frac{\partial v(p, Y)}{\partial Y}\left[H^P - H^C\right]dp > 0$, since the last two factors are negative according to the terms and pattern of trade. Welfare increases forever because this equilibrium is sustainable. Indeed, harvest being smaller than in autarky, by construction the resource stock is necessarily conserved. Therefore, steady state and discounted welfare are necessarily greater than in autarky. □

When $p^W < p_\infty^A$, welfare is unambiguously improved, in the short and the long run, because there are gains from trade, and the dynamic externality due to the open access exploitation regime is lessened in this case under diversification or altogether eliminated if there is specialization in the manufactures. Case 2 of the open access model with trade is illustrated in Figure 5.4.

Figure 5.4. Open access resource exploitation and trade, Case 2: $p^W < p^A_\infty$



The welfare results for the open access model with free trade are qualitatively comparable to those found in Brander and Taylor (1997a). Indeed, when harvest decreases after the home country opens to trade, then steady state welfare decreases as compared to autarky, and even discounted welfare could decrease as compared to what it would have been in autarky. However, Brander and Taylor's specific functional forms made it so that extinction could occur in autarky but not in free trade, which seems counterintuitive when thinking of extinction problems. Here however, when $p^W > p^A_\infty$, we may have extinction under free trade, which seems more plausible when free trade raises the relative price of the resource. Our example differs from Brander and Taylor's in that instantaneous net gain, *i.e.*, $\underset{\ell_h(t)}{\mathrm{Max}}\left[p(t)h\left(\ell_h(t)\right)-\omega(t)\ell_h(t)\right]$, is not affected directly by the resource stock. However, in a different model where stock affects instantaneous net gains, extinction could still be a possible event in open access; see Gould (1972) and Hoel (1978) for discussions on extinction with stock dependence of instantaneous net gains.

5.3.7. Summary of results for the open access model

In Tables 5.1 and 5.2, we summarize our findings regarding the possible impact of free trade on welfare and resource conservation, when the resource is exploited in open access. Recall that we have assumed that, when trade opens, the resource stock is at its autarkic steady state, s_∞^A, such that $g'\left(s_\infty^A\right)<0$. There are three possible scenarios when $p^W > p^A$ while there is only one outcome when $p^W < p^A$.

Table 5.1. Open access resource exploitation and trade, Case 1: $p^W > p_\infty^A$.

Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Conservation	+	+	+	Prop. 5.1 Fig. 5.3
Extinction	-	-	+	
Extinction	-	-	-	

Table 5.2. Open access resource exploitation and trade, Case 2: $p^W < p^A_\infty$.

Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Conservation	-	+	+	Prop. 5.2 Fig. 5.4

5.4. First Best World: Costless Management, or Utopia

The model presented here is the welfare benchmark. The dynamic distortion in the home country, due to the lack of property rights on the resource, is corrected at no cost through a harvest unit-tax, $\tau(t)$, imposed on the harvesters. Hence, in this first best model, individuals and firms behave optimally, even though they have unilateral incentives not to. Indeed, they could cheat and not pay the tax for example, but they do not; this is Utopia.

5.4.1. Production of the resource good

In this model, the social planner must understand the harvesting firms' behavior in order to make them pay the optimal per-unit harvest tax, $\tau(t)$. Once $\tau(t)$ is optimally set, harvesting firms react to it and behave optimally. As usual, the problem must be solved by backward induction. Accordingly, in what follows, we solve the harvesting firms' problem first, and then we use the information obtained about their behavior in the social planner's problem.

5.4.1.1. Harvesting firms

The resource price, the wage rate and the tax rate are exogenously given to each harvesting firm. Since firms do not own the resource, they are open access harvesters. As such, they hire labor to maximize static profits, and there is entry of harvesting firms until profits are equal to zero. The harvesters' objective now includes the per-unit harvest tax:

$$\underset{\ell_h(t)}{\mathrm{Max}}\left[p(t)h\left(\ell_h(t)\right)-\omega(t)\ell_h(t)-\tau(t)h\left(\ell_h(t)\right)\right] \tag{5.18}$$

The harvesters' first order condition and the open access zero-profit condition lead to the same result as before: each firm harvests at its maximum average productivity of labor, at level $\tilde{h}$, as defined by equation (5.4). Therefore, we obtain the usual result that with a per-unit harvest tax, the quantity of inputs used per firm does not change; instead, it is the total number of firms that is affected by the tax.

Hence, from the first order condition to problem (5.18) and equation (5.4), when the resource good is produced in the economy, we must have that

$$\frac{\omega(t)}{p(t)-\tau(t)}=\tilde{h}\,. \tag{5.19}$$

We use the previous definition and notation for the optimal level of hired labor by each firm, $\tilde{\ell}_h$. Aggregate harvest is still written as $H^P\left(L_H(t)\right)=N(t)\tilde{h}\tilde{\ell}_h$. Since $\tilde{h}$ and $\tilde{\ell}_h$ are constant, it is again through N(t) that equilibrium occurs. Here however, if the per-unit harvest tax, $\tau(t)$, changes through time, N(t) also changes. Hence, harvest may not be fixed over time as it was with open access resource exploitation.

5.4.1.2. The resource planner

In this Utopian world, we suppose that a resource planner has the power to charge a per-unit harvest tax to the harvesting firms. His objective is to maximize the discounted inter-temporal welfare (*i.e.*, total economic surplus) of the resource sector. The tax is to be re-distributed in the economy in a non-distortionary manner, and only serves to eliminate the dynamic distortion due to the lack of property rights over the renewable resource.

We note that, since the solution to (5.18) is given by equation (5.4), then the harvest of each identical harvesting firm is $h(\ell_h *) = \tilde{h}\tilde{\ell}_h$. Hence, we can write aggregate production as $H^P(t) = N(t)\tilde{h}\tilde{\ell}_h$ in the resource planner's problem. This way, the planner charges a tax, $\tau(t)$, in order to induce the optimal number of firms, N(t), in the industry. In autarky, the resource planner's problem is therefore

$$\underset{N(t)}{\mathrm{Max}} \int_0^\infty \left[\int_0^{N(t)\tilde{h}\tilde{\ell}_h} p(x)\,dx - \omega(t)N(t)\tilde{\ell}_h \right] e^{-\delta t} dt \tag{5.20}$$

subject to

$$\begin{gathered} \dot{s}(t) = g(s(t)) - N(t)\tilde{h}\tilde{\ell}_h \\ s(t=0) = s_0 \text{ is given} \\ s(t), N(t) \geq 0, \forall t, \end{gathered}$$

where x is a placeholder.

The current value Hamiltonian corresponding to the resource planner's autarkic problem is:

$$\tilde{H} = \int_0^{N(t)\tilde{h}\tilde{\ell}_h} p(x)\,dx - \omega(t)N(t)\tilde{\ell}_h + \mu(t)\Big(g(s(t)) - N(t)\tilde{h}\tilde{\ell}_h\Big) \tag{5.21}$$

where $\mu(t)$ is the corresponding current value co-state variable or shadow value of the resource. Using Leibnitz' rule of differentiation of integrals where appropriate and assuming an interior solution, the necessary conditions for this problem are as follow.

$$\tilde{H}(t)_{N(t)} = p\left(N(t)\tilde{h}\tilde{\ell}_h\right)\tilde{h} - \omega(t) - \mu(t)\tilde{h} = 0 \quad (5.22)$$

$$-\tilde{H}(t)_{s(t)} = \dot{\mu}(t) - \mu(t)\delta = -\mu(t)g'\left(s(t)\right) \quad (5.23)$$

$$\tilde{H}(t)_{\mu(t)} = \dot{s}(t) = g\left(s(t)\right) - N(t)\tilde{h}\tilde{\ell}_h \quad (5.24)$$

$$\lim_{t\to\infty}\mu(t)e^{-\delta t} \geq 0, \ \lim_{t\to\infty}\mu(t)e^{-\delta t}s(t) = 0. \quad (5.25)$$

For an interior solution, the necessary Legendre condition holds: $\tilde{H}(t)_{N(t)N(t)} = p'(\cdot)\left(\tilde{h}\right)^2\tilde{\ell}_h < 0$. Second order conditions are also satisfied to guarantee a unique solution to this problem. Indeed, $\tilde{H}(t)_{s(t)s(t)} = \mu(t)g''\left(s(t)\right) < 0$, $\tilde{H}(t)_{s(t)N(t)} = 0$, and therefore, $\tilde{H}(t)_{N(t)N(t)}\tilde{H}(t)_{s(t)s(t)} - \left(\tilde{H}(t)_{s(t)N(t)}\right)^2 > 0$, which means we have a strictly concave problem.

We see, by comparing the harvesters' first order condition of problem (5.18) to equation (5.22), that the optimal per-unit harvest tax is equal to the resource current value marginal rent: $\tau^*(t) = \mu^*(t)$. We then have, $\dfrac{\omega(t)}{p(t) - \mu^*(t)} = \tilde{h}$ from equation (5.19), (5.4) and (5.22), when the resource good is produced in autarky. Also, if $\mu(t) > 0$ for s(t) such that g'(s(t)) = δ, then according to (5.23), the unique optimal steady state occurs where g'(s(t)) = δ. Therefore, optimally, if g'(0) > δ, the resource is conserved in the long run, while if g'(0) ≤ δ, then extinction is optimal. To summarize, we write the steady state stock as $s_\infty^* = \inf\{s : g'(s) \le \delta\}$, which includes both potential outcomes since s(t) ≥ 0.

In order to better understand the dynamics of the resource planner's model, we first rewrite (5.22) as $\mu(t) = p\left(N(t)\tilde{h}\tilde{\ell}_h\right) - \frac{\omega(t)}{\tilde{h}}$. From this, we substitute μ into (5.23):

$$\dot{\mu}(t) = \left(p\left(N(t)\tilde{h}\tilde{\ell}_h\right) - \frac{\omega(t)}{\tilde{h}}\right)\left(\delta - g'(s(t))\right). \tag{5.26}$$

We find $\dot{\mu}$ by differentiating (5.22) with respect to time:

$$\dot{\mu}(t) = \dot{N}(t)p'\tilde{h}\tilde{\ell}_h \tag{5.27}$$

Therefore, from (5.26) and (5.27), we obtain the path for the number of harvesting firms in autarky:

$$\dot{N}(t) = \left(p\left(N(t)\tilde{h}\tilde{\ell}_h\right) - \frac{\omega(t)}{\tilde{h}}\right)\left(\frac{\delta - g'(s(t))}{p'\tilde{h}\tilde{\ell}_h}\right) \tag{5.28}$$

Proposition 5.3.

In autarky, the resource planner's optimal path for s(t) and $H^P(t)$ are monotonic over time. As s increases (or decreases) towards its steady state, then the harvest increases (decreases) through the increase (decrease) of N(t), until the optimal steady state, s_∞^*, is attained.

Proof.

The optimal steady state stock, s_∞^*, was deducted from (5.23). Necessary conditions lead to (5.28), whose first right-hand-side factor is positive for a scarce resource, and whose second right-hand-side factor has the sign opposite to that of $\delta - g'(s)$. Since g"(s) < 0, it must be that N increases (decreases) as s increases (decreases). Since $H^P = N\tilde{h}\tilde{\ell}_h$, total harvest increases (decreases) with N and s. □

Proposition 5.4.

In autarky, the optimal tax path, $\tau(t)$, is monotonic; it increases as s(t) decreases towards the steady state, and *vice versa*.

Proof.

Since, $\tau^*(t) = \mu^*(t)$, Proposition 5.4 follows directly from equation (5.27) and Proposition 5.3. □

5.4.2. Production of the manufactured good

As in the open access model of section 5.3, we find necessary condition (5.7): $\omega(t) = M'(L_M(t))$. Given the results we found for resource production in the first best model, when both goods are simultaneously produced, we conclude that the marginal value products are equalized and equal to the wage rate:

$$M'(L_M(t)) = (p(t) - \tau^*(t))\tilde{h} = (p(t) - \mu(t))\tilde{h} = \omega(t). \tag{5.29}$$

5.4.3. Consumption

As we found in the open access model, the necessary conditions on the utility maximization problem of consumers lead to (5.10): $p(t)=\frac{u_h^C(t)}{u_m^C(t)}$. Aggregated demands are the same as (5.11).

5.4.4. Walrasian equilibrium

Constraints (5.12) and (5.13) must still be obeyed in the economy, except that here, N(t) depends not only on the same parameters as in the open access model, but also on the resource stock level, through the shadow price, $\mu^*(t)$, and therefore, through the optimal tax, $\tau^*(t)$. Since the resource stock changes over time, $\mu^*(t)$ does too, and therefore $\tau^*(t)$ as well. This implies that N(t) is not fixed over time.

5.4.5. Autarky: temporary and long-run *equilibria*

Equation (5.14)-(5.16) must hold at all times, as in the open access model, but now, N(t) depends on the resource stock size through the per-unit harvest tax charged to harvesters. The dynamics of the first best model is therefore richer than that of the open access model presented in section 5.3.

We saw that the resource planner's optimal path towards the steady state is monotonic in s(t) and that N(t) changes over time. In a general equilibrium setting, a change in N(t) will trigger changes elsewhere in the economy, since it implies labor migration from one sector to the other. This leads to the following proposition.

Proposition 5.5.

General equilibrium dynamic paths are monotonic in this autarkic economy. Furthermore, as s increases (decreases) towards its steady state, then the harvest increases (decreases), the production of manufactures decreases (increases), the wage rate increases (decreases), the relative price of the resource good decreases (increases), and the instantaneous welfare of individuals increases (decreases).

Proof.

Production

From equation (5.28) we have $\dot{N} = \left(p\left(N\tilde{h}\tilde{\ell}_h\right) - \frac{\omega}{\tilde{h}} \right)\left(\frac{\delta - g'(s)}{p'\tilde{h}\tilde{\ell}_h} \right)$, so that N varies in the same direction as s. For the resource good, at any given time, $H^P = N\tilde{h}\tilde{\ell}_h$. Therefore $\dot{H}^P = \dot{N}\tilde{h}\tilde{\ell}_h$. Hence, H^P varies in the same direction as N and s. For the manufactured good, at any given time, $M^P\left(L_M\right) = M^P\left(L - L_H\right) = M^P\left(L - N\tilde{\ell}_h\right)$. Therefore, $\dot{M}^P = -\dot{N}M^{P}{}'(\cdot)\tilde{\ell}_h$. Therefore H^P varies in the opposite direction of N and s.

Equilibrium prices

From the utility maximization given the economy's budget constraint, we obtained $p = \frac{u_h}{u_m} = \frac{u_H}{u_M} = \frac{\partial u}{\partial H^C}\frac{\partial M^C}{\partial u}$, where $H^C = h^C(p)Y$ and $M^C = m^C(p)Y$. In autarkic equilibrium however, $M^C = M^P$ and $H^C = H^P$. This must hold over time in autarky, and so we can replace $\dot{H}^C$ by $\dot{H}^P$ and $\dot{M}^C$ by $\dot{M}^P$ for the evolution of harvest and manufactures over time in the Walrasian equilibrium. We find that, since $u = u\left(H^C, M^C\right)$, the relative price changes as follows

$\dot{p} = \dfrac{\dot{H}[u_M u_{HH} - u_H u_{MH}] + \dot{M}[u_M u_{MH} - u_H u_{MM}]}{(u_M)^2}$. Given that H changes in the same direction as s, and M changes in the opposite direction, and since for a homothetic utility function $[u_M u_{HH} - u_H u_{MH}] < 0$ and $[u_M u_{MH} - u_H u_{MM}]>0$, we conclude that changes in p are opposite to changes in s.

From the manufactures production sector, we found that $\omega = M'(L_M)$. Since $L_M = L - N\tilde{\ell}_h$, we find that $\dot{\omega} = -\dot{N}M^{P}{}''(\cdot)\tilde{\ell}_h$. Therefore, the wage rate, ω, varies in the same direction as N and s.

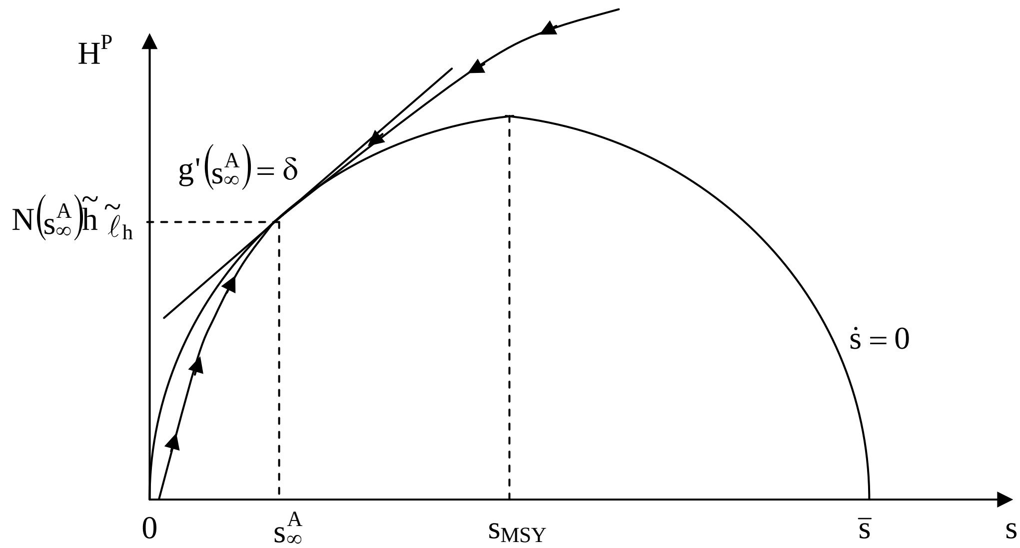
Instantaneous welfare

Welfare changes are measured by changes in the indirect utility function v(p,Y). Therefore welfare changes over time as follows

$$\begin{aligned}\dot{v} &= \frac{\partial v(p,Y)}{\partial p}\dot{p} + \frac{\partial v(p,Y)}{\partial Y}\left(H\dot{p} + p\dot{H} + \dot{M}\right)\\ &= \dot{p}\frac{\partial v(p,Y)}{\partial Y}\left[\frac{\partial v(p,Y)}{\partial p}\frac{\partial Y}{\partial v(p,Y)} + H\right] + \frac{\partial v(p,Y)}{\partial Y}\left(p\dot{H} + \dot{M}\right).\end{aligned}$$

We note that $\left[\dfrac{\partial v(p,Y)}{\partial p}\dfrac{\partial Y}{\partial v(p,Y)} + H\right] = -H^C + H^P = 0$ in autarky (see Appendix IV). Given our assumption of homotheticity of the utility function, then $\dot{v} = \nu(p)(p\dot{H} + \dot{M})$, which given our findings above leads to $\dot{v} = \nu(p)\dot{N}\tilde{\ell}_h(p\tilde{h} - M')$. From equation (5.7), in equilibrium we have M' = ω, and from (5.22), we also have $p\tilde{h} - \omega = \mu\tilde{h} > 0$. Then, welfare changes can be rewritten as $\dot{v} = \nu(p)\dot{N}\tilde{\ell}_h\mu\tilde{h}$. Therefore welfare changes in the same direction as N and therefore s as well. □

Figure 5.5. Autarkic phase diagram with first best management



The first best autarkic dynamics is illustrated in Figure 5.5 for the resource sector. In Table 5.3, we summarize the autarkic trajectories for the first best model.

Table 5.3. Summary of first best autarkic trajectories

Components of the economy ↓ / Initial stock →	$0 < s_0 < s_\infty$	$s_\infty < s_0 \leq \bar{s}$
Resource stock, s(t)	increases	decreases
Implicit current value of the resource stock, μ(t)	decreases	increases
Number of harvesting firms, N(t)	increases	decreases
Equilibrium quantity of resource good, H(t)	increases	decreases
Equilibrium quantity of manufactures, M(t)	decreases	increases
Wage rate, ω(t)	increases	decreases
Relative price, p(t)	decreases	increases
Welfare, v(p(t))Y(t)	increases	decreases

5.4.6. Free trade: temporary and long-run *equilibria*

We assume that g'(0) > δ, and that when trade opens, the resource stock is at its autarkic steady state s_∞^A, such that $g'\left(s_\infty^A\right)=\delta$. The equilibrium autarky price just before trade opens is noted p_∞^A. Since we assume that the home country takes world prices as given, there are two cases of interest: $p^W > p_\infty^A$, and $p^W < p_\infty^A$.

Case 1. $p^W > p_\infty^A$

Proposition 5.6

If $p^W > p_\infty^A$, production remains the same as in the autarkic steady state forever. The home country exports some $H^P(t)$ and imports some $M^C(t)$. Welfare is always higher due to the new international exchange possibilities; hence the discounted welfare is higher than it would have been in autarky, and the steady state welfare is higher than it would have been in autarky as well. Finally, the resource is conserved.

Proof.

We have $p^W > p_\infty^A$. The home country has a comparative advantage in the resource good, and therefore, $\mu^*(t) > 0$ with free trade, as it was in autarky. In free trade, the steady state stock is unique and is the same as in autarky, since it only depends on the discount rate and on the biological growth function: $g'\left(s_\infty^A\right)=g'\left(s_\infty^T\right)=\delta$. The resource is therefore conserved in the long run.

In market equilibrium, since $p=\frac{u_H}{u_M}$, $p^W > p_\infty^A$, and since preferences are homothetic, this means that the price change leads to a decrease in the consumption of

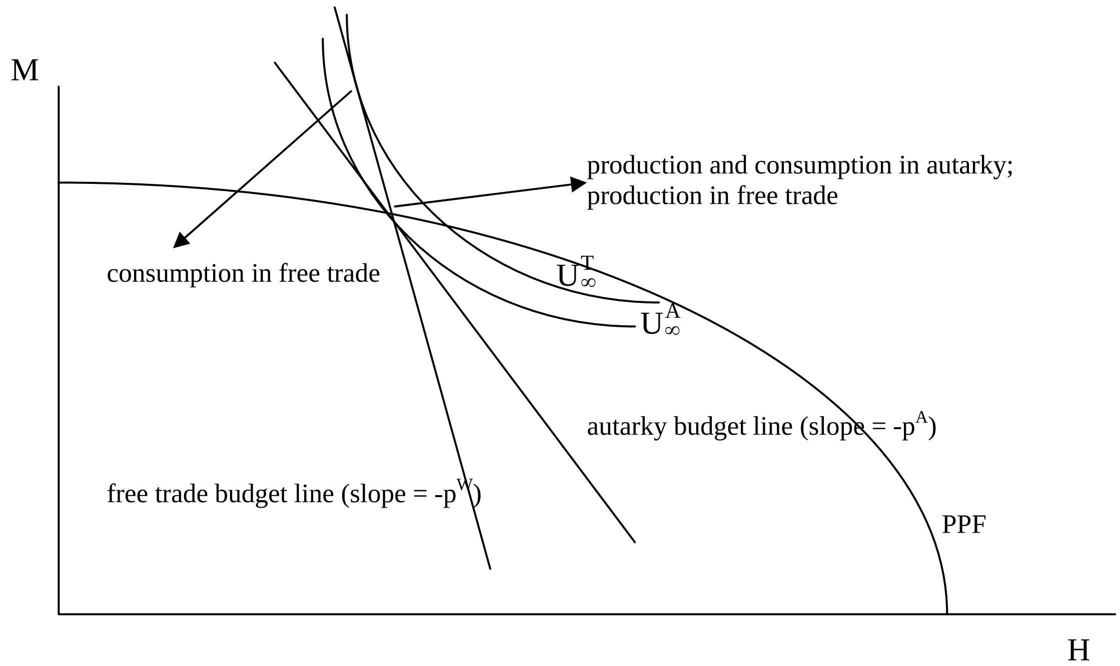
H and an increase in the consumption of M. However, the same quantity as before is produced since the economy is already at the optimal steady state. Therefore, H is exported and M is imported. Utility is higher than in autarky initially and forever, since the economy is already at its steady state production.

Indeed, the change in welfare (equation A.4) is $dv = \frac{\partial v(p, Y)}{\partial Y}\left[-H^C + H^P\right]dp > 0$, from the pattern of trade and change in relative price (see Appendix IV). Therefore, welfare necessarily increases with free trade in this case, both in the short and long run.

□

Case 1 of the first best model with trade is illustrated in Figure 5.6. We note that the autarky budget line is not tangent to the production possibilities frontier (PPF) because an inter-temporal user cost is considered in the problem while the PPF is a static notion. In the inter-temporal problem, the optimal relative price of the resource is greater than it would be in the static problem, such as the open access problem presented in section 5.3.

Figure 5.6. First best resource management and trade, Case 1: $p^W > p^A_\infty$



Case 2. $p^W < p^A_\infty$

Case 2 in the first best model can be subdivided into two sub cases, depending on the magnitude of the change in the relative terms of trade.

Case 2a: $\left[M'\left(L^A_{M\infty}\right)\big/\tilde{h}\right] < p^W < p^A_\infty$

Proposition 5.7a. Production remains the same as in autarky

If $p^W < p^A_\infty$, but the difference between the two relative prices is not great, then there is still a positive rent on the resource and therefore it remains managed. Production remains the same as in autarky. Given the new, lower relative price, the home country exports $M^P(t)$ and imports $H^C(t)$, which is now relatively cheaper than in autarky. Welfare is initially higher, and since production does not change, the initial equilibrium is also a steady state. Therefore, steady state welfare is higher than in autarky, and discounted welfare also is. Finally, the resource is conserved.

Proof.

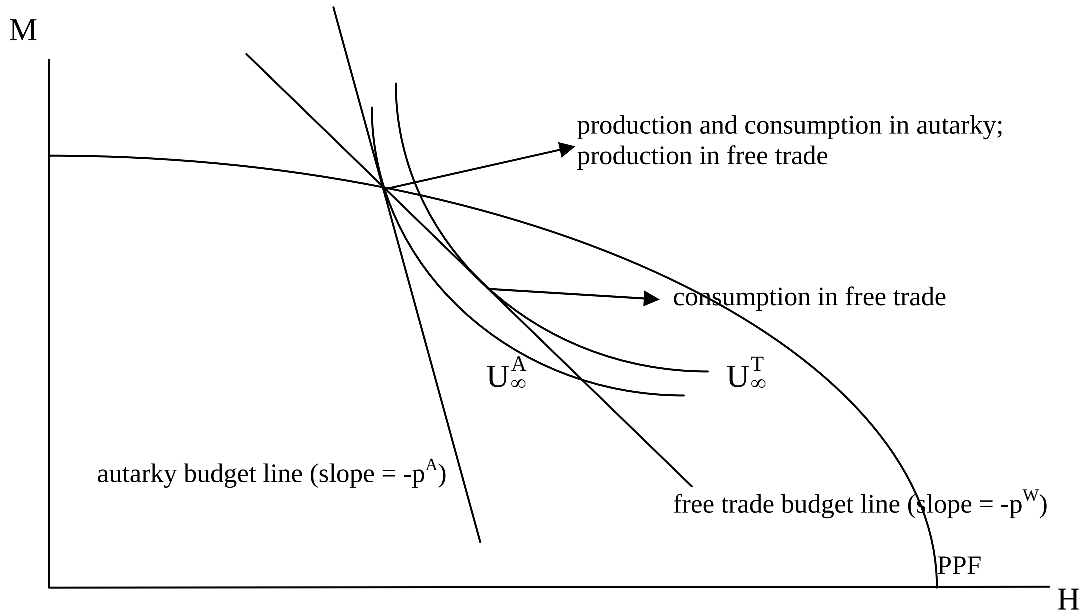
If $p^{W} < p_{\infty}^{A}$, but the difference between the two relative prices is not great, *i.e.*, smaller than the autarkic steady state rent, $\mu_{\infty}^{A}(t)$, then the resource rent is $p^{W} - \left[M'\left(L_{M\infty}^{A}\right)/\tilde{h}\right] = \mu_{\infty}^{T} > 0$. Since it is positive, the resource remains managed. Since $g'\left(s_{\infty}^{A}\right) = g'\left(s_{\infty}^{T}\right) = \delta$, production remains the same and the steady state stock is the same as in autarky. Hence the resource is conserved.

Given the new terms of trade, the consumption of M decreases and that of H increases, which, with the production equilibrium and instantaneous budget constraint, implies that some $H^{C}(t)$ is imported and $M^{P}(t)$ is exported.

With free trade, the welfare change initially is $dv = \frac{\partial v(p,Y)}{\partial Y}\left[H^{P} - H^{C}\right]dp > 0$, from the new pattern and terms of trade. Since the home country remains at the same steady state, then this situation continues forever; welfare is always higher than it would have been in autarky, and therefore discounted welfare is unambiguously higher than it would have been in autarky as well. □

Case 2a of the first best model with trade is illustrated in Figure 5.7.

Figure 5.7. First best management and trade, Case 2a: $\left(\frac{M'\left(L_{M,\infty}^{A}\right)}{\tilde{h}}\right) < p^{W} < p_{\infty}^{A}$



Case 2b: $p^{W} \leq \left[M'\left(L_{M\infty}^{A}\right)/\tilde{h}\right] < p_{\infty}^{A}$

Proposition 5.7b. Production changes with free trade.

If $p^{W} < p_{\infty}^{A}$, and the decrease in relative price of the resource good is large enough so that the resource no longer has a positive inter-temporal shadow value, then the resource is no longer managed, the home country produces more M(t) than in autarky (or the exact same amount if $p^{W} = \left[M'\left(L_{M\infty}^{A}\right)/\tilde{h}\right]$) and it exports some of it. It produces less, maybe none at all, H(t), and it imports it for at least part of its consumption. It consumes less M and more H.

Welfare is always higher; hence the discounted welfare is higher than it would have been in autarky, and the steady state welfare is higher than it would have been in autarky as well. Finally, the resource is conserved at a stock greater or equal to s_∞^A.

Proof.

If $p^W < p_\infty^A$, and the difference between the two relative prices is large enough, *i.e.*, at least the magnitude of the autarkic steady state rent, $\mu_\infty^A(t)$, then the resource rent disappears since $p^W - \left[M'\left(L_{M\infty}^A\right)/\tilde{h}\right] \leq 0$.

If $p^W - \left[M'\left(L_{M\infty}^A\right)/\tilde{h}\right] = 0$, then the resource rent is zero at s_∞^A, and the production pattern remains the same since this is equivalent to having the resource being "just managed" because $g'\left(s_\infty^A\right) = g'\left(s_\infty^T\right) = \delta$ and here it turns out that $s_\infty^T = s_\infty^A$. In that case, the rest of the proof is the same as that of Proposition 5.7a, except that the resource rent is exactly zero.

If $p^W - \left[M'\left(L_{M\infty}^A\right)/\tilde{h}\right] < 0$ however, then resource management is wasteful, and open access is the first best level of resource management. This implies that with the new terms of trade, there is no more economic scarcity of the resource stock at s_∞^A. In that case, more $M^P(t)$ and less $H^P(t)$ are produced. Since the aggregate production of manufactures is strictly concave in labor, with trade and $p^W < p_\infty^A$, the home country will produce more manufactures than in autarky (or the same amount in the special case where $p^W = M'\left(L_{M\infty}^A\right)/\tilde{h}$), and it may or may not specialize in it. Specialization occurs only if $M'(L) \geq p^W\tilde{h}$. However, if $M'\left(L_M^T(t)\right) < p^W\tilde{h}$, then labor is hired in the manufactures sector up to the point where $M'\left(L_M^T(t)\right) = p^W\tilde{h}$ is satisfied, which leads to diversification. In such instance, the home country's harvest is positive bit less than it was in autarky: $H^P\left(L_H^T(t)\right) = H^P\left(L - L_M^T(t)\right) < H^P\left(L_{H,\infty}^A(t)\right)$.

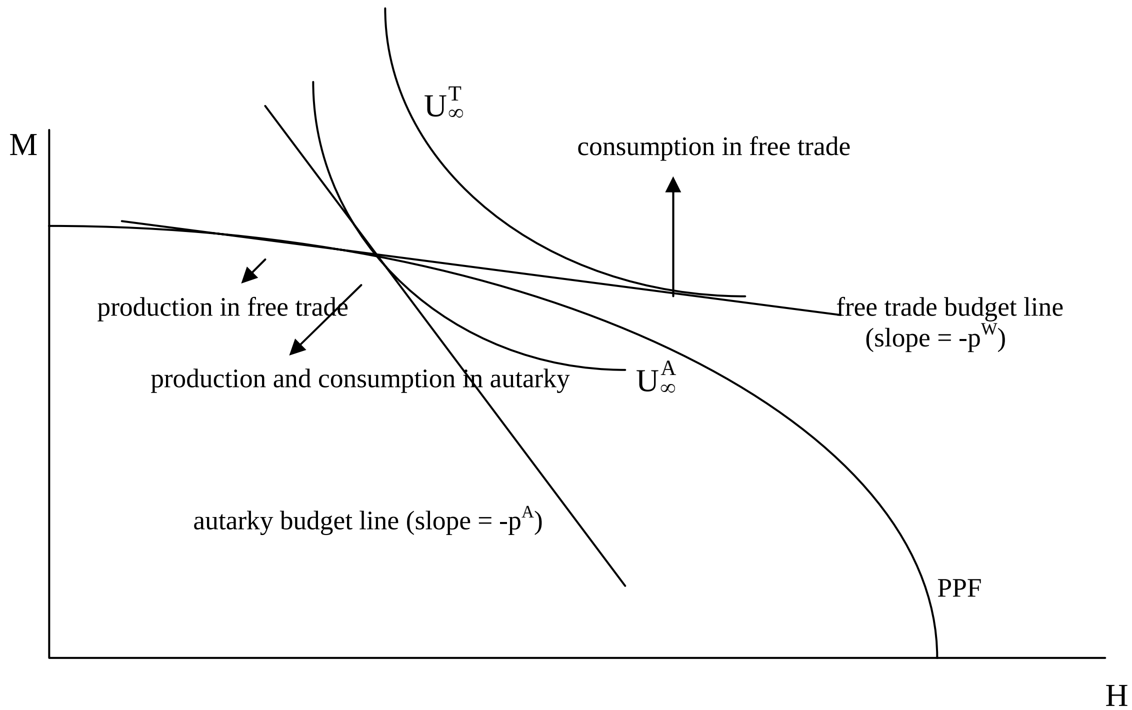
In consumption, since $p(t) = \dfrac{u_h^C(t)}{u_m^C(t)}$, and since preferences are homothetic, and the instantaneous budget must be balanced, then the price change leads to an increase in the consumption of $H^C(t)$ and a decrease in the consumption of $M^C(t)$. Along with the new production pattern, this implies that at least some $H^C(t)$ is imported and some $M^P(t)$ is exported.

From the pattern and terms of trade, the initial change in welfare due to trade is $dv = \dfrac{\partial v(p,Y)}{\partial Y}\left[H^P - H^C\right]dp \geq 0$.

We conclude that welfare unambiguously increases with trade initially and forever. Hence, both steady state and discounted welfare are higner than they would have been in autarky. In either the diversified case or the specialized case, the long run equilibrium stock with free trade, s_∞^T, is such that $H^P\left(L - L_M(t)\right) = g\left(s_\infty^T\right)$ and $s_\infty^T \geq s_\infty^A$. Therefore when $p^W < p_\infty^A$, extinction cannot occur due to trade. □

Case 2b of the first best model with trade is illustrated in Figure 5.8.

Figure 5.8. First best management and trade, Case 2b: $p^W \leq \left(\frac{M'\left(L^A_{M\infty}\right)}{\tilde{h}} \right) < p^A_\infty$



5.4.7. Summary of results for the first best model

In Tables 5.4 and 5.5, we summarize our results about the impact of free trade on welfare and resource conservation, for the first best model, which is the welfare benchmark. We assume that $g'(0) > \delta$, so the resource is always conserved in the long run. We further assumed that when trade opens, the resource stock was at its autarkic steady state.

Table 5.4. First best resource management and trade, Case 1: $p^W > p^A_\infty$.

Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Conservation	*no change*	+	+	Prop. 5.6 Fig. 5.6

Table 5.5. First best resource management and trade, Case 2: $p^W < p^A_\infty$.

Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Conservation	*no change*	+	+	Prop. 5.7a Fig. 5.7
Conservation	-	+	+	Prop. 5.7b Fig. 5.8

5.5. Second best world: fixed cost of resource management

In reality, resource management is costly because it requires the use of inputs. Different bodies of literature would call this a *transactions cost* or an *agency cost*. Empirical studies, from Harberger's pioneering estimate of 5% (1964) to more recent estimates of up to 300% for the US, have clearly shown that theoretical deadweight losses due to taxation have important empirical impacts for a country. In their summary of this body of empirical literature, Vedder and Gallaway (1999), retain a cost of 40¢ per marginal tax dollar collected in the US as a reasonable midpoint estimate of what they consider to be several serious studies.

In our model, as a rough approximation, we assume that the fiscal apparatus in the home country generates an instantaneous fixed cost of tax collection and redistribution, no matter what the tax rate may be. This fixed cost needs to be paid at each instant when resource taxes are collected; it is a flow fixed cost. We further assume that taxpayers do not evade taxation. In subsection 5.5, we analyze the model under second best management, in autarky and in free trade, in steady state and along the transitory paths. We also compare this second best management regime to the first best welfare benchmark.

5.5.1. Production of the resource good

For this second best model, we first solve the harvesting firms' problem. We then use the result into the benevolent social planner's problem. The only difference with section 5.4.1 is that the social planner must pay an instantaneous fixed cost to manage the resource.

5.5.1.1. Harvesting firms

The harvesting firms' problem is the same as in the first best model. From (5.4), their equilibrium average harvest is $\frac{h(\ell_h(t))}{\ell_h(t)} = h'(\ell_h(t)) = \tilde{h}$ = constant. In equilibrium, we must have $\frac{\omega(t)}{p(t)-\tau(t)} = \tilde{h}$, or $p(t) = \frac{\omega(t)}{\tilde{h}} + \tau(t)$. Therefore the tax chosen by the resource planner, $\tau(t)$, affects the market price.

5.5.1.2. The resource planner

In this second best, more realistic world, the resource planner can charge a per-unit harvest tax to the harvesters, but the collection and redistribution of the tax is costly in terms of a fixed amount of labor, $L_\tau(t) = L_\tau$. In that case, the resource planner's autarkic problem is

$$\underset{N(t)}{\text{Max}} \int_0^\infty \left[\int_0^{N(t)\tilde{h}\tilde{\ell}_h} p(x)\,dx - \omega(t)N(t)\tilde{\ell}_h - \omega(t)L_\tau \right] e^{-\delta t}\,dt \tag{5.30}$$

subject to

$$\dot{s}(t) = g(s(t)) - N(t)\tilde{h}\tilde{\ell}_h$$
$$s(t=0) = s_0 \text{ given}$$
$$s(t), N(t) \geq 0, \forall t,$$

where x is a placeholder.

The current value Hamiltonian corresponding to the resource planner's autarkic problem is:

$$\tilde{H}(t) = \int_0^{N(t)\tilde{h}\tilde{\ell}_h} p(x)\,dx - \omega(t)N(t)\tilde{\ell}_h - \omega(t)L_\tau + \mu(t)\left(g(s(t)) - N(t)\tilde{h}\tilde{\ell}_h\right) \tag{5.31}$$

where $\mu(t)$ is the corresponding current value co-state variable. Using Leibnitz' rule of differentiation of integrals where appropriate and assuming an interior solution, the necessary conditions for this problem are the same as those for the first best model (equations (5.22)-(5.25)). Second order conditions therefore hold as well here, and we have a strictly concave problem. We therefore obtain the same result as before that $\tau^*(t) = \mu^*(t)$, but $\mu^*(t)$ differs from what it was in the first best model because, here, the general equilibrium wage rate and price ratio are affected by the cost of the planner's policy, $\omega(t)L_\tau$. Also, the unique steady state of this second best management regime is at the same stock level than in the first best model, $s_\infty^* = \{s(t) : g'(s(t)) = \delta\}$, assuming that $g'(0) > \delta$. Propositions 5.3 and 5.4, which establish that all paths are on monotonic, hold here too.

5.5.2. Production of the manufactured good

Again, manufactures are produced according to (5.7): $\omega(t) = M^{P}{}'(L_M(t))$. If the resource good is also produced, then (5.29) must hold:

$(p(t) - \mu^*(t))\tilde{h} = (p(t) - \tau^*(t))\tilde{h} = \omega(t)$.

5.5.3. Consumption

Equilibrium price and aggregate demands are as in (5.10) and (5.11) in this model too: $p(t) = \dfrac{u_h^C(t)}{u_m^C(t)}$, $H^C(t) = h^C(p(t))Y(t)$ and $M^C(t) = m^C(p(t))Y(t)$.

5.5.4. Walrasian equilibrium

The budget constraint (5.13) must be obeyed in the economy: $Y(t) = p(t)H^P(t) + M^P(t)$. Equation (5.12) is however replaced by

$$\begin{aligned} L &= L_H(t) + L_M(t) + L_\tau \\ &= N(t)\tilde{\ell}_h + L_M(t) + L_\tau \\ &= N(t)\tilde{\ell}_h + M'^{-1}(\omega(t)) + L_\tau \end{aligned} \tag{5.32}$$

As in the first best model, N(t) depends on the resource stock level through its shadow price, $\mu^*(t)$, and in turn, through the optimal tax, $\tau^*(t)$.

5.5.5. Autarky: temporary and long-run *equilibria*

The dynamics of this second best model is also characterized by equations such as (5.26)-(5.28) although magnitudes of optimal production and resulting income, for a given s(t), differ because of the use of L_τ in this second best world. Due to the use of labor for tax collection and re-distribution, equation (5.16) is replaced by

$$M^C\left(p\left(t\right)\right)Y\left(t\right)=M^P\left(L_M\left(t\right)\right)=M^P\left(L-N\left(t\right)\tilde{\ell}_h-L_\tau\right). \tag{5.33}$$

In this second best management regime, Proposition 5.5, on the monotonicity and direction of all paths in autarky, also holds. Here however, the use of a portion of the labor force L_τ, results in a different wage rate than in the first best model, hence a different price ratio, a different consumption and resource extraction path, and a different optimal tax as well, since μ(t), the shadow price of the resource, is affected by the need for L_τ.

Indeed, in autarkic equilibrium, the use of L_τ takes labor away from both sectors, as compared to the first best, because of the homotheticity of preferences. Hence, there is less M(t) and less H(t) produced for any stock level. Producing less M(t) implies that, for a given s(t), the wage rate is higher than in the first best model, since $\omega(t) = M'(L_M(t))$. Even though the necessary conditions of the resource production problem are the same as in first best, (5.32) differs from (5.12). There is a greater demand on labor, and therefore, a higher equilibrium wage rate than in first best. In other words, in this second best model, the solution is similar to exogenously having L_τ less labor than in the first best model. Welfare is always lower than in the first best model because less goods are produced and therefore, consumed.

For a given s(t), the autarky equilibrium relative price p(t) differs in an undetermined fashion from that in the first best model, depending on preferences. Since

$p(t) = \dfrac{u(t)^{C}_{h(t)}}{u(t)^{C}_{m(t)}}$, we know that $dp(t) = \dfrac{dH[u_M u_{HH} - u_H u_{MH}] + dM[u_M u_{MH} - u_H u_{MM}]}{(u_M)^2}$.

Given that H(t) and M(t) both decrease as compared to the first best model, and since for our homothetic utility function $[u_M u_{HH} - u_H u_{MH}] < 0$ and $[u_M u_{MH} - u_H u_{MM}] > 0$, we conclude that for any given s(t), the difference in p(t) as compared to the first best is unclear. It depends on how much of L_τ was taken from the resource sector and the manufactures sector as compared to the first best management regime.

5.5.6. Free trade: temporary and long-run *equilibria*

Again, we assume that when free trade occurs, the resource stock is at a positive steady state stock such that $g'(s^A_\infty) = \delta$. The equilibrium autarky price just before trade opens is noted p^A_∞. Since we assume that the home country takes world prices as given, then we need to analyze two possible cases: $p^W > p^A_\infty$, and $p^W < p^A_\infty$. Welfare and resource conservation results are similar to those for the first best model.

Case 1. $p^W > p^A_\infty$

Proposition 5.8.

If $p^W > p^A_\infty$, production remains the same as in the autarkic steady state forever. The home country exports some $H^P(t)$ and imports some $M^C(t)$. Welfare is always higher due to the new international exchange possibilities; hence the discounted welfare is higher than it would have been in autarky, and the steady state welfare is higher than it would have been in autarky as well. Finally, the resource is conserved.

Proof.

See the proof of Proposition 5.6 from section 5.4.6. □

Case 2. $p^W < p^A_\infty$

Case 2 in the second best model with fixed cost of management can also be subdivided into two sub cases, depending on the magnitude of the change in the relative terms of trade.

Case 2a: $\left[M'\left(L^A_{M\infty}\right)/\tilde{h}\right] < p^W < p^A_\infty$

Proposition 5.9a. Production remains the same as in autarky

If $p^W < p^A_\infty$, but the difference between the two relative prices is not great, then there is still a positive rent on the resource and therefore it remains managed. Production remains the same as in autarky. Given the new, lower relative price, the home country exports $M^P(t)$ and imports $H^C(t)$, which is now relatively cheaper than in autarky. Welfare is initially higher, and since production does not change, the initial equilibrium is also a steady state. Therefore, steady state welfare is higher than in autarky, and discounted welfare also is. Finally, the resource is conserved.

Proof.

See the proof of Proposition 5.7a in section 5.4.6. □

Case 2b: $p^{W} < \left[M'\left(L^{A}_{M\infty}\right) / \tilde{h} \right] < p^{A}_{\infty}$

Proposition 5.9b.

If $p^{W} < p^{A}_{\infty}$, and the decrease in relative price of the resource good is large enough so that the resource no longer has a positive inter-temporal shadow value, then the resource is no longer managed, the home country produces more M(t) than in autarky (or the exact same amount if $p^{W} = \left[M'\left(L^{A}_{M\infty}\right) / \tilde{h} \right]$) and it exports some of it. It produces less, maybe none at all, $H^{P}(t)$, and it imports it for at least part of its consumption. It consumes less $M^{C}(t)$ and more $H^{C}(t)$.

Welfare is always higher; hence the discounted welfare is higher than it would have been in autarky, and the steady state welfare is higher than it would have been in autarky as well. Finally, the resource is conserved at a stock greater or equal to s^{A}_{∞}.

Proof.

See the proof of Proposition 5.7b in section 5.4.6. □

In Case 2b of this second best resource management economy, L_{τ} will be reallocated to M^{P} and perhaps H^{P}, depending on whether the economy specializes in the manufactures or remains diversified. This is different of course from the first best model where there is no L_{τ} devoted to resource management.

5.6. Empirically-relevant resource management regimes and regime switches

We now consider the possibility that open access turns out to be the second best optimal resource management regime, *i.e.*, that open access is chosen by the resource planner when resource management is "too" costly. Hence we allow for open access and effective costly management to be optimally chosen at different resource stocks, s(t); we call his option *The resource management regime problem*.

First, let us point out that for some resource stock range, open access can be the first best management regime, *i.e.*, it can be optimal even when resource management is costless. This was shown in a continuous time framework by Kemp and Long (1980) and by Levhari *et al.* (1981) in discrete time. This is so because, in a concave infinite horizon autonomous problem, the shadow price of the resource, which represents the economic scarcity of the resource stock, varies inversely with the resource stock.[15] Therefore, for high resource stocks, the shadow price could be zero, *i.e.*, there could be no economic scarcity at all. Open access exploitation of the resource would then be first best optimal. In the first best model however, as the resource stock decreases, the shadow price of the resource can eventually become positive, and therefore effective management can be optimal for smaller stocks.

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[15] See Long (1979) for a proof that $\dot{\mu}(t)\dot{s}(t) \leq 0$ for an infinite horizon autonomous concave problem, and that $\dot{\mu}(t)\dot{s}(t) < 0$ for an infinite horizon autonomous *strictly* concave problem.

The same inverse relationship between the shadow price, $\mu(t)$, and the resource stock, $s(t)$, holds true in our second best model with fixed cost of management. Indeed, our second best problem is also an infinite horizon autonomous problem, which implies that the relationship $\dot{\mu}(t)\dot{s}(t) \leq 0$ must hold (Long, 1979). Equation (5.26) makes it clear for our specific model.

In our second best model however, if $\mu^*(s) > 0$ for large stocks, then open access can be the preferred management regime for some resource stock range only because of the fixed flow of management cost, not due to lack of economic scarcity. As in section 4.4, we consider the possibility that open access is the second best resource management regime. First, we must solve the social planner's resource management regime problem. That problem is solved in Appendix IV and we use the necessary condition found there in the analysis that follows. As in Chapter 4, at stocks where the second best resource management regime changes from costly management to open access (or *vice versa*), we must have $\tilde{H}\left(H^P, \mu^*, s\right) = 0$.

In order to characterize the stock range(s) for which the second best management could be open access, we must first describe the locus $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ in (s, H^P)-space in order to plot it on the phase diagram. To do so, let us use the current value Hamiltonian (5.31), and let us simplify the notation slightly by setting the harvest level $H^P = N_{SP}(t)\tilde{h}\tilde{\ell}_h$, where N_{SP} is the number of harvesters under costly resource management. Let us also substitute $\mu(t)$ according to first order condition (5.22) by

$\left(p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right)$. Further, let us set $\int_0^{H^P} p(x)\,dx = U\left(H^P\right)$. After some algebraic manipulation, we finally obtain the locus

$$\tilde{H} = U\left(H^P\right) - p\left(H^P\right)H^P + \left(p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right)g(s) - \omega L_\tau = 0. \qquad (5.34)$$

The characterization of $\tilde{H}\left(H^P,\mu^*,s\right)=0$ on the phase diagram will be done in a similar fashion as in Chapter 4, that is, by considering the zero profit locus, $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$, and the surplus locus $U\left(H^P\right)-p\left(H^P\right)H^P = \omega L_\tau$.

Assume that the resource manager cares about maximizing total inter-temporal welfare from the resource sector, but he does not take general equilibrium externalities into account. This implies that he takes ω, the wage rate, as given. As in Chapter 4, we will find three cases of interest. Case A occurs when the $\tilde{H}\left(H^P,\mu^*,s\right)=0$ locus intersects with the zero profit locus, which is also the open access path; we will see that this implies that the zero profit locus and the surplus line intersect. In Cases B and C, the zero profit locus and the surplus line do not intersect. In Case B the zero profit line is above the surplus line for all feasible resource stocks; in Case C it is the opposite.

Case A: The locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ intersects the zero profit line, $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$.

First consider points where the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ intersects the vertical axis, where $s=0$. At $s=0$, the equation $\tilde{H}\left(H^P,\mu^*,s\right)=0$ implies $U\left(H^P\right)-p\left(H^P\right)H^P = \omega L_\tau$:

the instantaneous consumer surplus generated by costly resource management is equal to the instantaneous cost of management, ωL_τ. Let H_τ be the harvest level that satisfies $U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau$ at $s=0$.

Now consider the point(s) where the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ intersects the zero profit line defined by $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$, or equivalently, with no restriction on g(s), $\left[p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right]g\left(s\right)=0$. If an intersection exists, it occurs at (s,H^P) that satisfies

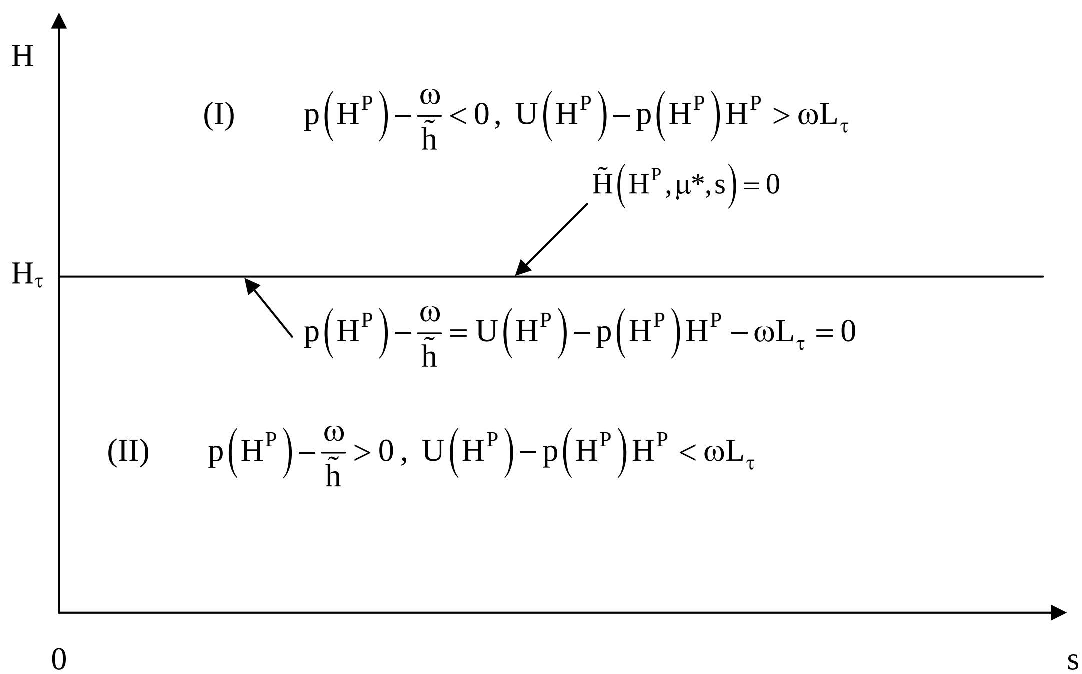
$$\tilde{H}\left(H^P,\mu^*,s\right)=U\left(H^P\right)-p\left(H^P\right)H^P+\left[p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right]g\left(s\right)-\omega L_\tau=\left[p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right]g\left(s\right)=0,$$

which implies that $U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau$, the instantaneous consumer surplus generated by management is equal to ωL_τ. Since neither $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$ nor $U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau$ depend on s, their slopes are null. Therefore, in Case A, the fact that $\tilde{H}\left(H^P,\mu^*,s\right)=0$ intersects $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$ implies that $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=U\left(H^P\right)-p\left(H^P\right)H^P-\omega L_\tau=0$: the zero profit line and the surplus line overlap completely. In Case A, given a demand function, a wage rate, and a marginal productivity of labor per harvester ($\tilde{h}$), only one specific fixed amount of resource management labor, L_τ, can make this equality hold. This is therefore a special case and most possible cases will differ from it.

Figure 5.9 illustrates Case A, where the zero profit line and $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ intersect, as well as the different regions defined by them. In this special case, the locus $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ overlaps with the zero profit line and the surplus line as well. This is a case where open access is the second best optimal management regime for all feasible resource stocks, given that resource management is costly.

Figure 5.9. Regions delimited by the intersection of *loci* $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ and

$$p\left(H^P\right) - \frac{\omega}{\tilde{h}} = 0 .$$



In order to gain insight into more general cases, let us characterize the slope of the $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ locus. The slope of (5.34) is

$$\left.\frac{dH^P}{ds}\right|_{\tilde{H}(H^P,\mu^*,s)=0} = \frac{\left(p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right)g'(s)}{p'\left(H^P\right)\left[H^P-g(s)\right]}. \tag{5.35}$$

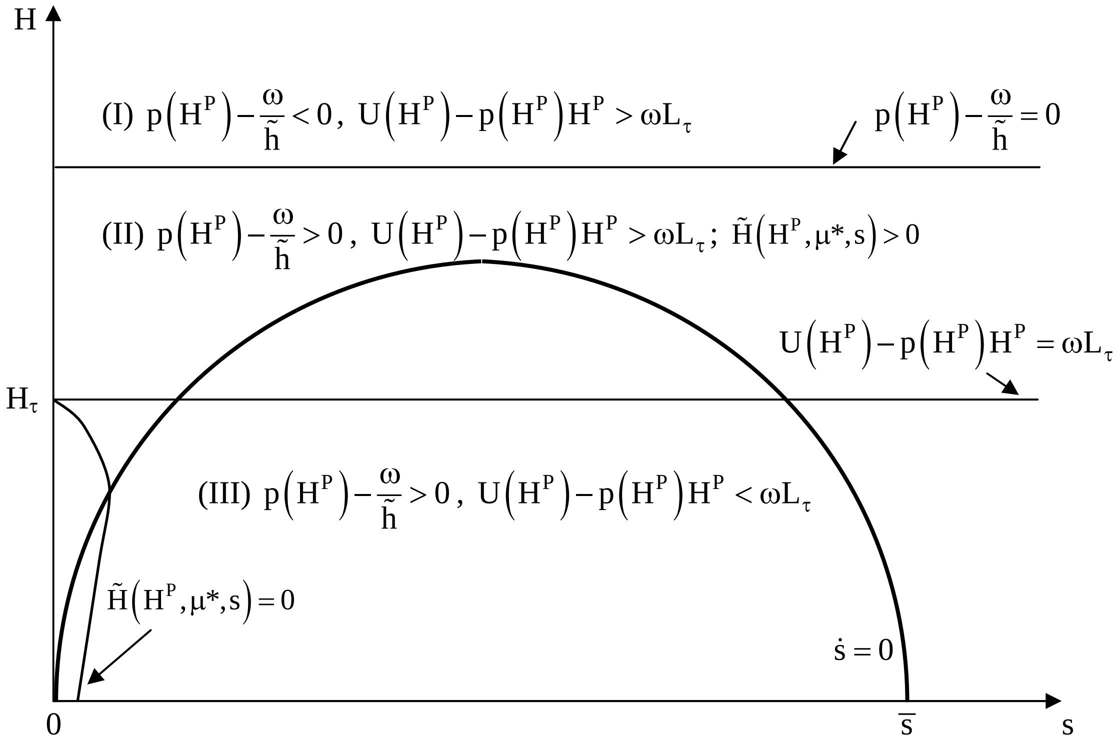
At s=0, $\tilde{H}\left(H^P,\mu^*,s\right)=0$ always coincides with the surplus locus, whether we are analyzing Case A, B or C.

Case B: The surplus locus is below the profit line for all feasible stocks.

In Case B $\left(p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right)>0$ at s=0. From (5.35), above the growth function where $H^P > g(s)$, the slope of the $\tilde{H}\left(H^P,\mu^*,s\right)=0$ locus is negative, as long as g'(s)>0. The slope is negative below the growth function, and it is infinite as it crosses the growth function.

Figure 5.10 illustrates Case B, where the surplus locus is below the zero profit line, as well as the different regions defined by them. The $\tilde{H}\left(H^P,\mu^*,s\right)=0$ locus is illustrated as well. As per (5.35), at s=0, the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ and the surplus locus coincide and the slope of $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is negative. The slope is infinite as $\tilde{H}\left(H^P,\mu^*,s\right)=0$ crosses the growth function, and it is positive below it. Therefore, the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is in region (III) of Figure 5.10. It could not be in region (II) since $\tilde{H}>0$ there. The locus could possibly be in region (I), but its slope at s=0 takes it away from that region.

Figure 5.10. Case B: $U(H^P)-p(H^P)H^P=\omega L_\tau$ lies below $p(H^P)-\frac{\omega}{\tilde{h}}=0$.



We now need to show that the $\tilde{H}(H^P,\mu^*,s)=0$ locus as illustrated in Figure 5.10 eventually reaches the horizontal axis at some point (s_h,0). At that point, equation (5.34) becomes

$$\begin{aligned}\tilde{H} &= U(0)-p(0)0+\left(p(0)-\frac{\omega}{\tilde{h}}\right)g(s_h)-\omega L_\tau \\ &= \left(p(0)-\frac{\omega}{\tilde{h}}\right)g(s_h)-\omega L_\tau=0\end{aligned} \tag{5.36}$$

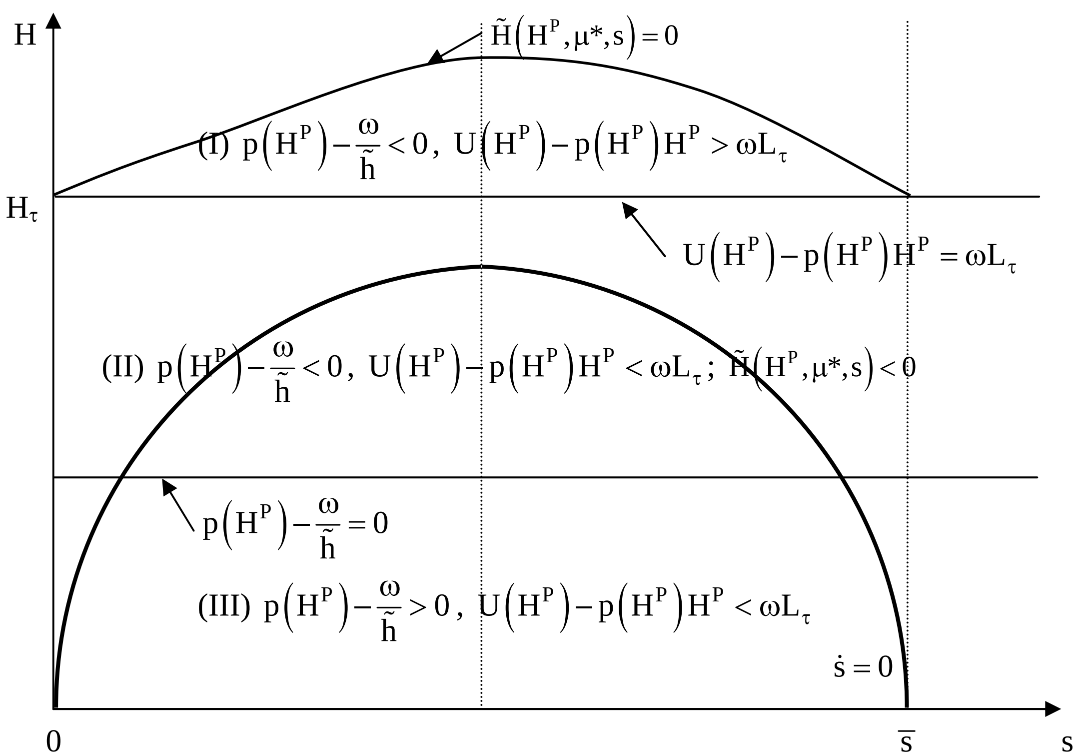
Since $\omega L_\tau>0$, and $\left(p(0)-\frac{\omega}{\tilde{h}}\right)$ are positive constants, it is through s_h that (5.36) holds.

Hence, $s_h=g^{-1}\left(\frac{\omega L_\tau}{p(0)-\frac{\omega}{\tilde{h}}}\right)$.

Case C: The surplus locus is above the profit line for all feasible stocks.

Case C implies that on the surplus locus, $\left(p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right)<0$. In that case, from (5.35), the sign of the slope of $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is positive at s=0, and the same as g'(s) for all feasible s. Hence it is negative at $s=\bar{s}$ and zero at the maximum sustainable yield, where g'(s)=0. Figure 5.11 illustrates this case.

Figure 5.11. Case C: $U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau$ lies above $p\left(H^P\right)-\frac{\omega}{\tilde{h}}=0$.



Let us figure out how the surplus line ($U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau$) is affected by a change in fixed flow cost of management, ωL_τ. Since ω is considered fixed by the resource manager, ωL_τ increases if L_τ, the quantity of labor required to manage the resource, increases. Using U'(H^P) = p(H^P), we find that

$$\left.\frac{dH^P}{dL_\tau}\right|_{U\left(H^P\right)-p\left(H^P\right)H^P=\omega L_\tau} = \frac{-\omega}{p'\left(H^P\right)H^P} > 0. \tag{5.37}$$

The surplus line moves up on the phase diagram as the required labor for resource management increases. Hence, with a relatively low cost of resource management, Case B occurs. As L_τ increases, special Case A is reached, and then Case C.

Let us now characterize how the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ changes in Case B as L_τ increases. Using (5.34), we find

$$\left.\frac{dH^P}{dL_\tau}\right|_{\tilde{H}=0} = \frac{\omega}{p'\left(H^P\right)\left[g\left(s\right)-H^P\right]}, \tag{5.38}$$

which means that H^P increases above the growth function (since $\left[g\left(s\right)-H^P\right]$<0) and decreases below the growth function if L_τ increase. Also, we find that

$$\left.\frac{ds}{dL_\tau}\right|_{\tilde{H}=0} = \frac{\omega}{\left[p\left(H^P\right)-\frac{\omega}{\tilde{h}}\right]g'\left(s\right)}, \tag{5.39}$$

which implies that the stock increases as L_τ increases as long as g'(s)>0: the stock is smaller than the maximum sustainable yield. Overall then, as L_τ increases, the area encompassed by the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$, and therefore the area for which $\tilde{H}\left(H^P,\mu^*,s\right)<0$, increases.

Now let us do the long run analysis, *i.e.*, the analysis that takes general equilibrium considerations into account, so we can plot the general equilibrium phase diagram. While the resource manager does not take these considerations into account directly, he will perceive that the parameters of the economy change as the resource stock changes and we assume he will adjust accordingly. The parameter that changes as the resource stock changes under management is the wage rate: $\omega = \omega(s)$ and $\omega'(s) > 0$, as reported in Table 5.3. Hence both the zero profit line and the surplus locus will move as the resource stock does.

In the long run, the zero profit line is $p(H^P) - \frac{\omega(s)}{\tilde{h}} = 0$. Its slope is no longer null but instead $\frac{dH^P}{ds} = \frac{\omega'(s)}{p'(H^P)} < 0$.[16] Similarly, the surplus locus is $U(H^P) - p(H^P)H^P = \omega(s)L_\tau$ and its slope is $\frac{dH^P}{ds} = \frac{-\omega'(s)L_\tau}{p'(H^P)H^P} > 0$. These long term zero profit and surplus *loci* can cross or not, leading to three long term cases as depicted in Figures 5.12-5.14.

Figure 5.12 illustrates general equilibrium Case A_{GE}, where the zero profit line and $\tilde{H}(H^P, \mu^*, s) = 0$ intersect, as well as the different regions defined by them. Figure

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[16] The equation $p(H^P) - \frac{\omega(s)}{\tilde{h}} = 0$ is used here only for the purpose of characterizing the locus $\tilde{H}(H^P, \mu^*, s) = 0$ in general equilibrium. In this model where instantaneous returns do not depend the s(t), actual open access behavior (zero profit path) implies a fixed division of labor in general equilibrium, and therefore, a fixed wage rate, ω, as shown in section 5.3.1.

5.13 illustrates Case B_{GE}, where the surplus locus is below the zero profit line for all feasible stocks. Figure 5.14 shows Case C_{GE}, where the surplus locus is above the profit line for all feasible stocks.

We want to characterize the shape of the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ in these figures. In general equilibrium, we substitute ω by $\omega(s)$ in (5.34) and obtain

$$\tilde{H}=U\left(H^P\right)-p\left(H^P\right)H^P+\left(p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}\right)g(s)-\omega(s)L_\tau=0\,. \qquad (5.40)$$

As before, at s=0, the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ coincides with $U\left(H^P\right)-p\left(H^P\right)H^P=\omega(s)L_\tau$ in all three cases. The slope of $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is

$$\left.\frac{dH^P}{ds}\right|_{\tilde{H}\left(H^P,\mu^*,s\right)=0}=\frac{\left(p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}\right)g'(s)-\omega'(s)\left[\frac{g(s)}{\tilde{h}}+L_\tau\right]}{p'\left(H^P\right)\left[H^P-g(s)\right]}\,. \qquad (5.41)$$

We keep a similar nomenclature as impartial equilibrium (Case A, B and C become A_{GE}, B_{GE} and C_{GE}), but we analyze the cases in reverse order. The simplest case is Case C_{GE}, illustrated in Figure 5.12; the surplus line lies above the zero profit line. At s=0, since $\tilde{H}\left(H^P,\mu^*,s\right)=0$ coincides with $U\left(H^P\right)-p\left(H^P\right)H^P=\omega(s)L_\tau$, and the surplus line is above the zero profit line, then $\left(p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}\right)<0$. Also, at that point, $\left[H^P-g(s)\right]=H^P>0$. Since $g'(0)>0$, then $\left.\frac{dH^P}{ds}\right|_{\tilde{H}\left(H^P,\mu^*,s\right)=0}>0$ at s=0. Notice that at $s=\overline{s}$, $\tilde{H}\left(H^P,\mu^*,s\right)=0$ coincides with $U\left(H^P\right)-p\left(H^P\right)H^P=\omega(s)L_\tau$ as well. Since

$\omega'(s)\left[\frac{g(s)}{\tilde{h}}+L_\tau\right]>0$ for all feasible stocks and since $g''(s)<0$, we could have

$\left.\frac{dH^P}{ds}\right|_{\tilde{H}(H^P,\mu^*,s)=0}=0$ at a stock such that $s_{MSY}<s<\bar{s}$, or the slope could remain positive for the entire range of feasible stock. Hence in Case C_{GE}, open access is the second best management regime for all feasible stocks.

A slightly more complicated case is Case B_{GE}, illustrated in Figure 5.13. As usual, at s=0, $\tilde{H}(H^P,\mu^*,s)=0$ coincides with $U(H^P)-p(H^P)H^P=\omega(s)L_\tau$. Since the surplus line is below the zero profit line for all feasible stocks, then

$\left(p(H^P)-\frac{\omega(s)}{\tilde{h}}\right)>0$ for all feasible stocks. Also, at s=0, $\left[H^P-g(s)\right]=H^P>0$. From (5.41), the slope of the locus $\tilde{H}(H^P,\mu^*,s)=0$ is indeterminate at s=0. However, if it were positive, the locus $\tilde{H}(H^P,\mu^*,s)=0$ would be in the area between the zero profit line and the surplus line where we know that $\tilde{H}(H^P,\mu^*,s)>0$. This means that the only possibility in Case B_{GE} is $\left.\frac{dH^P}{ds}\right|_{\tilde{H}(H^P,\mu^*,s)=0}<0$ at s=0. If $\tilde{H}(H^P,\mu^*,s)=0$ crosses the growth function, $\left.\frac{dH^P}{ds}\right|_{\tilde{H}(H^P,\mu^*,s)=0}=\infty$, and then below the growth function, the slope is positive. Alternatively in Case B_{GE}, it is possible that the $\tilde{H}(H^P,\mu^*,s)=0$ locus has a null slope at some positive stock and then a positive slope before meeting the surplus line again at $s=\bar{s}$. This possibility occurs for higher fixed flow of management costs as it leads to open access for all possible stocks. Both possibilities are illustrated on Figure 5.13 as $\tilde{H}_A\left(H^P,\mu^*,s\right)=0$ and $\tilde{H}_B\left(H^P,\mu^*,s\right)=0$.

The most complicated case is Case A_{GE}, illustrated in Figure 5.14. From the partial equilibrium analysis of Figure 5.11 and the general equilibrium analysis of Figure 5.12, we know that at stocks greater than the stock where the zero profit and the surplus lines intersect, the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is above the surplus and zero profit lines. At the intersection, locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ also intersects the two lines and from (5.41), its slope is positive at the intersection because $\left(p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}\right)=0$ and $\left[H^P-g(s)\right]>0$.

We know that at s=0, the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ and the surplus line coincide at H_τ. Also, at s=0, the slope of $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is negative. Since the locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ is continuous, we conclude that its slope becomes null as s increases, and then it becomes positive so the locus reaches the intersection of the zero profit and surplus lines from the left hand side as well. The locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ never crosses the growth function since its slope would be reversed under the growth function and it would move away from the intersection between the zero profit and the surplus lines. See Figure 5.14. We conclude that in Case A_{GE}, open access is the second best management for all feasible stocks. Hence only in Case B_{GE}, where the surplus line lies below the zero profit line, do we have costly resource management for higher stocks.

As the fixed flow of management cost varies, locus $\tilde{H}\left(H^P,\mu^*,s\right)=0$ varies in a similar way as we found before. Indeed, H^P varies in the same way as in the partial equilibrium (see equation (5.38)): above the growth function, H^P increases as L_τ increases, and below the growth function, it decreases as L_τ decreases. Therefore, as the fixed flow of management cost increases, the area for which $\tilde{H}\left(H^P,\mu^*,s\right)<0$ expands, like was found in the partial equilibrium analysis.

Figure 5.12. Case C_{GE}: $U\left(H^P\right)-p\left(H^P\right)H^P=\omega(s)L_\tau$ lies above $p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}=0$.

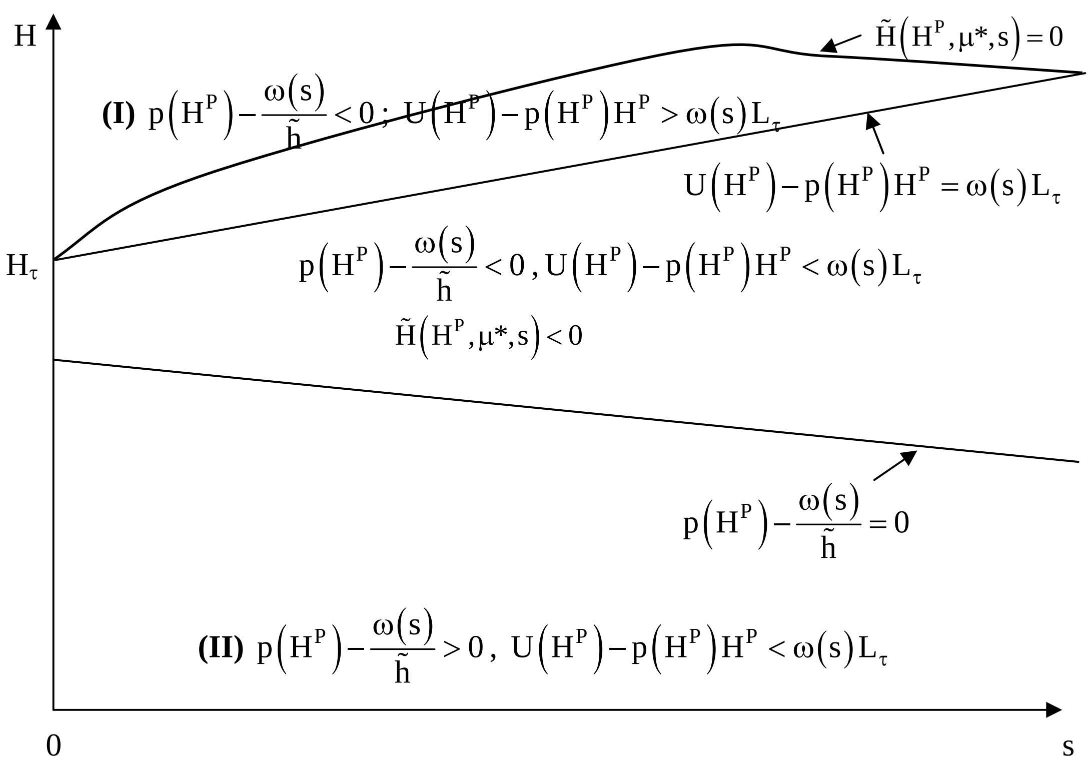


Figure 5.13. Case B_{GE}: $U\left(H^P\right)-p\left(H^P\right)H^P=\omega(s)L_\tau$ lies below $p\left(H^P\right)-\frac{\omega(s)}{\tilde{h}}=0$.

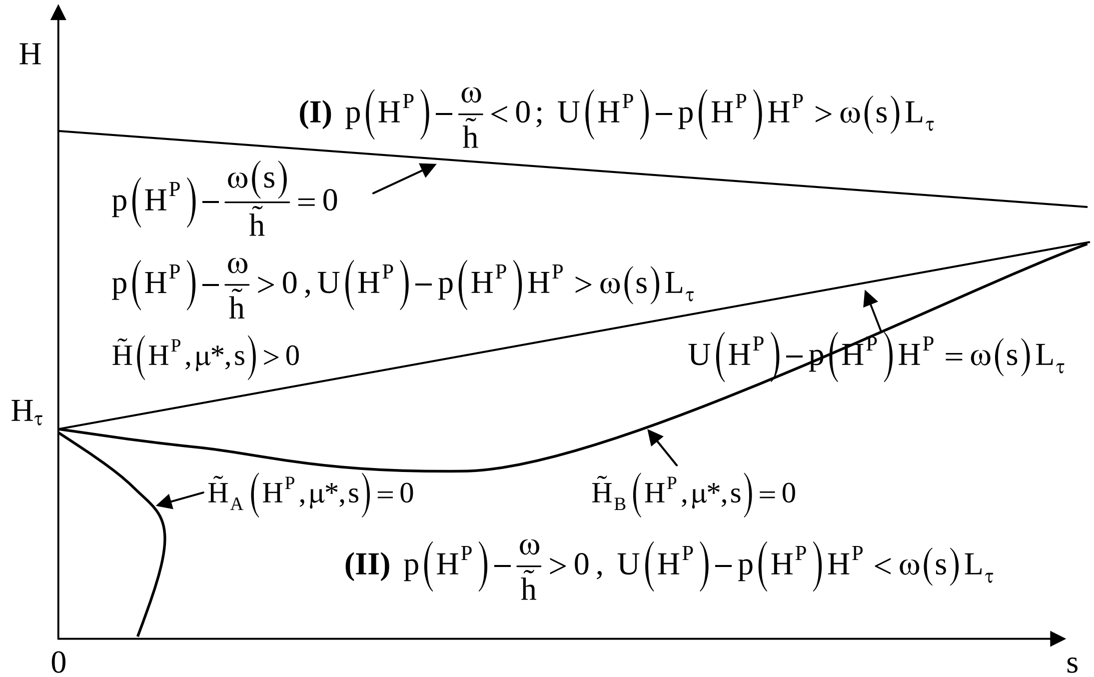
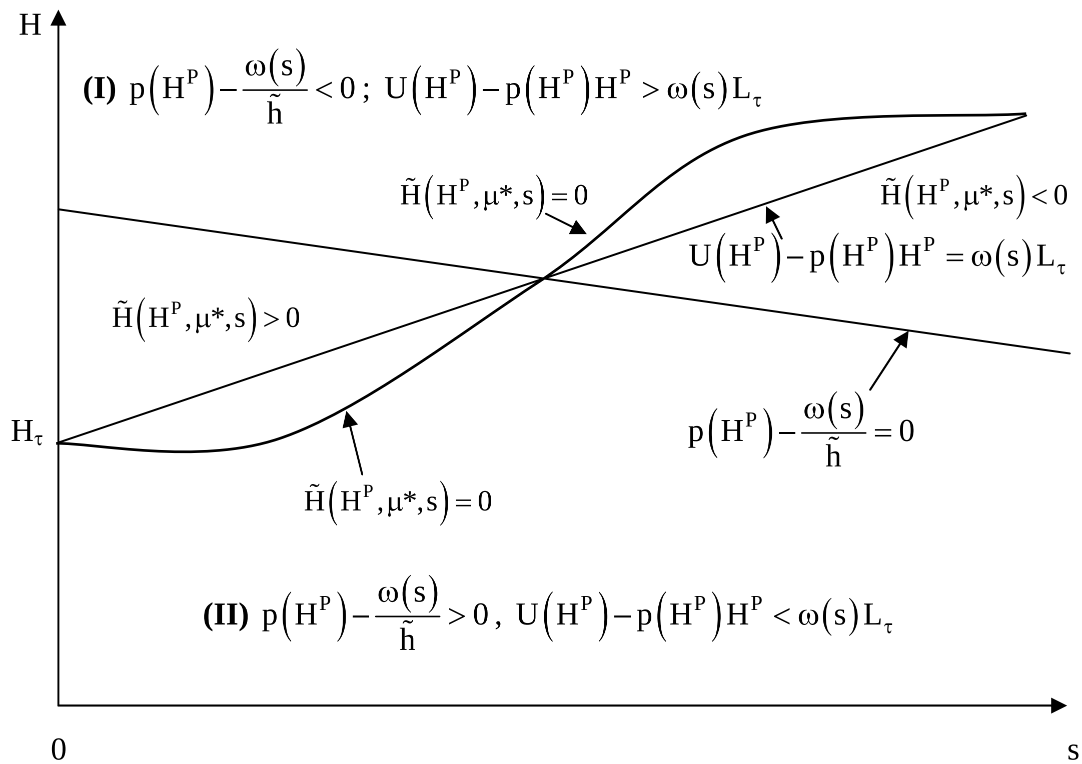


Figure 5.14. Case A_{GE}: $U(H^P) - p(H^P)H^P = \omega(s)L_\tau$ and $p(H^P) - \frac{\omega(s)}{\tilde{h}} = 0$ intersect.



We are now ready to do the trade analysis with the possibility that open access or costly management can be second best optimal. We assume that when the country opens to free trade, the resource stock is above the maximum sustainable yield, where g'(0)=0.

Cases C_{GE} and A_{GE}, presented in Figures 5.12 and 5.14, lead to open access exploitation for all stocks. In Case B_{GE}, presented in Figure 5.13, we found that costly management for could be second best optimal for larger stocks. In the long run, what matters is if $\tilde{H}(H^P, \mu^*, s_\infty^*) < 0$ or if $\tilde{H}(H^P, \mu^*, s_\infty^*) \geq 0$. Only in the later case could we reach the optimal steady state. Otherwise, open access is preferred at s= s_∞^* and extinction could eventually occur due to open access exploitation.

In the next section, we examine the impact of free trade on welfare and conservation in the home country.

5.6.1. Free trade: temporary and long-run *equilibria*

The equilibrium autarky price just before trade opens is noted p_{∞}^{A}. We assume that a steady state, s_{∞}^{A}, has been attained in open access in autarky, such that $g'\left(s_{\infty}^{A}\right) \leq 0$. Hence the resource is conserved in autarky. Again, let us look at the two cases: $p^{W} > p_{\infty}^{A}$ and $p^{W} < p_{\infty}^{A}$.

Case 1. $p^{W} > p_{\infty}^{A}$

Results in Case 1 depend on how large p^{W} is in relation to the parameters of the home country. Scenario (i) occurs if the home country has a *relatively small* comparative advantage in the resource good. In this scenario, p^{W} is greater than p_{∞}^{A}, but not be enough to trigger costly management. There are two possible outcomes in that scenario. The first outcome occurs as open access leads to greater harvest, but instantaneous harvest smaller than the maximum sustainable yield harvest. In that outcome, the resource is conserved and welfare is greater immediately as the country opens to trade and forever after. The second outcome occurs if open access leads to greater harvest that is larger than the maximum sustainable yield harvest. In that outcome, the resource becomes extinct. Welfare is greater than in autarky immediately as the country opens to trade but it is smaller once extinction occurs. The change in discounted welfare between free trade and the autarkic alternative is therefore ambiguous. This outcome is the worst-case scenario where free trade allows greater exchange possibilities, but exacerbates the open access exploitation problem, which ultimately impoverishes the home country.

Scenario (ii) occurs if the home country has an *important* comparative advantage in the resource good. In this scenario, the difference between p^W and p_∞^A is large enough to trigger costly management. Initially the resource stock decreases under costly management. Two outcomes exist in this scenario as well. The first outcome occurs if $\tilde{H}\left(H^P, \mu*, s_\infty^*\right) \geq 0$. In this outcome, the steady state is the infinite horizon steady state, s_∞^*. This outcome is a complete success story of free trade, because free trade not only generates more wealth but also triggers institutional changes for resource management that lessen the dynamic distortion in the home country. Welfare is initially greater than under autarky and discounted welfare from free trade is greater than in autarky. Steady state welfare may be greater or lower than in autarky. In the second outcome of scenario (ii), $\tilde{H}\left(H^P, \mu*, s_\infty^*\right) < 0$, so under costly management a finite horizon path is followed until the open access zero profit line [17] and the $\tilde{H}\left(H^P, \mu*, s\right) = 0$ locus [18] are reached simultaneously. Afterwards, the resource is exploited in open access and extinction is eventually reached. Initial welfare is greater than in autarky, steady state

[17] The finite horizon transversality condition $\mu * s = 0$ is respected since $\mu* = 0$.

[18] This is the necessary condition for a resource management regime change as found in APPENDIX IV.

welfare is lower and the change in discounted welfare in free trade compared to autarky is ambiguous.

Let us analyze both scenarios in more details.

Scenario (i): open access under free trade

In scenario (i) of Case 1, even though $p^W > p_\infty^A$, open access can still be the preferred resource exploitation regime under free trade. This is because the cost of management, $\omega(t)L_T$, could still be prohibitively high and render resource management welfare-decreasing as compared to open access exploitation. The comparative advantage is not advantageous enough for the management cost to be worth incurring.

Proposition 5.10.

In scenario (i) of Case 1, as the home country opens to free trade, it produces more resource good and may or may not specialize in it. In any case, welfare is higher initially. The resource good is exported, and the manufactured good is imported. In the first outcome, under free trade, harvest is smaller or equal to the resource maximum sustainable yield, *i.e.*, $H^P = N\tilde{\ell}_h\tilde{h} \le g(s_{MSY})$, so this equilibrium is sustainable in the long run; in such a case, utility is higher than in autarky forever, and therefore discounted utility is greater. In the second outcome of this scenario, harvest is greater than the resource maximum sustainable yield, *i.e.*, $H^P = N\tilde{\ell}_h\tilde{h} > g(s_{MSY})$. As a result, extinction occurs in finite time. The home country must then export some $M^P(t)$ in order to import some $H^C(t)$, even though $p^W > p^A_\infty$. Utility is lower thereafter, although utility discounted to the time when trade opens could be higher or lower than it would have been in autarky since it is initially higher until extinction is reached.

Proof.

See the proof of Proposition 5.1 in section 5.3.6. □

In this second outcome of scenario (i), therefore, second best management could lead both to extinction, to a decrease in steady state welfare, and possibly to lower discounted inter-temporal welfare as compared to the autarkic steady state alternative. This scenario is the least appealing for free trade; autarky could be better, both for welfare and conservation, even though with trade, open access is second best optimal from the resource planner's standpoint. Hence, trade can be inter-temporally welfare-decreasing, even with "proper" management, *i.e.*, second best management.

For illustrative purposes of Proposition 5.10, see Figure 5.15, in which welfare is unambiguously increased with free trade and the resource is conserved (scenario (i)), and Figure 5.16, in which the resource becomes extinct with free trade, and steady state welfare is decreased; again, discounted welfare could also be lower than it would have been in autarky (scenario (ii)).

Figure 5.15. One possible second best outcome; scenario (i)

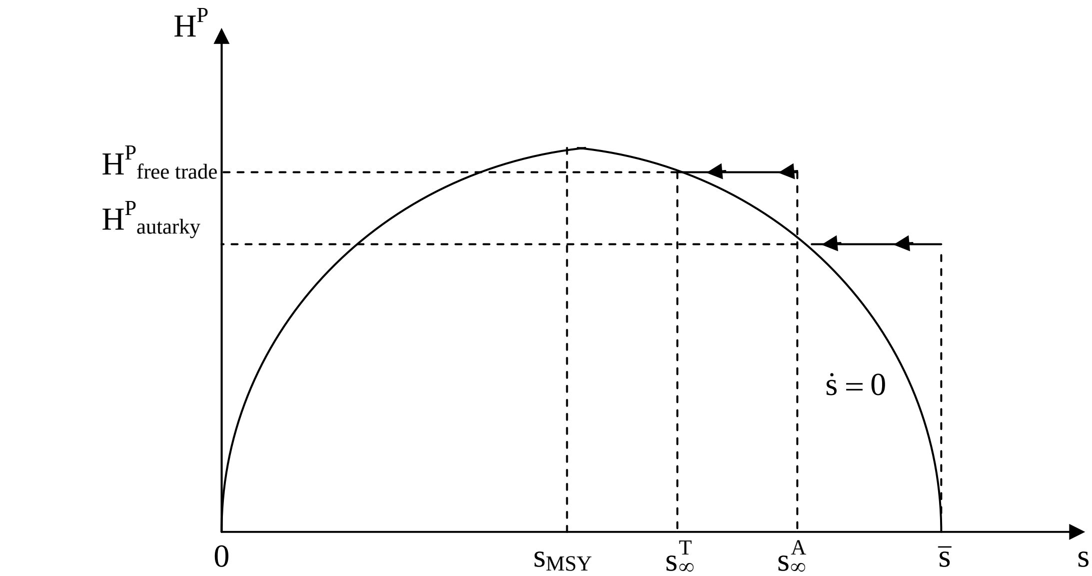
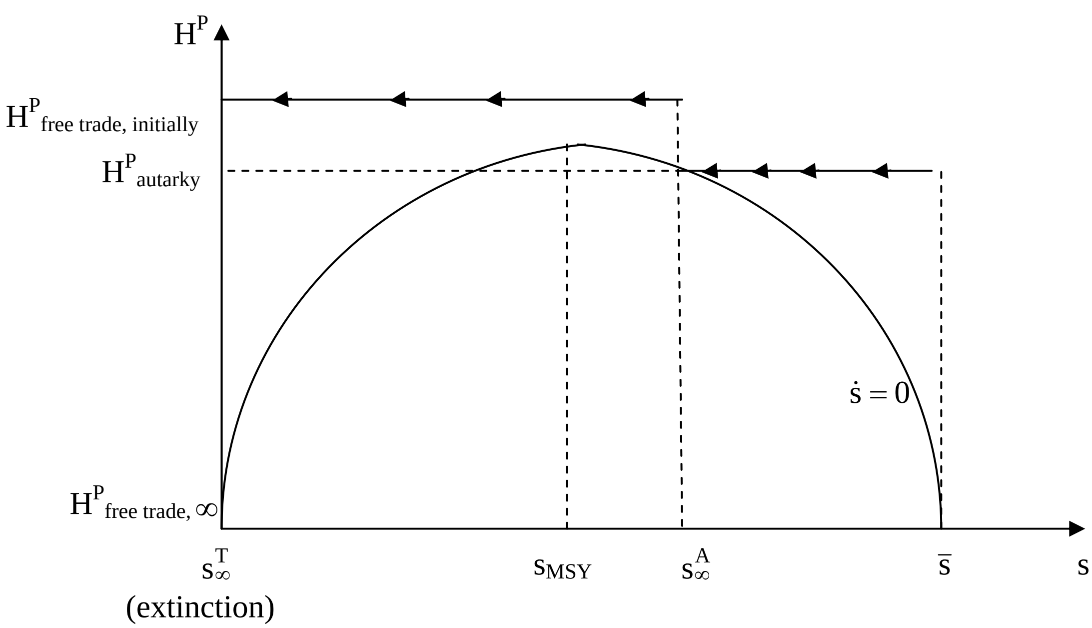


Figure 5.16. Another possible second best outcome; scenario (i)



Scenario (ii): costly management under free trade

In this scenario, we assume that the comparative advantage of the home country in the resource good is important, which leads to costly management at the moment when the country is opened to free trade. This means that the world price p^W is equal or greater than the critical relative world price (which depends on the resource stock), $p_C^W\left(s\left(t\right)\right)$. The critical relative world price is the minimum price that triggers a change from open access exploitation to costly resource management. Hence, $p_C^W\left(s\left(t\right)\right)$ is such that $\tilde{H}\left(H^P, \mu^*, s_\infty^A\right) = 0$ under free trade. In scenario (ii) therefore, $p^W \geq p_C^W\left(s\left(t\right)\right)$.

Proposition 5.11a.

In scenario (ii) of Case 1, where free trade triggers resource management, then H^P initially increases, M^P initially decreases, consumption in H^C decreases and M^C increases. H^P is exported and M^C is imported.

Initial welfare increases, but it decreases as the resource stock and H^P decrease, and as M^P increases. There could be trade reversal at some point, if H^P decreases and M^P increases enough. Welfare would then be lower than it would have been in autarky, and it would be so until the new steady state, s_∞^T, is reached. As long as $g'\left(0\right) > \delta$, s_∞^T is such that $g'\left(s_\infty^T\right) = \delta$. Hence, the resource is conserved in the long run.

Regardless of the instantaneous welfare comparison with autarky, discounted welfare is higher than it would have been in autarky, regardless of steady state welfare.

Proof.

The new terms of trade imply that initially H^P increases, M^P decreases, consumption in H^C decreases and it increases in M^C. Initially, some H^P is exported and some M^C is imported. Therefore, initial welfare increases: $dv = \frac{\partial v}{\partial Y}\left[H^P - H^C\right]dp > 0$.

However, there could be trade reversal on the optimal path, if H^P decreases and M^P increases until $p^W = \frac{u_H}{u_M} < \frac{H^P{}'\left(L_H(t)\right)}{M^P{}'\left(L - L_H(t) - L_\tau\right)} = \frac{\tilde{h}}{M^P{}'\left(L - L_H(t) - L_\tau\right)}$. Then welfare would be lower than it would have been in autarky. It would be so until the new steady state s_∞^T is reached because H^P decreases and M^P increases until then. In that case, steady state welfare would be lower than it would have been in autarky.

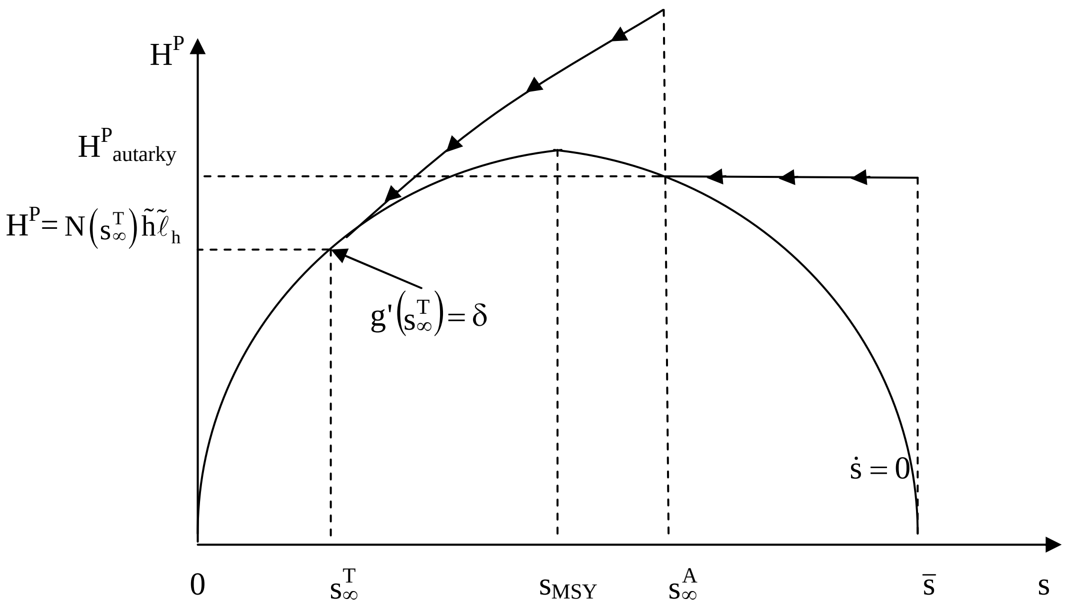
However, if resource management is chosen between the initial free trade resource stock and the steady state resource stock, s_∞^T, such that $g'\left(s_\infty^T\right) = \delta$, then by the Maximum Principle, it must lead to a higher discounted stream of welfare than open access would.

If steady state harvest in free trade is greater or equal to the steady state harvest in autarky, *i.e.*, $\left(H^P\right)_\infty^T > \left(H^P\right)_\infty^A$, then, given the terms of trade, steady state welfare is unambiguously greater in free trade than in autarky: $dv = \frac{\partial v}{\partial Y}\left[H^P - H^C\right]dp > 0$.

However, if $\left(H^P\right)_\infty^T < \left(H^P\right)_\infty^A$, then for a large enough difference in the steady state harvests, steady state welfare could be smaller than in autarky. However, discounted welfare is greater in free trade with management than in autarky under open access, even if instantaneous welfare is lower than in autarky for part of the optimal path in free trade.

See Figure 5.17 for the outcome of scenario (ii) treated in Proposition 5.11a. In relation to the location of locus $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ on the phase diagram, the critical world price, $p^W_{c,\infty}$, above which conservation occurs and below which we could have extinction is given by condition $\tilde{H}\left(H^P, \mu^*, s^*_\infty\right) = 0$. The only instance of locus $\tilde{H}\left(H^P, \mu^*, s\right) = 0$ under which management can occur is Case B_{GE} (see Figure 5.13, locus $\tilde{H}_A\left(H^P, \mu^*, s\right) = 0$).

Figure 5.17. One possible second best outcome; scenario (ii)



Proposition 5.11b.

In this other possible outcome of scenario (ii), the home country's comparative advantage in the resource good triggers resource management as the country is opened to free trade, Hence H^P initially increases, M^P initially decreases, consumption in H^C

decreases and M^C increases. H^P is exported and M^C is imported. Consequently, initial welfare increases

As the stock decreases, open access becomes second best optimal (because $\tilde{H}\left(H^P, \mu^*, s_\infty^*\right) < 0$). This means that extinction eventually occurs and from that time on, welfare is lower than in autarky. Welfare is initially higher than in autarky and it is lower in the long run. The change in discounted welfare due to the free trade regime as compared to the autarkic steady state is ambiguous.

Proof.

For the portion of the transitory path where costly management is second best optimal, the proof proceeds as for Proposition 5.11a. For the portion where open access is optimal, the proof proceeds as that of Proposition 5.1, section 5.3.6. □

See Figure 5.18[19] for the outcome of scenario (ii) treated in Proposition 5.11b.

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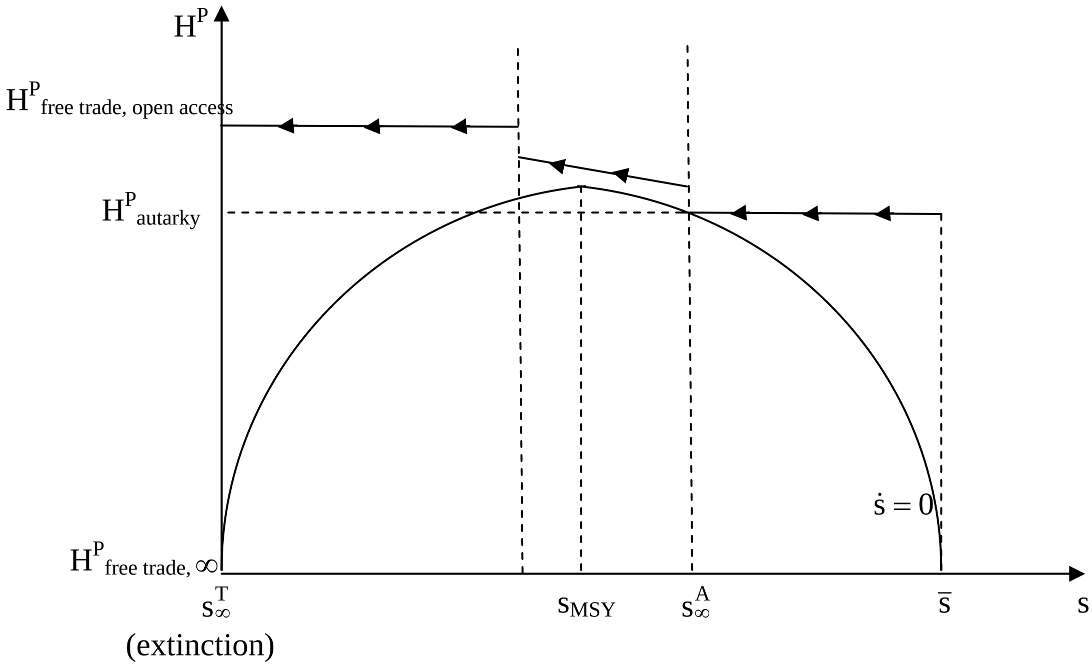
[19] In Figure 5.18, there is a discrete jump in harvest between the open access and second best management regime. This is due to the full employment constraint and the homotheticity of preferences, which together imply that the fixed management input, L_τ, must be diverted towards, the resource sector in part and the manufactures sector in part. There is a corresponding jump up in the relative wage rate in the home country.

Figure 5.18. Another possible second best outcome; scenario (ii)



Case 2. $p^W < p^A_\infty$

Results here are as in the same case for the open access model: welfare is unambiguously improved and extinction is prevented.

Proposition 5.12.

If $p^W < p^A_\infty$, the home country produces more manufactures than in autarky, and it may or may not specialize in it. In either the diversified case or the specialized case, the long run equilibrium stock with free trade, s^T_∞, is such that $H^P\left(L - L^T_M\right) = g\left(s^T_\infty\right)$ and $s^T_\infty > s^A_\infty$. Therefore extinction cannot occur in this case due to trade. Also, manufactures are exported and the resource good is imported. Furthermore, utility is higher initially and forever. Hence overall, welfare is unambiguously improved, both inter-temporally and in steady state.

Proof.

See the proof of Proposition 5.2 in section 5.3.6. □

When $p^W < p^A_\infty$, even though the resource may remain exploited under open access, there are net gains from trade because the dynamic externality due to the open access exploitation regime is lessened under diversification or altogether eliminated if there is specialization in the manufactures. Also, usual gains from trade are realized by producing more manufactures. Overall then, welfare is unambiguously improved.

The results of a change in trade regime with costly resource management are summarized in Table 5.6 and Table 5.7.

Table 5.6. Second best resource management with trade, Case 1: $p^W > p_\infty^A$.

Steady state autarky resource management regime	Steady state free trade resource management regime	Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Open access	Open access[20]	Conservation	+	+	+	Prop. 5.10 Fig. 5.15
		Extinction	-	-	+	Prop. 5.10 Fig.5.16;
		Extinction	-	-	-	Prop. 5.11b Fig. 5.18
	Effective costly management	Conservation	+ or -	+ or -	+	Prop. 5.11a Fig. 5.17
Effective costly management	Effective costly management	Conservation	No change	+	+	Prop. 5.8 Fig. 5.6

[20] With stock dependence of instantaneous net gains, welfare change could be negative even without extinction. This occurs, for example, in Brander and Taylor (1997a).

Table 5.7. Second best resource management with trade, Case 2: $p^W < p^A_\infty$.

Steady state autarky resource management regime	Steady state free trade resource management regime	Long-run impact of free trade on resource stock	Change in steady state harvest	Steady state welfare change due to trade	Discounted welfare change due to trade	Related Proposition(s) and Figure(s)
Open access	Open access	Conservation	-	+	+	Prop. 5.12 Fig. 5.3
Effective costly management	Effective costly management	Conservation	No change	+	+	Prop. 5.9a Fig. 5.7
	Open access	Conservation	-	+	+	Prop. 5.9b Fig. 5.8

5.7. Policy implications

In economics, it is common to hear that trade unambiguously raises welfare if proper environmental policies are in place. This is true only for the empirically irrelevant first best world where resource management is costless. However, due to costly resource management, "proper" management of the resource is less than perfect. In a second best world, where renewable resource management is not free, trade does not unambiguously raise welfare when "proper" environmental policies are in place. Some cases illustrating this finding have been shown.

A very contemporary question is whether freer trade helps or hinders environmental protection. We obtained a partial answer to this, by looking at whether or not free trade can cause the extinction of a renewable resource. The answer is yes, free trade can cause the extinction of a species. Therefore, we conclude that freer trade can hinder the environment. However, it could also help it, if it triggers better resource management, which can also happen in some cases. Therefore, there is ambiguity in the answer to this question; it depends on which case is considered.

In international trade theory, it is often said that the removal of trade restrictions and distortions can yield benefits for trading nations and for the environment. While this may be true for agricultural export subsidies for example, it is not so clear for environmental policies in general. In fact, we found that trade tariffs for a resource good can be second best optimal, when resource management is costly. Such policies can be welfare increasing for a resource good-exporting country with prohibitively high resource management cost. Let us recall that, for endogenous distortions, Bhagwati, Ramaswami and Srinivasan (1969) suggested trade tariffs and production factor tax-

cum-subsidy as competing second best policies when the first best policy is not feasible. In our model, a tax-cum-subsidy on factor input implies taxation on labor in the resource good sector. A tariff means that exporters of the resource good would pay some percentage of their export revenues. Both alternatives entail the collection and re-distribution of a tax or tariff.

Trade tariffs can also be beneficial for an resource good-importing country (importing from the home country) that values the *in situ* resource stock, and therefore may agree to bear part of the cost of conservation policy. Therefore, trade tariffs for the resource good can be second best optimal, as opposed to trade tariffs on "normal" (not resource-based) goods.

Given our results, an important question is: "In which cases must we be careful about free trade in the presence of a resource-based production sector?" In our model, if resource management is ineffective or weak in autarky, then the relative price increase due to trade needs to be either low enough to allow conservation in autarky (see Proposition 5.10, Figure 5.15) or high enough to trigger effective costly management leading to a positive steady state (see Proposition 5.11a, Figure 5.17). Otherwise, the losses due to greater harvest with ineffective resource management could overcome the gains from trade.

Knowing this, what can be done? Trade tariffs for the resource good are a possible type of policy, which in time could perhaps be decreased if some level of trade-based growth promotes the improvement of resource management technology. Our model does not address this possibility directly however, and it seems like an interesting subject for future research.

Aid in the form of technology transfer and expertise could also be considered, but their positive effect on resource management would be long term. Such international cooperation already exists under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). CITES, an international environmental voluntary agreement, was introduced in 1973, to keep track of renewable resources being traded worldwide, to protect them from illegal trade and possibly from extinction. CITES policies generally are trade quotas and trade bans. We note however that our model serves to show that free trade can be welfare-decreasing for nations that have ineffectively managed resources *in general*, not endangered resources only. Unfortunately, current policy under CITES only covers the resources that are in danger of extinction, and WTO policy prevents trade tariffs unless a species is covered under CITES. Hence, there seems to be a gap in current policy relating to renewable resources that are traded.

5.8. Conclusion

In this chapter, we have proposed a trade model where the benevolent resource planner's management is costly and therefore endogenous. This allows for the analysis of free trade impacts when resource management regimes other than the polar open access and first best regimes. Interestingly, the second best endogenous management considered is more realistic than the textbook first best policy prescription.

With a model where instantaneous net gains do not depend on the resource stock, and where resource management incurs an instantaneous fixed cost, we have characterized cases where a move from autarky to free trade is welfare increasing and cases where it could be welfare-decreasing. We have also shown that free trade can cause the extinction of a resource and that this is welfare decreasing, at least in steady state, but perhaps even when we consider the discounted stream of welfare under free trade. Overall, we have characterized the impact of free trade on social welfare and on the conservation of the resource under open access exploitation of the resource, in the first best management regime and under costly management of the resource, *i.e.*, under a second best policy. More specifically, in the second best model, we have characterized cases where the move from autarky to free trade can be welfare decreasing, and by extension, where some level of barrier to trade would be better.

Furthermore, we have considered second best, empirically relevant, resource management switches and characterized cases where the resource management regime could change as a result of a change in trade regime, going from autarky to free trade.

We have also characterized cases where the move from autarky to free trade can cause the extinction of the renewable resource. For this, we explicitly took the dynamic constraints and potential irreversibility into account, which are often ignored in renewable resource models that consider international trade and concentrate on positive steady state results only.

Finally, we want to make it clear that there are cases where trade is welfare increasing and where it also can help the environment. But knowing when it does not and why it may not is helpful for policy-making, which is what motivated this chapter.

CHAPTER 6. CONCLUSION

The main motivation for this dissertation was that while property right problems and policy prescriptions are clear, open access exploitation is still observed empirically. The fact that resource management is costly can explain empirical observations. Another motivation was the growing interest for the impact of free trade of natural resources. The empirically relevant resource management cost was identified as a distortion compared to the first best model, which leads to second best analyses. Costly resource management was considered not only in partial equilibrium, but also in trade analyses, where welfare and resource conservation were analyzed, moving from autarky to free trade. For this, we have developed applied theoretical bio-economic models to analyze renewable resource dynamic problems in continuous time, making use of the Maximum Principle developed in optimal control theory.

In Chapters 3 and 4, we developed partial equilibrium models, where management cost was assumed to be either an enforcement cost against poaching or an instantaneous fixed cost of tax collection and re-distribution. In Chapter 3, we have characterized the optimal policy for the management of a scarce renewable resource. We have explained how it may be optimal to observe legal and illegal harvests separately or simultaneously. Furthermore, we provided policy prescriptions for a scarce renewable resource that is owned by a sole owner who wishes to act as a monopolist (the pseudo-monopolist). We have also considered resource non-market values, and we provided policy prescriptions that take them into account. In Chapter 4, we considered resource management regime switches, and found that resource management costs can affect the conservation of the resource negatively, irrespective of the discount rate.

In Chapter 5, international trade was explicitly considered. We characterized the impact of free trade on social welfare and on the conservation of the resource under different resource management regimes. We showed that the empirically relevant second best management regimes and regime switches can render free trade discounted welfare decreasing, even with "proper" management. In such instances, some level of barrier to trade would be better than free trade. We have also shown that in the empirically relevant second best model, free trade can cause the extinction of the renewable resource, which we interpret as free trade hurting the environment. In the debate over international trade and the environment, rather than taking a one-sided stance, we find it important to understand the pros and cons of free trade, so that proper policy can be put in place.

The importance of relative resource management costs is likely greater in poorer countries. Therefore, our findings are especially important for less developed economies that consider relying more on the export of their renewable resources to trigger economic growth. In some cases it may be a good solution, while in others, it can turn out to be immiserizing, even in terms of discounted welfare.

In future research, it would be interesting to investigate distributional issues, by replacing our implicit social welfare function with one that takes wealth distribution into account, both in partial equilibrium models and in trade frameworks. In relation to international trade, a natural extension to Chapter 5 would be the analysis of a trade model where net instantaneous gains would depend directly on the resource stock. Also, it would be interesting to go one step further and consider a growth model where initial trade-generated wealth can be invested into better resource management technologies instead of the home country passively moving towards potential doomsday.

APPENDIX I: DETAILS ON CITES-REGULATED SPECIES

Table I.A.1. Statistics on CITES-listed species

	Appendix I[a]			Appendix II[a]			Appendix III[a]		
	Spp[b]	Sspp[c]	Popns[d]	Spp	Sspp	Popns	Spp	Sspp	Popns
Mammals	228	21	13	369	34	14	57	11	0
Birds	146	19	2	1401	8	1	149	0	0
Reptiles	67	3	4	508	3	4	25	0	0
Amphibians	16	0	0	90	0	0	0	0	0
Fish	9	0	0	68	0	0	0	0	0
Invertebrates	63	5	0	2030	1	0	16	0	0
Plants	298	4	0	28074	3	6	45	1	2
Total	***827***	***52***	***19***	***32540***	***49***	***25***	***292***	***12***	***2***

Legend:

a: CITES listings: species in CITES Appendix I are most endangered and most severely regulated (trade bans typically); species in CITES Appendix II are less endangered and less regulated (trade quotas typically); species in CITES Appendix III are not endangered yet or their level of endangerment is unknown, and data is being collected on trade.

b: species;

c: sub-species;

d: populations.

APPENDIX II: STEADY STATE ANALYSIS, CROPPER *ET AL.* (1979)

In this appendix, we show how to obtain Figure 4.2 and Figure 4.3 in our model, by summarizing Cropper *et al.*'s (1979) analysis. For this, we use our two *loci* in (s,Q)-space:

$$\dot{s}(t) = g(s(t)) - Q(t) = 0 \tag{4.24}$$

and

$$\dot{Q}(t) = \frac{\left[P(Q(t)) - K(s(t))\right]\left[\delta - g'(s(t))\right] + K'(s(t))g(s(t))}{P'(Q(t))} = 0\,. \tag{4.26}$$

In (s, Q)-space, (4.24) is easy to draw for a compensatory biological growth function. However, locus (4.26) needs more analysis for plotting. Since P'(Q(t)) < 0, (4.26) implies that the following equation must hold along locus $\dot{Q}(t) = 0$:

$$\left[P(Q(t)) - K(s(t))\right]\left[\delta - g'(s(t))\right] + K'(s(t))g(s(t)) = 0\,. \tag{II.A.1}$$

To characterize the shape of $\dot{Q}(t) = 0$, we differentiate (II.A.1) and obtain

$$\left.\frac{dQ(t)}{ds(t)}\right|_{\dot{Q}(t)=0} = \frac{-K'(\delta - g') - g''(P-K) + K''g + K'g'}{-P'(\delta - g')} \tag{II.A.2}$$

From the assumptions on the different functions, the slope of $\dot{Q}(t) = 0$ is strictly positive for $s > s_m$ because $g'(s > s_m) < 0$. For $s < s_m$, it is indeterminate.

The line $P(Q) - K(s) = 0$ on both Figure 4.2 and Figure 4.3 separates the area that yield instantaneous positive net marginal benefit, below the line, and the area that does not, above it. Also, the slope of $P(Q(t)) - K(s(t)) = 0$ is positive:

$\left.\frac{dQ(t)}{ds(t)}\right|_{\substack{\pi(t)=0\\M=0}} = \frac{K'(s(t))}{P'(Q(t))} > 0$. Its second derivative with respect to s(t) is

$$\frac{d\left[\left.\frac{dQ(t)}{ds(t)}\right|_{\pi(t)=0}\right]}{ds(t)} = \frac{K''(s(t))}{P'(Q(t))} < 0$$, which means that the ($P(Q(t)) - K(s(t)) = 0$)-*locus*

is increasing and concave in (s,Q)-space. Also, as long as $g'(0) \neq \delta$, then the line $P(Q) - K(s) = 0$ and the locus $\dot{Q}(t) = 0$ coincide at $s = 0$ and at $s = \bar{s}$.

In order to gain insight into $\dot{Q}(t) = 0$ for the interval $s < s_m$, we separate the analysis in two, which will lead to two phase diagrams, depending on whether $\delta < g'(0)$, which leads to Figure 4.2 or $\delta > g'(0)$, which leads to Figure 4.3. Let us analyze them successively.

Phase diagram for δ < g'(0) (Figure 4.2 or II.1))

The stock level $\tilde{s}$ is such that $\delta = g'(\tilde{s})$. The position of $\dot{Q}(t) = 0$ when $\delta < g'(0)$ depends on which side of $\tilde{s}$ the locus is.

For $s < \tilde{s}$, since K'g < 0, then from (II.A.1) the optimal locus is such that $P(Q(t)) - K(s(t)) < 0$. Hence, $\dot{Q}(t) = 0$ lies above the line $P(Q(t)) - K(s(t)) = 0$, in the region where instantaneous net marginal benefit are negative. This means that any *equilibria* to the left of $\tilde{s}$ are suboptimal.

For $s > \tilde{s}$, $\dot{Q}(t) = 0$ lies below the line $P(Q(t)) - K(s(t)) = 0$. The only optimal steady states are therefore to the right of $\tilde{s}$. In order to prove that at least one steady state exists in the interval $(\tilde{s}, \bar{s})$ we have to show that the two *loci* intersect at least once in that interval.

The locus $\dot{Q}(t) = 0$ intersects the s-axis at $\hat{s}$, where $\hat{s}$ is the smallest stock level for which the following equation holds:

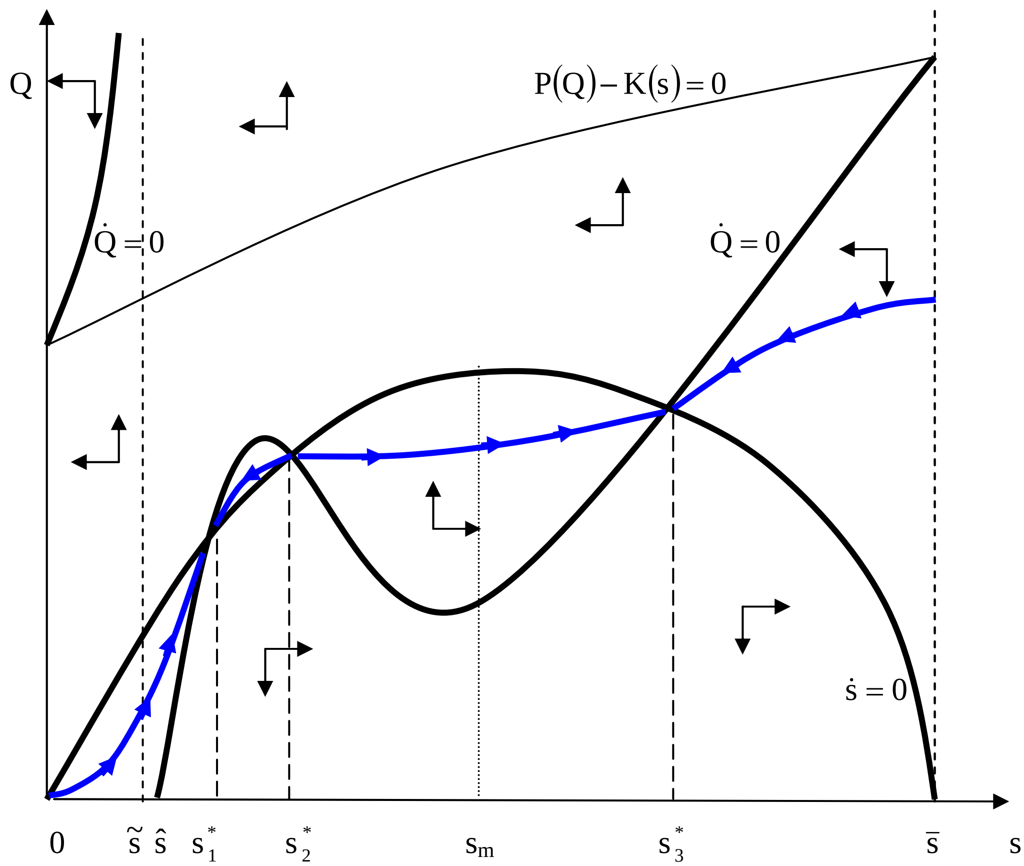
$$P(0) = \frac{-K'(s)g(s)}{\delta - g'(s)} + K(s) \equiv \Psi(s). \qquad \text{(II.A.3)}$$

Equation (II.A.3) is continuous. Since $\lim_{s \to \tilde{s}^+} \Psi(s) = \infty$ and $\lim_{s \to \tilde{s}^-} \Psi(s) = K(\bar{s}) < P(0)$, then equation (II.A.3) must have a solution in the interval $(\tilde{s}, \bar{s})$.

Since $\dot{Q}(t) = 0$ is below $\dot{s}(t) = 0$ at $\hat{s}$ and above it at $\bar{s}$, then it must intersect $\dot{s}(t) = 0$ at least once between these points. If it intersects it more than once, it must be an odd number of times.

Also, $\dot{Q}(t) = 0$ must intersect $\dot{s}(t) = 0$ from below first. This is because the first steady state stock, s_1^*, for which condition $P(g(s)) = \Psi(s)$, $\tilde{s} < s < \bar{s}$, necessarily lies to the right of $\hat{s}$. This is because $P(0) > P(g(s))$, $\tilde{s} < s < \bar{s}$, and $\Psi(s)$ is initially increasing in the interval $(\tilde{s}, \bar{s})$.

Figure II.1. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Costless Enforcement; $\delta < g'(0)$

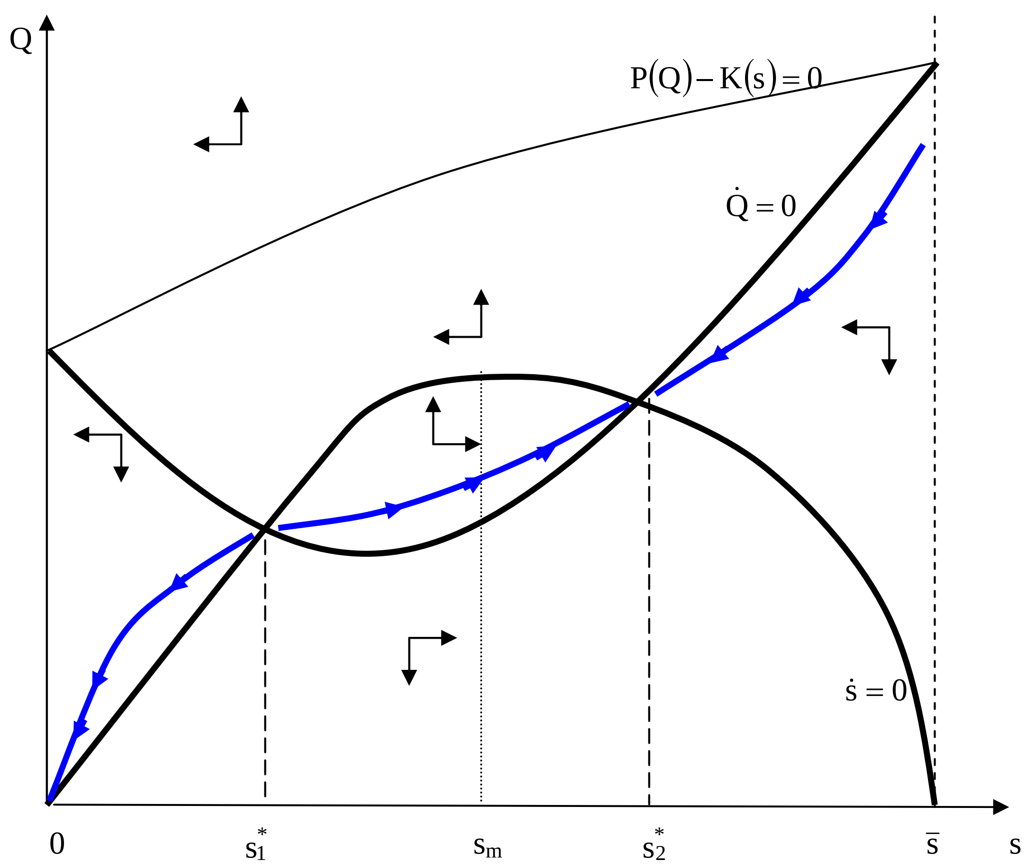


Phase diagram for δ > g'(0) (Figure 4.3 or Figure II.2)

In this case, (II.A.1) implies that $\dot{Q}(t) = 0$ is below the line $P(Q(t)) - K(s(t)) = 0$ for the entire domain of s. The parameter assumption $\delta > g'(0)$ does not restrict the slope of $\dot{Q}(t) = 0$ for s < s_m, but this slope is necessarily positive for the entire domain of s if $\delta > 2g'(0)$. In Figure 4.2, we have therefore assumed that $g'(0) < \delta < 2g'(0)$.

From the shape of $P(Q(t)) - K(s(t)) = 0$, the fact that it has a positive Q-intercept, and that $\dot{Q}(t) = 0$ coincides with it at $s = 0$ and at $s = \bar{s}$. This implies that $\dot{Q}(t) = 0$ and $\dot{s}(t) = 0$ intersect an even number of times or not at all. If there is at least one intersection, since $\dot{Q}(t) = 0$ has a positive Q-intercept, then $\dot{Q}(t) = 0$ must approach $\dot{s}(t) = 0$ from above. This means that s_1^* is an unstable steady state (saddlepoint).

Figure II.2. Steady State *Equilibria* with Stock-Dependent Harvest Costs and Costless Enforcement, $\delta > g'(0)$



APPENDIX III: NOTES ON WELFARE COMPARISONS FOR CHAPTER 5

A.III.1 Welfare comparisons using the indirect utility function in autarky

With homothetic utility functions, the expenditure function is written as $E(p,\mu) = e(p)\mu$, where μ is the utility level attained and $e(p) \equiv E(p,1)$ is the unit (utility) expenditure function. We note that e(p) can be interpreted as a price index or a "cost of living" index. By duality, the corresponding indirect utility function then takes the form:

$$v = v(p, Y) = Y/e(p) = \nu(p)Y . \tag{III.A.1}$$

Changes in welfare can be measured by changes in indirect utility as follows:

$$dv = \frac{\partial v(p,Y)}{\partial p} dp + \frac{\partial v(p,Y)}{\partial Y} dY . \tag{III.A.2}$$

We know that the economy's income is $Y = pH^P + M^P$. Therefore,

$$dY = H^P dp + pdH^P + dM^P . \tag{III.A.3}$$

This gives us a way of measuring welfare changes. Using (III.A.3), we obtain

$$\begin{aligned} dv &= \frac{\partial v(p,Y)}{\partial p} dp + \frac{\partial v(p,Y)}{\partial Y}\left(H^P dp + pdH^P + dM^P\right) \\ &= \frac{\partial v(p,Y)}{\partial Y}\left[\frac{\partial v(p,Y)}{\partial p}\frac{\partial Y}{\partial v(p,Y)} + H^P\right] dp + \frac{\partial v(p,Y)}{\partial Y}\left(pdH^P + dM^P\right). \end{aligned} \tag{III.A.4}$$

By Roy's identity, the first term of the factor in brackets $-H^C$. The factor in brackets is therefore the excess demand for H in the home country. In autarky, demand equals supply within the economy, and therefore

$$dv = \frac{\partial v(p,Y)}{\partial Y}\left(pdH^P + dM^P\right). \tag{III.A.5}$$

A.III.2 Welfare comparisons in free trade, using the indirect trade utility function

Since we assume no possibility of saving and borrowing, then we still have $Y = pH^P + M^P$ in free trade. We also suppose that prices are exogenous to the home country. That means that in equilibrium, $H^P = H^P(L_H(p))$ and $M^P = M^P(L_H(p))$. Therefore, using the first order condition of the GNP maximizing problem[21], we find

$$\begin{aligned}\frac{dY(p)}{dp} &= \left[H^P\left(L_H(p)\right) + \left[p\left(\frac{dH^P\left(L_H(p)\right)}{dL_H}\right) - \left(\frac{dM^P\left(L - L_H(p) - L_T\right)}{dL_H}\right)\right]\left(\frac{dL_H}{dp}\right)\right] \\ &= H^P\left(L_H(p)\right).\end{aligned} \tag{III.A.6}$$

This is Hotelling's lemma, which makes use of the envelope theorem. With this result, using the indirect *trade* utility function[22], we characterize the welfare changes due to free trade. Our small country assumption implies that price is exogenous. The indirect trade utility function is $v = v\left(p, Y(p)\right) = Y(p)/e(p) = \nu(p)Y(p)$. The welfare change is

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[21] The problem is $\underset{L_H}{\text{Max}}\, Y = pH^P\left(L_H\right) + M^P\left(L - L_H - L_T\right)$. Assuming an interior solution, the first order necessary condition is $p\dfrac{dH^P\left(L_H\right)}{dL_H} + \dfrac{dM^P\left(L - L_H - L_T\right)}{dL_H} = 0$, which leads to the unique solution $L_H = L_H(p)$.

[22] Woodland (1980) first used this terminology.

$$\begin{aligned}
dv &= \frac{\partial v(p, Y(p))}{\partial p} dp + \left(\frac{\partial v(p, Y(p))}{\partial Y(p)}\right)\left(\frac{dY(p)}{dp}\right) dp \\
&= \frac{\partial v(p, Y(p))}{\partial p} dp + \left(\frac{\partial v(p, Y(p))}{\partial Y(p)}\right) H^P\left(L_H(p)\right) dp \\
&= \frac{\partial v(p, Y(p))}{\partial Y(p)} \left[\left[\left(\frac{\partial v(p, Y(p))}{\partial p}\right) \Big/ \left(\frac{\partial v(p, Y(p))}{\partial Y}\right)\right] + H^P\left(L_H(p)\right)\right] dp.
\end{aligned}$$

The equation can be written more simply, by making use of Roy's Identity:

$$dv = \frac{\partial v(p, Y(p))}{\partial Y(p)} \left[H^P\left(L_H(p)\right) - H^C\right] dp. \tag{III.A.7}$$

Therefore, the change in welfare, dv, is proportional to the net export of the resource good, $[H^P - H^C]$.

APPENDIX IV. THE RESOURCE MANAGEMENT REGIME PROBLEM AND NECESSARY CONDITIONS

Much like in Chapter 4, in our trade model from Chapter 5, the social planner's problem of choosing between costly management and open access is a timing problem since switches can occur across management regimes as the resource stock varies. The timing of resource management regime switch(es) is a problem that includes the resource management sub-problems in open access (presented in section 5.3) and with costly management (problem (5.30) presented in section 5.5).

In order to find the second-best timing of management regime switch(es), we therefore assume that the current value Hamiltonian (5.31) is optimized, and we denote it as $\tilde{H}*(t)$. Let us write the optimized Hamiltonian as

$$\begin{aligned} H*(s) &= \begin{bmatrix} \int_0^{N_{SP}(s)\tilde{h}\tilde{\ell}_h} P(y)\,dy - \omega_{SP} N_{SP}(s)\tilde{\ell}_h - \omega_{SP} L_\tau \\ +\mu\left(g(s) - N_{SP}(s)\tilde{h}\tilde{\ell}_h\right) \end{bmatrix} e^{-\delta t} \\ &= \tilde{H}*(s)e^{-\delta t}. \end{aligned} \tag{IV.A.1}$$

where $\tilde{H}*(s)$ is the optimized current value Hamiltonian at stock s; x and y are placeholders. The social planner's costly management problem is autonomous, which is why its solution yields variables depending on s but not t in (IV.A.1).

The planner’s problem is to maximize (IV.A.1) at all times. Interestingly, with the flow of fixed cost of management, $\omega_{SP} L_\tau$, we could find that $\tilde{H}*(s) < 0$ even though $\mu* > 0$; in such a case, open access would be the preferred course of action even though the shadow price of the resource is positive. In what follows, we concentrate on this reason for the social planner to choose open access and that is why we restrict our attention to cases where Assumption 5.1 holds: $\mu^* > 0$ for all feasible s.

Assuming that $T_0 = 0$, the resource planner's timing problem is as follows:

$$\max_{T_{i+1},T_{i+2}} J(T_{i+1},T_{i+2}) = \sum_i \left[\int_{T_i^+}^{T_{i+1}^-} \tilde{H}^*(t) e^{-\delta t} dt \right]$$
$$= \sum_i \left[\int_{T_i^+}^{T_{i+1}^-} \left[\begin{array}{l} \int_0^{N_{SP}(s)\tilde{h}\tilde{\ell}_h} P(y)dy - \omega_{SP} N_{SP}(s)\tilde{\ell}_h - \omega_{SP} L_\tau \\ \qquad + \mu\left(g(s) - N_{SP}(s)\tilde{h}\tilde{\ell}_h\right) \end{array} \right] e^{-\delta t} dt \right], \quad i = 0,2,4,\ldots,\infty. \qquad \text{(IV.A.2)}$$

Using Leibnitz' rule of differentiation of integrals, the Kuhn-Tucker conditions that peg T_{i+1}, the time(s) when open access is chosen over costly management, are

$$\frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+1}} e^{\delta T_{i+1}} = \tilde{H}^*\left(T_{i+1}^-\right) \le 0,$$

$$T_{i+1} \ge 0 \text{ and } \left[\frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+1}} T_{i+1} \right] e^{\delta T_{i+1}} = 0, \; i = 0, 2, 4, \ldots, \infty. \qquad \text{(IV.A.3)}$$

Similarly, the Kuhn-Tucker conditions that peg T_{i+2}, the time(s) when costly management is chosen over open access, are

$$\frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+2}} e^{\delta T_{i+2}} = -\tilde{H}^*\left(T_{i+2}^+\right) \le 0,$$

$$T_{i+2} \ge 0 \text{ and } \left[\frac{\partial J(T_{i+1},T_{i+2})}{\partial T_{i+2}} T_{i+2} \right] e^{\delta T_{i+2}} = 0, \; i = 0, 2, 4, \ldots, \infty. \qquad \text{(IV.A.4)}$$

According to (IV.A.3) and (IV.A.4), at both switch times T_{i+1}^- and T_{i+2}^+, $\tilde{H}^*(s) = 0$. Let us write the equality generally at time T, which could be T_{i+1}^- or T_{i+2}^+:

$$\tilde{H}^*(s) = \int_0^{N_{SP}(T)\tilde{h}\tilde{\ell}_h} P(x)dx - \omega_{SP} N_{SP}(T)\tilde{\ell}_h - \omega_{SP} L_\tau + \mu\left(g(s(T)) - N_{SP}(T)\tilde{h}\tilde{\ell}_h\right) = 0 \qquad \text{(IV.A.5)}$$

Hence, for a stock where the management regime changes, we must have $\tilde{H}^*(s) = 0$.

REFERENCES

Anderson, L.G. and D.R. Lee. 1986. Optimal Governing Instrument, Operation Level, and Enforcement in Natural Resource Regulation: The Case of the Fishery. *American Journal of Agricultural Economics*, 68: 678-690.

Anderson, R.S. 1997. Investigation, Prosecution, and Sentencing of International Wildlife Trafficking Offenses in the U.S. Federal System. *National Environmental Enforcement Journal*, 12(5):14-26.

Anonymous. 1996. Why we ought to hunt big animals - Killing to be kind. *The Economist*. April 20th 1996:76-77.

Anonymous. 1999. Kenyan Notes Rise in Elephant Poaching. *Washington Post*. November 22, 1999: A18.

Bark, T. 1987. Distortions and intertemporal welfare in a small open economy. *Journal of International Economics.* 23:151-66.

Becker, G.S. 1968. Crime and Punishment: An Economic Approach. *The Journal of Political Economy*. 76 (2):169-217.

Berck, P. 1979. Open Access and Extinction, *Econometrica*, 47(4):877-882.

Bhagwati, J.N. 1993. The Case for Free Trade. *Scientific American*, November: 42-49.

Bhagwati, J. and V.K. Ramaswami. 1963. Domestic Distortions, Tariffs and the Theory of Optimum Subsidy. *Journal of Political Economy*, 71(1):44-50.

Bhagwati, J., V.K. Ramaswami and T.N. Srinivasan. 1969. Domestic Distortions, Tariffs and the Theory of Optimum Subsidy: Some Further Results. *Journal of Political Economy*, 77(6):1005-1010.

Bhagwati, J.N. 1971."The Generalized Theory of Distortions and Welfare," in J.N. Bhagwati *et al*., (eds), *Trade, balance of payments and growth - Papers in International Economics in Honor of Charles P. Kindlenerger*, Amsterdam: North-Holland Publishing Company; Chapter 4: 69-90.

Brander, J. and S. Taylor. 1997a. International Trade and Open Access Renewable Resources: the small open economy case. *Canadian Journal of Economics*, XXX(3): 526-552.

Brander, J. and S. Taylor. 1997b. International Trade between Consumer and Conservationist Countries. *Resource and Energy Economics*, 19(4):267-297.

Brander, J. and S. Taylor. 1998. Open-Access Renewable Resources: Trade and Trade Policy in a Two-Country Model. *Journal of International Economics*, 44(2):181-209.

Broussard, P. 1997. The Endangered Species Trade. *World Press Review*, May 1997 (article translated and reprinted from “Le Monde”, Paris, Feb. 2-3, 1997).

Brower, K. 1994. Devouring the Earth. *The Atlantic Monthly*. 276(5 (Nov.)):113-126.

Brown, G. and D. Layton. 1997. Saving Rhinos. *Paper prepared for the 1997 AERE Workshop on the Economic Analysis of Ecosystems*, Annapolis, Maryland. Mimeo.

Carlton, D.W. and J.M. Perloff. 1994. *Modern Industrial Organization*, 2nd ed. NY: Harper Collins College Publishers.

Chichilnisky, G. 1993. North-South Trade and the Dynamics of renewable Resources, *Structural Change and Economic Dynamics*, 4(2):219-148.

Chichilnisky, G. 1994. North-South Trade and the Global Environment, *American Economic Review*, 84(4):851-874.

Chichilnisky, G. 1996. Property Rights and the Dynamics of North-South Trade, In: "Agriculture, Trade and the Environment: Discovering and Measuring the Critical Linkages," M.E. Bredahl et al., Eds. , Boulder and London: Harper Collins, Westview Press, Chapter 8:97-110

Clark, C. W. and G.R. Munro. 1978. Renewable Resource Management and Extinction: Note, *Journal of Environmental Economics and Management*, 5(2):198-205.

Clark, C.W. 1973. Profit Maximization and the Extinction of Animal Species, *Journal of Political Economy*, 81(4):950-961.

Clark, C.W. 1990. "Mathematical Bioeconomics – The Optimal Management of Renewable Resources," 2nd ed. Wiley-InterScience Publication, John Wiley & Sons, Inc., New York.

Coase, R.H. 1960. The Problem of Social Cost, *Journal of Law and Economics*, III (October 1960):1-44.

Colitt, R. 2002. Globalisation activists draw up battle lines. *Financial Times*, 5 Feb. 2002, Tuesday, London Edition 2.

Copeland, B.R. and M.S. Taylor. 1994. North-South Trade and the Environment, *Quarterly Journal of Economics*, 109(3):755-87.

Copeland, B.R. and M.S. Taylor. 2004. Trade, Tragedy and the Commons. Paper presented at the 38th Annual Meeting of the Canadian Economics Association, Ryerson University, Toronto, Ontario, June 2004.

Crabbé, P. and N.V. Long. 1993. Entry deterrence and overexploitation of the fishery. *Journal of Economic Dynamics and Control*, 17: 679-704.

Cropper, M.L. 1988. A Note on the Extinction of Renewable Resources, *Journal of Environmental Economics and Management*, 15:64-70.

Cropper, M.L., D.R. Lee and S.S. Pannu. 1979. The Optimal Extinction of a Renewable Natural Resource, *Journal of Environmental Economics and Management*, 6:341-349.

Daly, H.E. 1993. The Perils of Free Trade. *Scientific American*, November: 50-57.

de Meza, D. and J. R. Gould. 1992. The Social Efficiency of Private Decisions to Enforce Property Rights. *The Journal of Political Economy*, 100 (3): 561-580.

Demsetz, H. 1967. Toward a Theory of Property Rights. *American Economic Review*. 57 (1967):347-359.

Dollar, D. and A. Kraay. 2002. Spreading the Wealth, *Foreign Affairs*, Jan-Feb 2002, Council on Foreign Relations, New York City.

Emami, A. and R.S. Johnston. 2000. Unilateral Resource Management in a Two-Country General Equilibrium Model of Trade in a Renewable Fishery Resource, *American Journal of Agricultural Economics*, 82(1):161-172.

Feichtinger, G and F. Wirl. 2000. Instabilities in Concave, Dynamic, Economic Optimization. *Journal of Optimization Theory and Applications*, 107(2):275-286.

Francis, M. 2001. Trade and the Adoption of Environmental Standards. Carleton University, *Mimeo*. (obtained at: http://www.carleton.ca/economics/seminar%20papers/Francis-6July2001.pdf).

Glenn, A.A and D. Fino. 1998. Stealing Nature – The Black Market in Endangered Species. *ABCNews.com*, July 1998: http://abcnews.go.com/sections/world/poaching/poaching_intro.html

Gordon, H.S. 1954. The Economic Theory of a Common-Property Resource: The Fishery. *Journal of Political Economy*, 62:124-142.

Gould, J.R. 1972. Extinction of a Fishery by Commercial Exploitation: A Note, *The Journal of Political Economy*, 80(5):1031-1038.

Haberler, G. 1950. Some Problems in the Pure Theory of International Trade. *Economic Journal*, 60(238): 223-240.

Hannesson, R. 2000. Renewable Resources and the Gains from Trade, *Canadian Journal of Economics*, 33(1):122-32.

Harberger, A. 1964. “Taxation, Resource Allocation and Welfare,” in John Due, ed., *The Role of Direct and Indirect Taxes in the Federal Revenue System*, Princeton, NJ: Princeton University Press.

Hardin, G., 1968. The Tragedy of the Commons, *Science*, 162: 1243-1248.

Hoel, M. 1978. Extermination of Self-Reproducible Natural Resources under Competitive Conditions, *Econometrica*, 46(1):219-224.

Hotte, L., N.Van Long and H. Tian. 2000. International Trade with Endogenous Enforcement of Property Rights, *Journal of Development Economics*, 62(1):25-54.

Kemp, M.C. and N. Van Long. 1980. The management of a renewable resource: Monopoly versus competition, In: "Exhaustible Resources, Optimality, and Trade," M.C. Kemp and N.V. Long , Eds., North-Holland Publishing Company, Essay 6:71-80.

Kremer, M. and C. Morcom. 2000. Elephants. *American Economic Review,* 90(1):212-34.

Lavigne, L. 1998. Environnement Canada doit vider ses entrepôts. *La Presse*, Montréal, 6 juillet 1998, p. A7.

Le Duc, J.-P. 1990. Illicit trafficking in animal and plants – A lucrative form of crime. *International Criminal Police Review*. May-June, 13-29.

Léonard, D. and N.V. Long. 1992. Optimal Control Theory and Static Optimization in Economics. Cambridge, UK : Cambridge University Press.

Levhari, D., R. Michener and L.J. Mirman. 1981. Dynamic Programming Models of Fishing: Competition, *American Economic Review*, 71(4):649-61.

Lewis, T.R. and R. Schmalensee. 1977. Nonconvexity and Optimal Exhaustion of Renewable Resources. *International Economic Review*, 18(3): 535-52

Lewis, T.R. and R. Schmalensee. 1979. Non-convexity and Optimal Harvesting Strategies for Renewable Resources. *Canadian Journal of Economics,* 12(4): 677-91

Long, N.V. 1979. Two Theorems on Generalized Diminishing Returns and their Applications to Economic Analysis. *Economic Record*, 55(148): 58-63.

Long, N.V. 1994. On Optimal Enclosure and Optimal Timing of Enclosure. *Economic Record*, 70(211): 368-72.

Makris, M. 2001. Necessary conditions for infinite-horizon discounted two-stage optimal control problems. *Journal of Economic Dynamics and Control*, 25: 1935-1950.

Margolis, M. and J.F. Shogren. 2002. Unprotected Resources and Voracious World Markets. *RFF Discussion Paper 02-30.*

Marston, W. 1997. The Misguided Ivory Ban and the Reality of Living with Elephants. *The Washington Post*, June 8, 1997. P. C2.

Milliman, S.R. 1986. Optimal fishery management in the presence of illegal activity. *Journal of Environmental Economics and Management*, 13: 363-381.

Ostrom, E. 1990. Governing the Commons – The Evolution of Institutions for Collective Action. Cambridge, UK : Cambridge University Press.

Powell, M. and B. White. 2002. A Revolution in Reverse at Econ Forum; As Capitalists Co-Opt Message, Protesters Have Little to Say. *Washington Post*, 2 Feb.2002, Final Edition, Wash. DC.

Sabourin, G. 1998. Des souvenirs pas écolos. *Protégez-vous*, Office de la protection du consommateur, Gouvernement du Québec. Juillet 1998, p. 24-27

Samuelson, P.A. 1978. Free Trade's Intertemporal Pareto-Optimality. *Journal of International Economics*, 8:147-149.

Scott, A. 1955. The Fishery: The Objective of Sole Ownership. *Journal of Political Economy*, 116-124.

Skonhoft, A. and J.T. Solstad. 1996. Wildlife Management, Illegal Hunting and Conflicts. A Bioeconomic Analysis. *Environment and Development Economics*, 1(2): 165-81.

Smith, M.A.M. 1979. Intertemporal Gains from Trade. *Journal of International Economics*, 9:239-248.

Smith, V. 1968. Economics of Production from Natural Resources, *American Economic Review*, 58(3, Part 1):409-431.

Srinivasan, T.N. 1996. "The Generalized Theory of Distortions and Welfare Two Decades Later," in Feenstra, R.C., G.M. Grossman and D.A. Irwin (eds), *The Political Economy of Trade Policy: Papers in Honor of Jagdish Bhagwati* Cambridge, Mass.: MIT Press; 3-25.

Sutinen, J.G. and P. Andersen. 1985. The economics of fishery law enforcement. *Land Economics*, 61: 387-397.

Trexler, M.C. and L.H. Kosloff. 1991. “International Implementation: The Longest Arm of the Law,” in *Balancing on the Brink of Extinction*, K.A. Kohm, ed. Island Press, Washington D.C. p.114-133.

Varian, H.R. 1992. *Microeconomic Analysis*, 3rd ed. W. W. Norton & Company: New York, NY.

Vedder, R.K. and L.E. Gallaway. “1999. Tax Reduction and Economic Welfare.” Joint Economic Committee, Wash. DC (http://www.house.gov/jec)

Webster, D. 1997. The looting and smuggling and fencing and hoarding of impossibly precious, feathered and scaly wild things. *The New York Times Magazine*. February 16th 1997:27-61.

Woodland, A.D. 1980. Direct and Indirect Trade Utility Functions. *Review of Economic Studies*, XLVII: 907-926.

WTO. 2002a. http://www.wto.org/english/thewto_e/whatis_e/tif_e/bey4_e.htm; 22 May 2002.

WTO. 2002b. http://www.wto.org/english/tratop_e/envir_e/hist1_e.htm; 5 June 2002.

WTO. 2002c. http://www.wto.org/english/tratop_e/envir_e/hist2_e.htm; 5 June 2002.

WTO. 2002d. http://www.wto.org/english/tratop_e/envir_e/stud99_e.htm; 5 June 2002.