SUSTAINABILITY versus FISHING COLLAPSE: A REVIEW OF CAUSES AND WELFARE PRESCRIPTIONS*

Julio Peña Torres**

ABSTRACT

It is commonly held that fishing collapse is a public bad. Losses in genetic endowment and the closure of fishing industries underlie this concern. This paper discusses both the welfare functional as well as the technological factors that condition this belief. Fishing collapse is analysed as an opportunity cost within society's investment decision in other available, natural and man-made, assets. We also review and analyse conditions traditionally associated with the occurrence of fishing collapse. We discuss different causality links between these conditions and collapse, for different types of fishery settings. This analysis helps us to differentiate between superficial and more fundamental causes of collapse. Priorities in regulation policy can then be obtained.

SINTESIS

Comúnmente se sostiene que el colapso pesquero es un mal público. Las pérdidas en la dotación genética y el cierre de las industrias pesqueras subyacen a esta preocupación. Este trabajo analiza los factores funcionales de bienestar así como aquellos de índole tecnológica que condicionan esta creencia. El colapso pesquero se analiza como un costo de oportunidad en la decisión de inversión de la sociedad en otros activos disponibles, sean estos naturales o producidos por el hombre. También, se revisa y analiza las condiciones que tradicionalmente están asociadas a la ocurrencia de colapso pesquero. Se analiza diferentes vínculos de causalidad entre estas condiciones y el colapso para diferentes tipos de entornos pesqueros. Este análisis nos permite diferenciar entre las causas superficiales y aquellas más fundamentales del colapso. Esto permite establecer prioridades en la política regulatoria.

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** Departamento de Economía Universidad de Chile and Department of Economics QMW College University of London.

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Julio Peña T.

1. INTRODUCTION

It is often argued that fishing collapse is a public bad. On occasions this is due to concerns about losing option values that arise from non-reproducible genetic endowments. Other times, the emphasis is on losses arising from the economic closure of fishing industries; for instance, unemployment effects. Together with the standard argument of inefficient rent dissipation caused by common pool fish stocks (Scott, 1955; Gordon, 1954), the possibility of collapse has traditionally called for regulations on harvesting. They have frequently taken the form of direct entry restrictions, seasonal (biological) closures or restrictions on input choices (e.g., type of gear, fishing net, and boat size). Quotas and taxes on harvesting are normally perceived by incumbent firms as more exacting regulations (Scott, 1979; Munro, 1982; Peña, 1995a). Hence, quota and tax policy proposals have frequently encountered stronger and more effective opposition from incumbent firms' lobbying effort. This policy-game outcome has given rise to a folk wisdom such that restrictions with regards to access, the length of harvesting seasons, and input choices are often argued to be sufficient conditions to avoid fishing collapse.

This paper addresses two aspects of the debate on fishing collapse. First, we assess the robustness of the proposition that fishing collapse is a public bad. We discuss the welfare functional and the technological factors (cost, production, and biological growth functions) which condition this proposition. Under some particular conditions, fishing collapse can correspond to the welfare optimal solution. The key intuition is that fishing collapse represents an opportunity cost within society's portfolio investments in other available (natural and man-made) assets. A welfare assessment of collapse must balance this cost against the benefits from disinvesting in declining fish stocks. These benefits include the net saving of resources, if there is any, in the management services which are required to enforce user rights on the assets chosen for investment.

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Second, we discuss the necessity and sufficiency of some conditions which are traditionally associated with the occurrence of fishing collapse. Open access, immobile fixed capital, minimum viable population levels, and attractive profit margins are often perceived as factors which will very probably lead to collapse. Folk wisdom frequently thinks of these factors as direct causes of collapse. To some extent, this helps to understand the popularity of regulations based on direct access restrictions and fishing capacity freezing, or the frequent use of biological closures. Analysis on more fundamental causes, frequently related to issues of political economy, is less often pursued; for example, asking why enacted regulations are not always properly enforced, or why *de facto* open access conditions tend to last for long periods despite the increasing rival consumption in harvesting[1].

This paper does not develop the latter perspective. We assume that institutional rules, such as open access, are exogenous. Instead, we focus on two technological aspects of the collapse issue. We analyze the effects from: (i) increasing biological growth returns for low population levels (the so-called *depensation growth*) and (ii) sunk harvesting capacity. Both factors are commonly held to be important conditions contributing to collapse. Factor (i) is related to the idea of minimum viable population levels. Factor (ii) is usually thought as a reinforcer of the incentives leading to collapse. Our enquiry about these two aspects aims to contribute to the understanding of the right causes of collapse under different technological settings. This may help to address from improved thoughtful perspectives the setting of priorities between different available regulatory instruments.

The main findings in this part of the analysis are as follow. In terms of factor (i), the key message is that depensation growth is neither a necessary nor a sufficient condition for fishing collapse. The non-necessity result implies that the possibility of fishing collapse is more widely ranged than otherwise expected. The non-sufficiency result implies, for example, that management policies with intensive use of seasonal biological closures, aimed at avoiding collapse, should reconsider the proper balance with other regulatory instruments more directly related to the immediate incentives for overfishing.

In terms of factor (ii), a key aspect is how costly it is for individual firms to reduce fishing efforts, even when low harvesting performances may create incentives to attempt it. *Quasi-fixed* costs create incentives for intensive harvesting, by decreasing average unit harvesting costs as harvest increases. The relative importance of *re-entry* costs determines whether these incentives result in *sustained* depletion, and hence in the promotion of fishing collapse, or in *cyclical* harvesting which can avoid collapse. As re-entry costs increase, the harvesting indivisibilities (created by quasi-fixed factors) will tend to increase the likelihood of attaining a fishing collapse as the dominant outcome.

[1] Examples of this type of analysis are found in Scott, 1979, Gulland, 1989, Swanson, 1994 and Peña, 1995a.

The remainder of this paper is organized as follows. Section (2) discusses basic concepts. Section (3) develops a welfare model used as a yardstick in the analysis that follows. Section (4) discusses the necessity and sufficiency of conditions traditionally associated with the occurrence of fishing collapse. Section (5) offers final remarks.

2. BASIC CONCEPTS

Empirical evidence shows that the collapse of marine industrial fisheries is not a so uncommon phenomenon. Pelagic fisheries are among the riskiest to this respect[2]. Several well-known fishing collapses belong to this group: the collapse of the Japanese sardine industry in the early 1940s; of the Californian sardine fishery in the early 1950s; of the North Sea herring stocks in the late 1960s and early 1970s, and the collapse of the Peruvian anchovy fishery in 1972-73 (Idyll, 1973; Gulland, 1988; Cushing, 1988). Appendix 1 shows other examples of fishing collapses during the XX[th] century.

This evidence, however, does not imply a definite justification for regulation of industrial fisheries. A rigorous defense of fishing regulations should: (i) argue why collapse represents a *net* welfare worsening result, (ii) identify the conditions under which collapse can occur, and (iii) differentiate between the necessity and sufficiency of these conditions in different fishery settings. To make headway on these issues, we first discuss two important concepts: sustainability and welfare prescriptions.

2.1. Sustainability

Let us use the term *system* to denote the fish population that is subject to economic depletion. We denote by *system* the following function:

$$\dot{x}(t) = S(x(t);\alpha) \qquad (1)$$
$$x(0) = x_0$$

[2] *Pelagic* fish species (such as sardines, anchovies and herrings) tend to be stocks that are highly variable and difficult to assess and manage. This is related to the fact that pelagic species are usually shorter lived and faster growing by comparison to other important fish species (e.g., demersal). Therefore, they are more exposed to recruitment fluctuations. And *recruits* in these fish populations tend to show high variability due to environmental shocks. (Gulland, 1988, ch. 11).

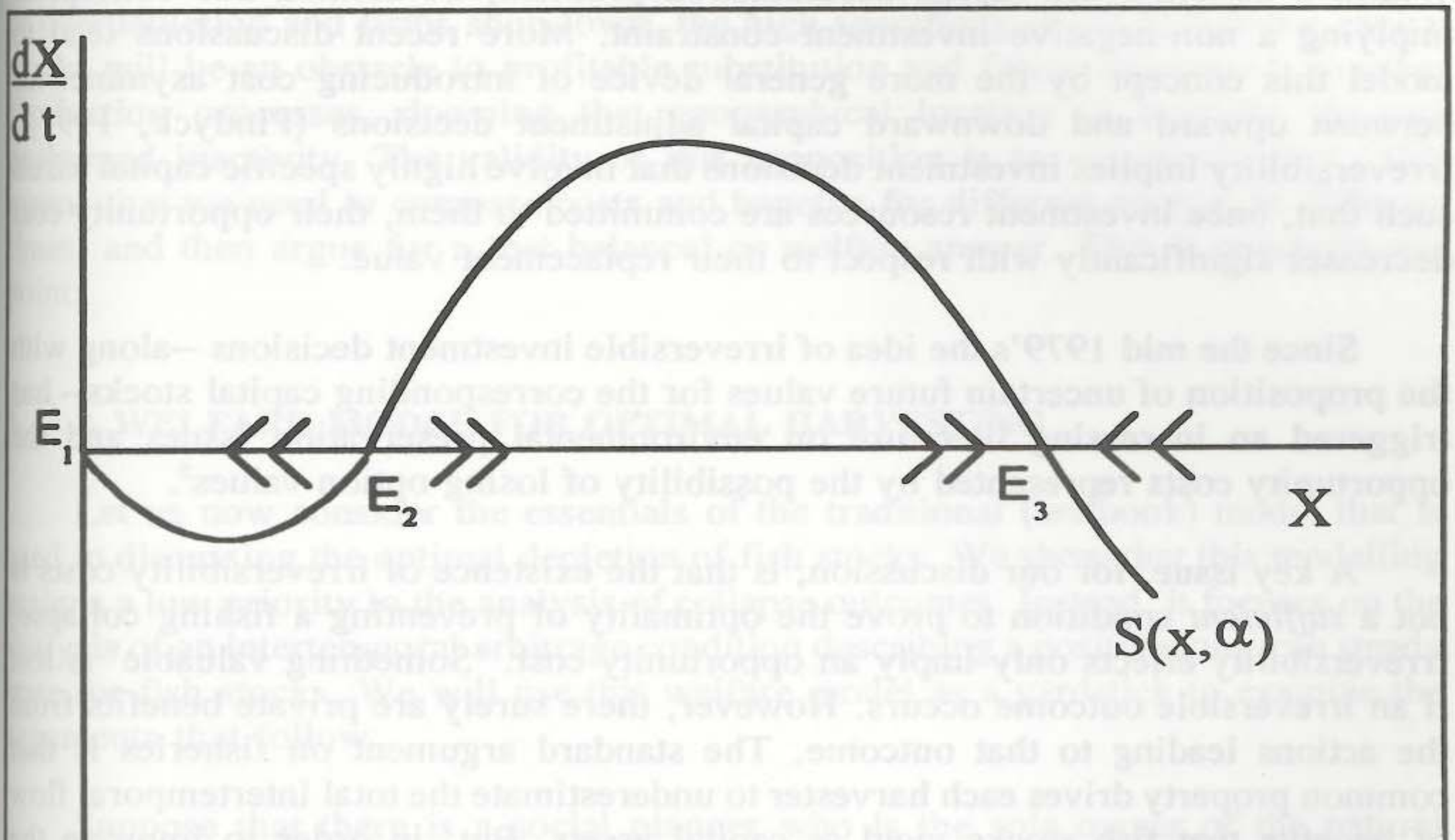
where x(t) denotes the state-variable vector at time t of this dynamic system, $\dot{x}$ its time derivative, x_0 the initial state, and α a parameter vector that can affect the rule of dynamic motion for x. For instance, in a simple case the state x can represent the population level of a homogeneous single fish species, whereas α may represent its exogenous rate of natural growth.

We can think of the sustainability argument as the aim of preserving the *economic* or *biological* survival of the system. In the first case, the argument refers to preventing the *economic collapse*, call it *closure*, of the fishing industry that exploits the fish population x. In the second, it refers to preventing the *extinction* of the biological population. By *closure* we mean a long run industry equilibrium with a sufficiently low fish stock level such that the industry's average variable costs are high enough to make it unprofitable, for a sufficiently high percentage of firms in the industry, to continue with positive harvesting operations in that fishery. A case with no catches from the fishing grounds can obviously be considered as a fishery under closure. Our interpretation of economic collapse also includes cases of fishing grounds with positive but sufficiently low aggregate harvesting such that undesired welfare effects arise; for example, undesired regional unemployment effects.

Clearly extinction implies closure, but not vice versa. Hence, these two concepts can have quite different welfare consequences. Moreover, the definition of each of them is not a trivial task. Each of them can represent a complex set of circumstances. For instance, when we talk about *extinction* what do we really refer to? Is it the *full* biological disappearance of a species? Is it within a country or the whole world? How do different geographical definitions affect the welfare consequences of identifying local versus global species extinction? It would not be difficult to add new questions and doubts. A similar process would occur if we start thinking more carefully about the definition of *closure*. Nonetheless, this paper makes no distinction between economic closure and biological extinction. It suffices for our purposes to define a *minimum* x-level x_m below which the regulator does not aim to be. Call this unwanted x range a *fishing collapse* outcome.

Figure 1 illustrates a simple case where $\dot{x}=S(x(t))$ has three *stationary* equilibria with two of them locally stable for a given neighbourhood. The vertical axis measures the derivative of x with respect to t and the horizontal axis the level of x. Points E_1 and E_3 represent two locally stable fixed points. The collapse outcome is represented by the lowest stationary equilibrium E_1. However, for a regulator that aims to avoid the outcome E_1 the unwanted x-range is defined by x levels below the minimum point $x_m = E_2$.

FIGURE 1



To make the definition of x_m more precise it would require to make explicit the welfare optimization model under analysis. At this stage we are not going to pursue this exercise. Hence, a sustainability target simply means the regulator's desire to prevent a fishing collapse outcome.

2.2. Welfare prescriptions

Regulations aimed at preventing a fishing collapse presuppose that it represents a welfare worsening result. If collapse is meant to imply *extinction*, folk wisdom says that we will be *permanently* losing valuable[3] genetic biological information. A key aspect in this argument is the underlying concept of irreversibility costs.

[3] The concept of valuable can represent an 'option value'. Weisbrod (1964) was a pioneering paper arguing the option value of current consumption when there exists uncertainty with respect to its future value. Extensions of this idea to the topics of "environmental preservation" can be found in Fisher, Krutilla and Cicchetti (1972), Arrow and Fisher (1974), Henry (1974). Similar applications to the problem of uncertain and irreversible investment decisions are found in Bernanke (1983), Brennan and Schwartz (1985) and the survey paper of Pindyck (1991).

Arrow (1968) was one of the first to define *irreversibility* in a precise manner. Within a deterministic capital accumulation problem, he defined this concept as implying a non-negative investment constraint. More recent discussions tend to model this concept by the more general device of introducing cost asymmetries between upward and downward capital adjustment decisions (Pindyck, 1991)[4]. Irreversibility implies investment decisions that involve highly specific capital assets such that, once investment resources are committed to them, their opportunity cost decreases significantly with respect to their replacement value.

Since the mid 1979's the idea of irreversible investment decisions --along with the proposition of uncertain future values for the corresponding capital stocks-- has triggered an increasing literature on environmental preservation issues and the opportunity costs represented by the possibility of losing option values[5].

A key issue, for our discussion, is that the existence of irreversibility costs is not a *sufficient* condition to prove the optimality of preventing a fishing collapse. Irreversibility effects only imply an opportunity cost. 'Something valuable' is lost if an irreversible outcome occurs. However, there surely are private benefits from the actions leading to that outcome. The standard argument on fisheries is that common property drives each harvester to underestimate the total intertemporal flow of benefits that fish stocks yield as capital assets. But, in order to improve the private internalization of these intertemporal benefit flows, society needs to invest scarce resources in management services that allow for an efficient enforcement of exclusive user rights (Swanson, 1994). Hence, a cost-benefit analysis is needed. Where then must the net balance be placed by the welfare yardstick? We need an explicit welfare model to provide an answer. This exercise does not seem to have an *a priori* answer.

Consider now collapse as an economic closure issue. Loosely defined, *closure* is meant to imply that a 'sufficiently high' percentage of firms in the industry have to shut down for a 'sufficiently long' period. An explicit welfare model should clarify what is understood by 'sufficiently high' and 'sufficiently long'. This is not relevant to our purposes here. What matters is that again we have a proposition arguing for some type of 'exit cost' function.

[4] The concept of sunk costs belongs to this line of thought. Sunk costs imply a positive difference between the replacement cost and the resale price of a given capital stock.

[5] This literature considers the basic 'learning option' proposition that it may be better (in a welfare sense) "to wait when we are unsure about future values" (Arrow and Fisher, 1974). However, it is far from clear that the combination of uncertain future values and current irreversible investment decisions lead to unambiguous welfare prescriptions in the sense of "better to wait" or "better to postpone current production". Sequential investment models can yield the opposite prescription: Roberts and Weitzman(1981) is an example where the investment process yields information about the uncertain future values (for instance, think of the discovery and value assessment processes in the oil extraction industry).

For example, folk wisdom frequently proposes that the economic closure of fishing industries is welfare worsening because once fish stocks achieve high levels of overdepletion and firms shut down, the high specificity of the remaining capital stocks will be an obstacle to profitable substitution and factor movements to other production processes, dooming that geographical location to languish through prolonged inactivity. The validity of this proposition is an empirical issue. This means that we need to compare costs and benefits for different people, at different times, and then argue for a 'net balance' or welfare answer. This is precisely our point.

3. A WELFARE MODEL FOR OPTIMAL HARVESTING

Let us now consider the essentials of the traditional (textbook) model that is used in discussing the optimal depletion of fish stocks. We show that this modelling assigns a low priority to the analysis of collapse outcomes. Instead, it focuses on the analysis of an intertemporal arbitrage condition describing a positive long-run steady state for fish stocks. We will use this welfare model as a yardstick to examine the arguments that follow.

Suppose that there is a social planner who is the sole owner of the natural resource, denoted by x, and whose objective function is the maximization of the total discounted net economic benefits derived from depleting x. The choice variable is the harvesting rate h(t), indexed for time t. Assume an infinite time horizon problem and a deterministic setting. The sole owner assumption is meant to imply that the planner's problem is defined independently from the ownership of the natural resource. Hence, we assume that the (first best) planner has full control over the harvesting of the fish stock. The planner's optimization problem is:

$$\max_{h(t)} V = \int_0^{\infty} e^{-\delta t}\, \Pi(x(t),h(t))\, dt \qquad (2)$$

subject to:

$$G(x,\ h) = \frac{dx}{dt} = F(x) - h(t)$$

$$x(t) \geq 0,\ \ h(t) \geq 0,\ \ x(0) = x_0 \qquad (3)$$

where V is the present value of the current and future net benefit streams that accrue from the resource depletion; with Π(x,h) as the flow of net economic benefits, x(t) as the resource stock, h(t) as the harvest rate and δ the relevant social discount rate. The social planner's benefit function Π may represent the social utility accruing from the resource consumption flows, or a profit function if we think of the social planner as a sole owner firm[6]. Let us assume the latter. Therefore, $\Pi(x,h)$ denotes the Ricardian rents that accrue from the depletion rate $h(t)$ of the natural resource $x(t)$.

The constraint for the problem arises from the net biological growth of x which is denoted by $G(x,h)$, where $F(x)$ represents the natural growth rate of x, such that $x(t) \geq 0$ and $h(t) \geq 0$[7]. The solution to problem (2)-(3) can be found by maximizing, for all t, the following current-valued Hamiltonian:

$$\max_{h} \; H = \Pi(x,h) + \lambda[F(x) - h] \tag{4}$$

where λ is the current valued scarcity value of x.

By imposing the assumption of strict convexity on this problem's choice space, i.e., when both functions $G(x,h)$ and $\Pi(x,h)$ are *(jointly) strictly concave* in the state variable $x(t)$ and the control variable $h(t)$, we know that the standard first-order conditions (Appendix 2) suffice to identify a trajectory pair (h^*, x^*) which maximizes V subject to (3)[8]. Solving for steady state conditions, we obtain the following equation that characterizes the steady state solution pair (x^*, h^*) :

$$F'(x^*) + \frac{\partial\Pi/\partial x^*}{\partial\Pi/\partial h}\Big|_{h=F(x^*)} = \delta \tag{5}$$

where $F'(x)$ denotes the derivative of function F with respect to stock x.

This result is known in the literature as "the fundamental rule of renewable resource depletion" (Pearce and Turner, 1990, ch.16). It describes the long-run stationary equilibrium for the system (2)-(3), which is represented by the stationary state x^*, such that $F(x^*) = h^*$, at which the net capital gains are zero. In order to assure that x^* is positive, it must be true that the left-hand side of equation (5), when the partial derivatives are evaluated at $x=0$, is greater than the discount rate δ.

[6] The profit function can be a measure of welfare if we assume *inter alia* that prices are taken as given.

[7] Note that we have excluded capacity constraints on the choice of h(t). This rules out a possible source of non-convexities in the choice problem (if the capacity constraint is binding at the optimal h(t)); consequently, this assumption eliminates a potential source of multiple equilibria.

[8] Strict joint concavity requires that $[H_{hh}H_{xx} - H_{xh} H_{hx}] > 0$. The uniqueness of the maximum solution (h^*, x^*) is assured if $G(x,h)$ and $\Pi(x,h)$ are (jointly) *strictly* concave *everywhere* in the feasible choice space for x and h. (Chiang, 1992, chapter 4.2).

The left-hand side of equation (5) is the marginal sustainable resource rent that results from an additional unit of investment in x(t), divided by the cost of that investment which is the foregone rent from current harvesting h[9]. This gives a rate of return for investments in x, which has to be equal to δ in equilibrium in order to have zero capital gains in terms of present value. This rate of return is composed of two factors: first, the "instantaneous marginal product" of the resource, F'(x). This is a direct productivity effect from marginal changes in x over the profit function. Second, in fishery models it is usually assumed that $\partial\Pi(x,.)/\partial x > 0$, presumably because the unit harvesting cost decreases, the higher x is. In this case, to postpone harvests today and hence make the resource more abundant and less costly to exploit, adds a marginal benefit to the marginal growth F'(x). This additional effect has been traditionally called the 'marginal stock' or 'user cost' effect in the literature on fisheries.

How is the long-run optimal steady state x^* arrived at in this model? Suppose that the profit function $\Pi(x,h)$ were linear in the harvest rate h(t), as the (textbook) fishery models normally assume. Due to this linearity assumption, the optimal approaching path to x^* is the Most Rapid Approaching Path (MRAP) or *bang-bang* solution; that is, whenever $\partial H/\partial h < 0$ then set $h=0$ (where H is the Hamiltonian function described by equation (4)); otherwise, if $\partial H/\partial h > 0$ then set $h=h^*$ such that the fish stock is *instantaneously* driven to its equilibrium steady state level x^*.

Owing to the linearity assumption, the decision maker always obtains a constant margin per additional unit of h. Hence, the optimizing agent has no 'scale sensitive' penalties for rapid resource investment or disinvestment decisions: the control variable h(t) fully adjusts to accommodate the desired state x^*.

We can incorporate scale related harvesting costs into the analysis by assuming that the benefit function is *strictly* concave in h, that is $\partial\Pi/\partial h > 0$ and $\partial^2\Pi/\partial h^2 < 0$.[10] In this case the optimal approaching path is no longer the MRAP. The optimal path becomes now an *asymptotic* approaching path to the long-run equilibrium vector (h^*,x^*); with this approaching path increasing or decreasing depending on the initial state x(0) (Wilen, 1985).

[9] To illustrate this reading, let us suppose that function Π is linear in h, with a margin per unit of harvest equal to (p- c(x)), with c(x) as the unit cost of harvesting. In this case, we can see that equation (5) corresponds to:

$$\frac{\partial[(p-c(x^*))F(x^*)]\ /\partial x^*}{p-c(x^*)} = \delta \qquad (6)$$

[10] This is consistent with the presence of decreasing returns in h or the effect of strictly convex harvesting costs. The introduction of strict convexity into the investment cost function is the traditional device that neoclassical investment theory has used to model asymptotic adjustment paths to the desired long-run capital stocks. Non-convex adjustment costs, for example due to irreversible investments, make it possible to model more complicated dynamic adjustment paths (Takayama, 1985, ch. 8.E).

Therefore, the analysis for the management of a renewable resource within a convex choice world seems to be clear: we set the conditions for the existence and uniqueness of a long-run optimal stationary equilibrium for the fish stock, and then we prove its stability properties. In this stationary solution, the stock x^* is held constant by continuously harvesting the resource's natural growth ($h^*=F(x^*)$). As a consequence, along with this steady state x^* we obtain a stable (*sustainable*) harvest rate h^*. Whenever the initial stock is greater than the optimal stationary level, the stock is harvested at a rate greater than its natural rate of growth, and vice versa, in order to attain the desired long-run stationary stock.

This standard methodology has had a strong appeal on the way we think of resource optimization problems as choices between stable long-run equilibria, with corresponding stable (sustainable) control variables, such as the concept of maximum sustainable yield (MSY) that we frequently encounter in fishery management discussions (Gulland, 1988). This style of thinking undoubtedly acquires more life and self-convincing power as we move closer to policy implementation issues, given the costs of implementing state adjustable harvesting controls. As a consequence, explicit analyses of approaching paths remain as peripheral issues.

There are clear advantages in relying on (strictly) convex choice spaces when we analyse dynamic optimization problems. We focus on unique, stable and positive long-run equilibrium states. However, this modelling strategy neglects important features of the fishery management problem. First, it places minor emphasis on multiple equilibria and related instability issues, among them the risk of collapse. Second, we encounter either no dynamic considerations at all (i.e., *bang bang* solutions) or they are captured by simple asymptotic solution paths. Both alternatives imply neglecting the analysis of economically meaningful dynamic trade-offs for the choice variables. For example, the choice between cyclical versus more stable harvesting. In the next section we will again refer to this issue.

4. CONDITIONS FOR FISHING COLLAPSE

We now discuss the necessity and sufficiency of two important technological conditions which are traditionally associated with the occurrence of fishing collapse: the existence of non-concavities in (i) the natural growth function and (ii) the harvesting technology.

Welfare considerations are excluded from this section. Three other important assumptions are made: First, we ignore the strategic interactions that can arise from a common property fish stock. We therefore bypass a formal analysis of the harvesting equilibria which can emerge in non-cooperative harvesting games arising from commonality[11]. Second, we exclude arguments related to uncertain fish stocks. We therefore abstract from collapse explanations based on costly monitoring of fish stocks and *persistent* random shocks[12]. Third, we focus on a single-species fishery.

4.1 Collapse in a convex choice space

Let us first consider the incentives that can lead to collapse in a strictly convex choice world.

(a) Sole-ownership

Consider the welfare problem described by equations (2)-(3). Given the joint strict concavity in h and x of this problem, equation (5) describes a unique stationary long-run equilibrium stock denoted by x^*. This equilibrium condition implies that x^* will be lower, the higher the discount rate δ is. For fish species with relatively low growth rates $F'(x)$, and where the profit function $\Pi(x,h)$ (i) is either 'relatively insensitive' to marginal changes in x (e.g., low x-sensitivity of marginal harvesting costs), or (ii) has a 'relatively high' and positive sensitivity to additional units of h (e.g., a 'high' per unit profit margin), we can expect that the higher the relevant discount rate, the higher the possibility that $x^*=0$ will be the long-run optimal steady state.

Hence, the intertemporal arbitrage condition that rules the investment in x can prescribe that, in terms of present value, it is *optimal* for a sole-owner type of decision maker to allow for collapse. Therefore, fishing collapse could be, under some particular conditions, the welfare optimal solution (e.g., Clark, 1973).

(b) Open access commonality

Common property with open access is usually interpreted as leading to *a stock myopic* harvesting such that firms will not internalize the opportunity cost of extracting an additional unit of fish stock. Although this can be a plausible

[11] Clemhout and Wan (1985; 1986) are two papers that attempt to link the analysis of fishing collapses (understood as extinction in both cases) with basic hypotheses for Nash non-cooperative harvesting. While the 1985 paper does so within a deterministic setting, the 1986 paper considers a random hazard of extinction whose probability of occurrence can be affected by the solution to the non-cooperative harvesting game.

[12] Both elements could be used to justify the occurrence of a locally stable collapse outcome. For both of them there exist some support from empirical evidence. Reference sources on fisheries and uncertainty can be found in Clark, Munro and Charles (1985), Munro and Scott (1985), and Lewis (1982).

interpretation, it is not an obvious proposition (Peña, 1995b). However, let us suppose that 'high' costs of excluding rivals' harvesting lead to a stock myopic harvesting competition that inefficiently dissipates the natural resource's rents. The traditional literature on fisheries has then suggested that the allocative effect of open access commonality with multiple harvesting firms is *analogous* to an infinite discount rate in the sole-owner case (Scott, 1955 and Clark, 1976, chapter 2.5); in the sense that, in both cases, the future state of the system under depletion has no implications for current harvesting decisions. This line of argument then proposes that such incentive structure could eventually lead to a fishing collapse. As a consequence, entry restrictions are usually prescribed.

To validate the collapse corollary within the myopic harvesting proposition, however, we need to assume that the industry as a whole still faces positive profit margins, per unit of marginal harvesting, when the fishery arrives at the critical x_m that triggers the local stability of fishing collapse (see section 2.1). This additional condition is not an obvious assumption. Think of the possibility of increasing marginal harvesting costs as stock x falls. In this case, harvesting firms would have incentives to reduce their catches as x falls. If marginal costs were sufficiently sensitive with respect to decreasing x levels, the open access equilibrium could imply long-run equilibrium x levels above the critical value x_m.

Nonetheless, by combining open access commonality with 'strong' profit incentives for intensive and continued current harvesting, it is possible to obtain a plausible explanation for some fishing collapse experiences. For instance, the collapse of the Blue Whale international fishery: the combination between a 'low' growth rate F'(x) with respect to the obtainable current per unit profit margin, and the existence of a *de facto* open access commonality are generally thought to have led to collapse. Similar arguments have been used to explain the economic collapse of several pelagic industrial fisheries. In this case, a special emphasis is put on the effect of falling average harvesting costs that result from the defensive strategies that pelagic fish follow at reduced population levels[13].

4.2. Non-concavities in the natural growth function

Several models that discuss fishing collapse problems are based on natural growth functions F(x) that do not exhibit strict concavity (e.g., Lewis and Schmalensee, 1982; Levhari, Michener and Mirman, 1982). This helps to model the

[13] As the fish stock becomes smaller, the individuals tend to increase their (density) concentration as a defensive response to natural predators. For species that live near the surface, like pelagic fish, this tends to reduce the fleet's harvesting costs.

possibility of a minimum viable population level. This is a dominant idea in the marine biologists' approach to the regulation of marine fisheries and has contributed to the widespread acceptance of seasonal biological closures as an important instrument of fishing regulation.

An initial non-concavity in F(x) usually aims to model the presence of increasing biological growth returns for low population levels; that is, that the proportional growth rate r(x)= [dx/dt]/x initially be an increasing function of x for low x levels[14]. But this is not always a *necessary* condition to obtain the local stability of a collapse outcome. For the case of a *strictly concave* natural growth function F(x)=dx/dt, with F(x)>0 for all x>0, we could model an initial region of negative *net growth* (natural growth minus total catches), by simply considering a *constant* positive rate of harvesting (independent of x values). The region of x values with negative net growth would imply local stability for the steady state equilibrium x=0. (e.g., Mirman and Spulber, 1984).

Models that consider non-concavities in F(x) normally work with harvesting functions which are linear in the stock x[15]. In the case of linear harvesting technologies, the use of strictly concave functions F(x) would allow to obtain only one stable steady state equilibrium, either positive or equal to zero (full depletion). The feature of initial non-concavity in F(x) helps to model more interesting (multiple equilibria) solutions, with at least two steady state equilibria showing local stability.

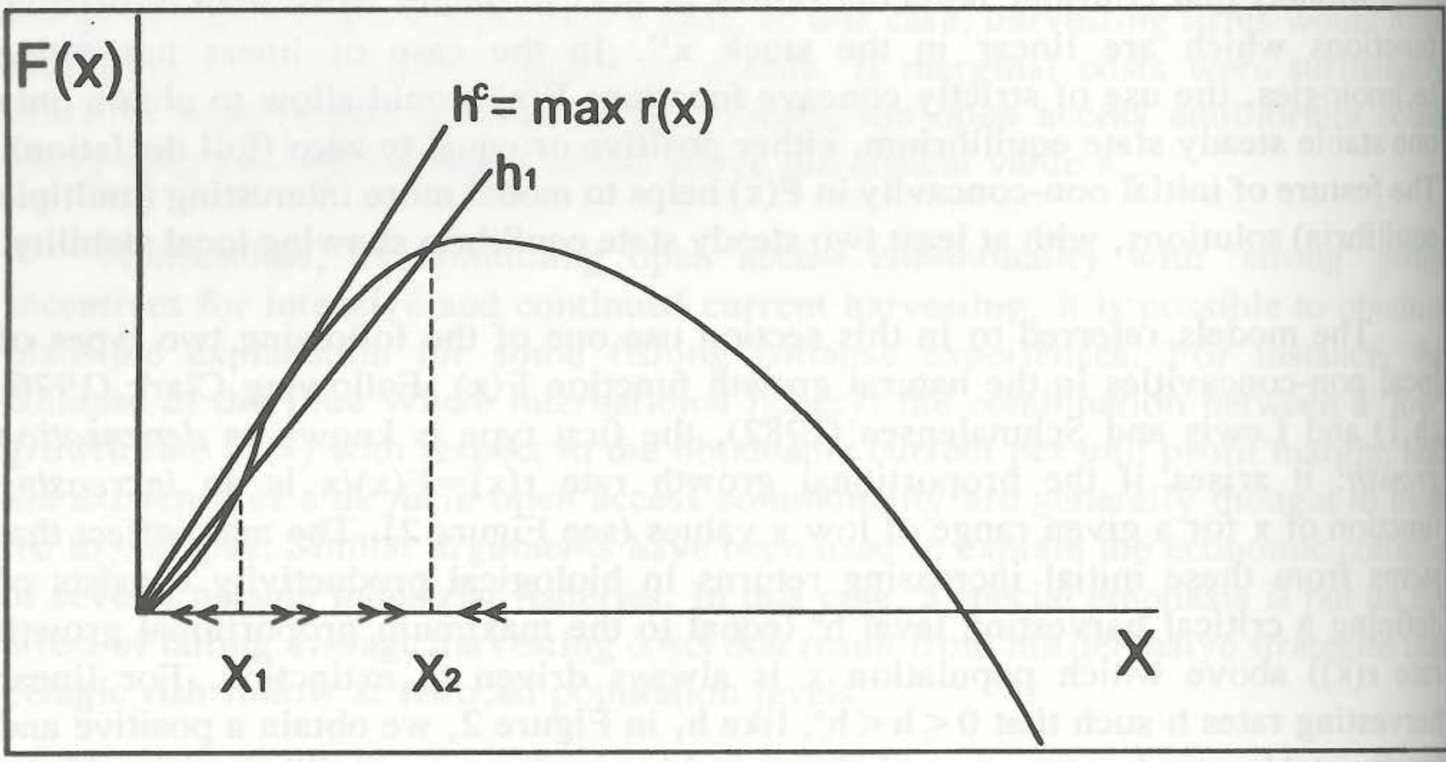
The models referred to in this section use one of the following two types of local non-concavities in the natural growth function F(x). Following Clark (1976, ch.1) and Lewis and Schmalensee (1982), the first type is known as *depensation growth*: it arises if the proportional growth rate r(x)=F(x)/x is an *increasing* function of x for a given range of low x values (see Figure 2). The main effect that stems from these initial increasing returns in biological productivity consists of defining a critical harvesting level h^c (equal to the maximum proportional growth rate r(x)) above which population x is always driven to extinction. For linear harvesting rates h such that $0<h<h^c$, like h_1 in Figure 2, we obtain a positive and locally stable steady state x_2 and the unstable steady state equilibrium x_1. If the initial stock level is above x_1, the harvest rate h_1 will drive the population to the positive equilibrium x_2. If the initial stock is below x_1, the population is driven to extinction (e.g., Clark, 1971).

[14] For example, it may be more difficult to find a mate and reproduce when the stock is small.

[15] These functions are of the type h=qzx, with h as the harvest rate, q as a constant productivity parameter, z denoting fishing effort and x as the fish stock. This technology corresponds to the well-known Schaefer production function within fishery economics (Clark, 1976, ch. 2).

A second type is usually modelled as implying $F(x)<0$ for a given range of low x values, in the vicinity of $x=0$ (see Figure 3). This case is known as *critical* depensation growth (Clark, 1976). It exhibits all of the features mentioned above for the first type but also an additional phenomenon: it defines a critical (*minimum viable*) population level x^c, with $F(x^c)=0$, such that if x falls below x^c then an *irreversible* process begins such that necessarily $x \to 0$, even without harvesting. As with the previous type of depensatory effects, any positive linear harvest rate, like h_2 in Figure 3, gives rise to two equilibria, x_1 and x_2, the former being unstable while the latter is locally stable. For initial stock levels below x_1, any positive harvest rate will drive the fish population to extinction[16].

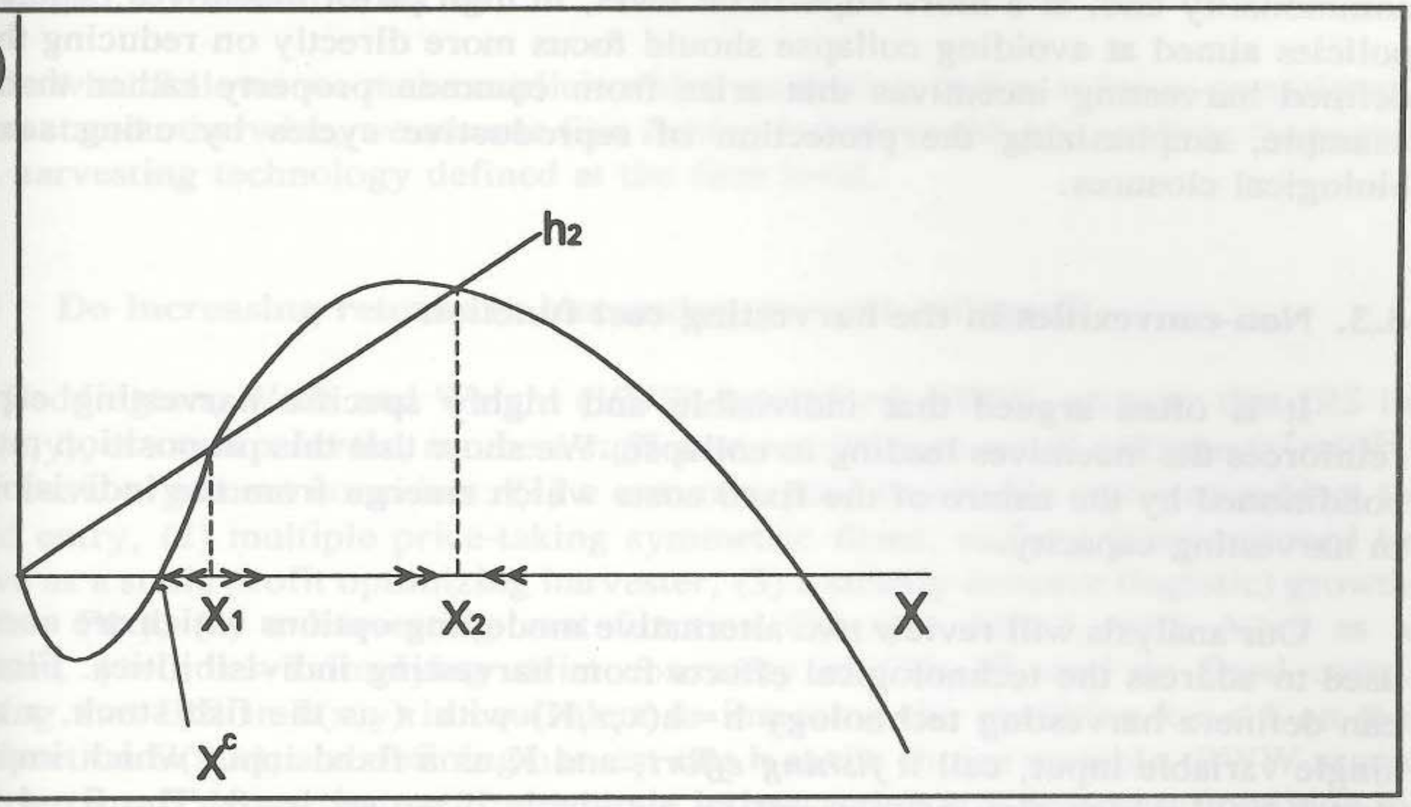
FIGURE 2
DEPENSATION GROWTH



Are these depensatory effects a sufficient condition for a collapse outcome? Are they a necessary condition? The answer to both questions is no. We have already seen that even within strictly convex choice problems we can argue for the possibility of a fishing collapse. Hence, depensatory effects in the biological growth function are not a strictly necessary condition to prove that x can collapse.

[16] We will keep the notation x^c to refer to *critical depensatory* effects. Notice in Figure 3 that x_1 corresponds to our previous notation x_m as the triggering x level of a locally stable collapse outcome.

FIGURE 3
CRITICAL DEPENSATION GROWTH



With respect to the sufficiency issue: when *critical* depensation growth exists, collapse inevitably occurs if x falls below x^c. The same result would occur with *non-critical* depensatory growth if the harvesting rate is located above h^c (Figure 2). However, why would firms, fully aware of this possibility or risk, presumably being risk averse agents[17], not reduce, or even stop, their harvesting when they approximate the critical levels x^c or h^c? We have already established that allowing for extinction could be the optimal fishing policy in the case of a sole-owner fishery. But then collapse would be explained by the arbitrage condition in equation (5). Hence, non-concavities in the natural growth function would be neither a sufficient nor a necessary condition for fishing collapse.

The question in the paragraph above surely loses interest when we think of *common pool* fisheries subject to *multiple* firms' *non-cooperative* harvesting. In this case, even if problems of uncertainty regarding the true state of stock x are left out, the high costs of excluding rival firms' harvesting can help to explain why individual firms may intensively harvest the fish stock, while positive operational profit margins allow doing so, even if they are aware of the risk of fishing collapse. Again

[17] The probability of risk aversion presumably increases, the smaller the size of the harvesting firm is and the more specific (sunk) the capital stocks required in the harvesting technology are.

in this case the non-concavity of function F(x) is neither a sufficient nor a necessary condition for fishing collapse. Instead, collapse would have its deeper roots in commonality and, at a more superficial level, in high profit incentives. Therefore, policies aimed at avoiding collapse should focus more directly on reducing the ill-defined harvesting incentives that arise from common property rather than, for example, emphasizing the protection of reproductive cycles by using seasonal biological closures.

4.3. Non-convexities in the harvesting cost function

It is often argued that indivisible and highly specific harvesting capacity reinforces the incentives leading to collapse. We show that this proposition must be conditioned by the nature of the fixed costs which emerge from the indivisibilities in harvesting capacity.

Our analysis will review two alternative modelling options which are normally used to address the technological effects from harvesting indivisibilities. First, we can define a harvesting technology $h=h(x,z,K)$ with x as the fish stock, z as the single variable input, call it *fishing effort*, and K as a fixed input which implies a cost $K>0$[18] which may or may not be avoidable if we set $h=0$. The fixed factor (cost) K introduces harvesting indivisibilities. Its presence generates increasing harvesting returns in the variable input z (a decreasing average cost of z) as the harvest level increases and the corresponding equilibrium x level falls.

Following Lewis and Schmalensee (1977, 1979 and 1982, call them LS), we will differentiate between two types of cost K: (i) a quasi-fixed cost $Q>0$ that is required if $h>0$, but it is *avoidable* $(Q=0)$ if the harvester shut downs his operations $(h=0)$[19], and (ii) a fixed cost $R>0$ that is *triggered by* the decision to stop harvesting operations with the intention to resume them later. We can think of $R>0$ as an *ex post* 're-entry' fixed cost, or as an *ex ante* 'exit' cost previous to the shutdown decision[20].

The second option is to assume a harvesting technology $h=h(x,y)$, where y denotes all other required inputs (in addition to x) for harvesting, with increasing returns to scale (IRS) at small x levels; that is, given an identical proportional change in x and y, the harvesting technology shows, at low x levels, a more than

[18] Let us suppose that the price per unit of fixed factor is equal to 1. Hence K units of fixed factor imply a fixed cost of K monetary units.

[19] Think of $Q>0$ as fixed searching costs or lump sum wage payments to the fleet's crew.

[20] For example, $R>0$ can represent fixed costs that arise with temporary shutdown if the harvesting firm is vertically integrated with a processing plant. Imagine that an important cost in the latter stage corresponds to energy inputs. The standard technology for fish meal industries, for instance, implies that energy costs increase discontinuously, and initially above its operational mode level, after a temporary shut down and the resumption of processing operations.

proportional change in h levels. This is the standard way to model increasing returns when long-run equilibria are considered. We assume that all the relevant inputs can be changed if we wish to do so[21].

In what follows we make explicit which modelling option is being considered. Unless stated otherwise, we assume (i) a fishing industry with price-taking firms and (ii) a harvesting technology defined at the firm level.

4.3.1 Do increasing returns in harvesting prevent collapse?

Beddington, Watts and Wright (1975), henceforth BWW, propose that IRS in $h=h(x,y)$, at small x levels, can be a *sufficient* condition to avoid collapse ($x^*=0$)[22]. Their basic argument considers: (1) a common pool renewable resource subject to closed entry, (2) multiple price-taking symmetric firms, each of them assumed to behave as a static profit optimizing harvester, (3) a strictly concave (logistic) growth function F(x), (4) a harvesting cost function $C(h,x)= Ah^k x^{-\eta}$, with $A>0$ as a constant, $\eta>0$, $k>1$ implying strict convexity of C(h,.)[23], and no fixed costs. Arguing that IRS in h(x,y) is equivalent to imposing the condition $k-\eta<1$ on the cost function C(x,h), and defining harvest rate h as the choice variable, BWW argue that constant or decreasing returns to scale in harvesting is a *necessary* condition to achieve a collapse result.

BWW offer the intuition that, if there were IRS at low x levels, harvesting firms would have incentives to increase stock x in order to reduce the average harvesting costs by taking advantage of the economies of scale. We will see that the assumption of zero fixed costs --in addition to the exclusion of non-concavities in the growth function F(x)-- plays an important role in BWW's proposition. In fact, as LS (1982) help to clarify later, this assumption implicitly supposes that to reduce h levels is a *costless* decision. Using the notation defined at the beginning of this section, BWW's result requires not only supposing that $Q=0$, but also that $R=0$.

Related to BWW's argument, there is a complementary line of reasoning that offers a way out to the possibility of collapse. The basic proposition is that fishing collapses are avoidable if the harvesting cost function $C=C(h,x)$ is 'sufficiently responsive' to changes in x when it approaches dangerous levels such as x_m, even for cases of free access to x and non-concavities in the growth function. Clark

[21] Economic intuition tells us that the proposition of IRS in h(x,y) also needs to make use, although it does it implicitly, of an assumption about the presence of some indivisible factor in the relevant technology. Otherwise, how could we justify the more than proportional productivity of the variable input choices?

[22] Berck (1979) cites other papers that follow a similar argument.

[23] The cost function C(h,x) is *defined* as corresponding to y combinations such that harvesting operations imply a least y-cost, for any given x level and any desired harvest rate h. The explicit functional form of C(h,x) is motivated as a combined result of (i) a Cobb-Douglas harvesting technology and (ii) the price-taking behaviour of harvesting firms.

(1971) is an example showing how *constant* average harvesting costs and constant selling prices help to obtain an extinction result. By contrast, several papers use the assumption that $C_x(x,h)<0$ in order to obtain stability for a positive steady state value of x. The classical paper by Scott (1955) belongs to this group. Other examples are Smith (1968), Levhari, Michener and Mirman (1982), Hartwick (1982) and Mirman and Spulber (1984).

To illustrate, let us consider Hartwick's (1982) model. Assume: (1) an *aggregate* harvesting function $H=Zg(x)$, with $g'(x)>0$ and Z as *aggregate* fishing effort, (2) a proportional-to-profit entry equation ($dZ/dt= k\Pi$, $k>0$ and Π denoting profits) that characterizes a *free-access* fishery such that $dZ=0$ when $\Pi=0$[24], (3) a continuous logistic (strictly concave) growth function F(x), (4) selling price responsiveness to H such that $p=p(H)$, $p'<0$, and (5) a constant cost w per unit of fishing effort. Using this structure, Hartwick proves the local stability of the steady state pair ($x^*>0$, $Z^*>0$) if two necessary conditions are satisfied.

The first condition is that the inverse demand function p(H) does not compensate sufficiently, via increases in price, the revenue effects [p(H)H] that arise from the reductions in the aggregate harvesting H as x becomes smaller. This condition requires that $|\epsilon|>1$, with $\epsilon=[dH/dp][p^*/H^*]$ denoting the demand price elasticity. This condition implies that a decline in harvest, due to a decline in x, will result in a decline in industry revenue, thus dampening the potential inflow of new entrants attracted by a higher price p. This condition plays a stabilizing role because it reduces harvesting pressures when x falls.

The second condition refers to a sufficiently x-responsiveness of the average cost harvesting function $c=w/g(x)$. This condition requires that $\eta=[dg/dx][x^*/g(x^*)]>1$, where η can be interpreted as the elasticity of (average) boat catch with respect to stock size. The condition $\eta>1$ implies that a decline in x leads to a more than proportionate decline in boat catch. This condition also implies that a fall in x produces a more than proportionate increase in the average harvesting cost c. Hence, on its own this condition suggests that exit will be encouraged by a decline in x at current prices.

The necessity of both conditions is meant to ensure that reductions in x will behave as a stabilizing force with respect to the free access harvesting incentives. Notice that these 'cost increases' models resort to the assumption that it is *costless* to reduce fishing effort when the low x harvesting performances create incentives to do so. Let us see how conclusions change when we explicitly introduce harvesting indivisibilities by the presence of a fixed cost $K>0$.

[24] Hartwick's discussion has no explicit modelling of each firm's optimization problem. The free entry equation solves for the endogenous variable Z.

4.3.b Increasing returns in 'costly to reduce' fishing efforts

Hoel (1978) rejects the sufficiency proposition of BWW (1975). He argues that IRS in harvesting by no means suffices to make the resource safe from extinction; neither does he accept that constant or decreasing returns to scale in harvesting is a necessary condition for achieving collapse. Among the different *ad hoc* intuitive counter-examples that Hoel offers, all of them for a closed entry fishery with price taking and static optimizing harvesting firms, he implicitly introduces the issue of *costly* downward adjustments in fishing effort levels.

Apart from the criticism that BWW exclude non-concavity effects from the growth function F(x), Hoel provides some counter-examples which imply aggregate harvests which always ($\forall x$) exceed the biological growth of stock x, in spite of exemplifying different individual harvesting technologies h(x,y) with IRS $\forall x$. Hence, despite the presence of IRS in individual harvesting technologies, the common pool resource is not safe from extinction. But *why* individual harvest rates are not downwardly adjusted in a faster way when $x \to 0$? Hoel's *ad hoc* examples do not answer it. Berck (1979) offers a complementary exposition which helps us to clarify the issue.

Modelling a free access fishery with a proportional-to-profits entry equation, subject to fully myopic harvesting, Berck considers the possibility of an x-range where $F(x) < 0$, calling the critical x^c level such that $F(x^c) = 0$ as the "minimum viable stock". Then Berck introduces a fixed cost $K > 0$ that defines a "minimum profitable" stock x^p. The presence of the fixed cost K introduces increasing returns in the choice of the harvesting rate. Berck's proposition is that collapse arguments need, to impose as a necessary condition, a restriction on the ratio $r(x) = [x^c/x^p]$ such that if $r(x) > 1$, then collapse is possible. The intuition is that the indivisibility introduced by $K > 0$ will tend to promote intensive harvesting, making the occurrence of fishing collapse more likely.

However, Berck (1979) does not deal explicitly with the issue of why harvesting firms would not follow *cyclical* harvesting strategies, given the presence of fixed factors. That is, harvesting 'heavily' for a while and hence taking advantage of the increasing returns in fishing effort z, but reducing or even stopping $z > 0$ when the system F(x) approaches a 'dangerous' x level such as x^c; then allowing for a period of recovery of x and, finally, restarting harvesting only when a safer level of x is achieved. To justify the arrival at a collapse outcome would require to assume that it is not profitable to stop harvesting even if we know that we are arriving at x^c. As with Hoel's counter-examples to BWW's proposition, the latter condition calls for an assumption of costly downward adjustments in fishing effort levels. LS (1977, 1979 and 1982) develop this idea.

Assuming a sole owner harvester, whose objective function is identical to that of a social planner, LS abstract from the issue of commonality externalities. Within a continuous time framework, their models evaluate the optimality of cyclical or pulse fishing strategies, when the optimization problem considers non-convexities arising from the growth function and from the existence of two different types of harvesting indivisibilities: (i) a fixed cost $Q>0$ that is required if $h>0$, but is *avoidable* if $h=0$, and (ii) a fixed cost $R>0$ that is *triggered by* the decision to stop harvesting operations with the intention to resume them later.

LS's models argue for the optimality of *cyclical* harvesting when harvesting technology requires quasi-fixed (avoidable) costs $Q>0$ along with positive, though 'not sufficiently high', re-entry costs R. Given this particular combination of Q and R values, pulse fishing strategies will not only be optimal from the sole-owner perspective, but they will also prevent collapse. The assumption that it is *costless* to reduce harvesting or fishing efforts, when increasing returns at low x offer incentives to do so, corresponds to a case with $R=0$. This is the framework within which BWW (1975) build up their proposition.

In a similar setting to BWW, by considering the case when $R=0$, LS (1982) argue for the possibility of 'convexifying' an originally non-convex choice problem (given $Q>0$ and $x^c>0$[25]), by making use of infinitely frequent adjustments in the fishing effort rate[26]. The key issue in this proposition, valid only for continuous time settings, is the sole owner's ability to stop, and later resume, fishing efforts without any explicit cost attached to the decision "set $z=0$; then resume $z>0$". In a case of this type, $Q>0$ will effectively reduce the initial level of investment in x; however, because Q is avoidable if we set $h=z=0$ when the fishery approaches x^c, 'quick' pulse fishing operations will help to avoid collapse.

Let us now impose $R>0$ costs to the use of chattering harvesting controls. If R becomes 'large enough' to discourage the use of *any* cyclical harvesting, then the optimal harvesting strategy will become to either harvest the resource on a sustained basis or to extinguish it in finite time (LS, 1977 and 1982). The corollary is that, as $R>0$ increases, the harvesting indivisibilities (generated by $Q>0$) tend to increase the likelihood of attaining extinction as a dominant (preferred) strategy within the sole ownership framework.

If, on the contrary, the relevant fishery setting defines an 'intermediate' level for $Q>0$ and $R>0$, a *regeneration* cyclical harvesting strategy can become optimal; that is, to stop harvesting to avoid fixed costs Q; then to allow stock x to increase and recuperate; and finally, to restart harvesting when the stock has become large or safe enough.

[25] The latter results from LS's modelling of critical depensation growth.
[26] Clark (1976, p.171) refers to this as a "chattering control" solution.

In other words, increases in $R>0$ tend to increase the time taken on each harvesting cycle[27] and also tend to increase the difference between the upper and lower bounds for stock x levels[28]. By contrast, as $Q>0$ increases, *ceteris paribus*, time spent in harvesting tends to be reduced, because of the more intensive harvesting that arises from the indivisibility introduced by Q.

In the case of *discrete time* settings it is not feasible to 'convexify' an originally non-convex optimization problem by 'infinitely rapidly' setting and changing the harvesting rate, even if $R=0$ (see Clark, 1976). Instead, for cases with $Q>0$ and $R=0$ the optimal policies correspond to *cyclical* harvesting strategies. They resemble the regeneration strategies that arise within continuous time models with $Q>0$ and $R>0$. Other combinations between Q and R values, within discrete time models, imply qualitatively similar results to those already described for continuous time settings. The models of Spulber (1983), Jacquete (1974) and Reed (1974) are some examples of discrete time models, with sole ownership and $Q>0$ assumptions, that bring about results in favour of optimal pulse fishing strategies. These three models also consider random shocks within the growth function F(x).

5. FINAL REMARKS

First, to propose that a particular fishing collapse is welfare worsening requires to argue not only that collapse is possible and that what is lost includes valuable assets, but also that the (social) value of those capital losses overcompensates the (social) benefit streams that result from disinvesting in the declining fish stock. These benefits include, on the one hand, the direct (social) yields that arise from investing in alternative assets and, on the other hand, the potential savings in the institutional and management resources which are required to enforce user rights upon the assets chosen for investment. Nonetheless, much work is needed, quoting Weitzman (1992), to provide "more-or-less usable measures of the value of *sustainability targets* that can tell us how to trade off one form of asset against another".

Second, our analysis of conditions traditionally associated with the occurrence of fishing collapse has discussed different types of causality, for different types of fishery settings. Open access, attractive profits, immobile fixed capital, and minimum viable population levels are frequently thought as direct causes of collapse. But of course they are not at the same level of causality. Minimum viable population levels contribute indeed to the occurrence of fishing collapse, but they are neither a sufficient nor a necessary condition to obtain such a type of result. Similarly, quasi-fixed harvesting capacity needs not necessarily promote heavy and sustained

[27] Or, a greater R tends to reduce the 'periodicity' of each cycle.

[28] Or, a greater R tends to increase the 'amplitude' of the harvesting cycles.

harvesting, as folk arguments often argue. Sunk capacity may produce incentives to pursue *cyclical*, and long-run sustainable, harvesting. Further analyses of the latter issue, for example allowing for risk bearing problems, seem to be particularly relevant, as real world fisheries frequently show this type of fishing strategy.

Open access commonality and attractive current profits are at a deeper level of causality. Even though, it cannot be taken for granted that entry restrictions or enacted taxes on harvesting, for example, will be the right policies to avoid collapse. It is not very difficult to imagine how access restrictions and taxes can be cheated. Efficient policies should take care of more fundamental causes. For example, one should ask why enacted regulations are not always properly enforced? Or, why *de facto* open access conditions have been allowed to persist, in several cases despite the increasing evidence of a more scarce natural resource? This type of result depends on the resources invested in management services and their enforcement. This in turn depends on policy priorities. Rent-seeking games, induced by the existence of commonality, surely contribute to shape these priorities. The regulation of fishing collapse must give attention to these issues.

Appendix 1

Examples of collapsed marine fisheries during XXth century

Species	Peak annual catch (year)	Catch in 1980-84
Antarctic blue whales	29.000 whales (1931)	Nil (1981)
Antarctic fin whales	27.000 whales (1938)	Nil (1981)
Hokkaido herring	850.000 tons (1913)	Nil (1981)
Peruvian anchovy	12,3 million tons (1970)	0,7 million tons (1980)
Southwest African pilchard	1,4 million tons (1968)	Nil (1981)
North sea herring	1,5 million tons (1962)	Negligible (1981)
California sardine	640.000 tons (1936)	Nil (1981)
Georges bank herring	374.000 tons (1968)	Nil (1981)
Japanese sardine	2,3 million tons (1939)	17.000 tons(1981)
Humpback whales	5.063 whales (1950)	16 (1980)
Sei whales	25.454 whales (1965)	102 (1980)
Sperm whales	25.842 whales (1970)	2.091 (1980)
Tiger prawn	1.200 tons (1975)	< 100 tons (1983)
Greenland cod	363.000 tons (1960-64)	50.000 tons (1984)

Sources: Clark (1985), Pearce and Turner (1990), Gulland (1988).

Appendix 2

The following first-order conditions suffice to identify a trajectory pair (h^*,x^*) which optimizes the problem in equation (4).

$$[\frac{\partial H}{\partial h}]h^* = 0 \ ; \ for \ h^* > 0, \ then \ [\frac{\partial H}{\partial h}] = 0 \ \Rightarrow \frac{\partial \Pi}{\partial h} = \lambda \tag{A1}$$

$$\dot{x} = \frac{\partial H^*}{\partial \lambda}; \ with \ H^* = H(h^*) \quad such \ that \ \dot{x} = F(x) - h^* \tag{A2}$$

$$\dot{\lambda} = \delta\lambda - \frac{\partial H^*}{\partial x} = \delta\lambda - \frac{\partial \Pi^*(h^*)}{\partial x} - \lambda F'(x) \tag{A3}$$

$$\lim_{t \to \infty} [\lambda(t) \ e^{-\delta t}] \ x(t) = 0 \tag{A4}$$

The simultaneous fulfilment of (1) the joint strict concavity of functions G(x,h) and Π(x,h) in the variables x and h, and (2) the transversality condition in (A4), ensures that the optimal trajectories will converge to a steady state in which the harvest rate and the fish stock are constant (Chiang, 1992, p.124). This implies $\dot{x}=0$, $\dot{\lambda}=0$; hence, by introducing (A1) into (A3) and then combining it with (A2), we obtain equation (5) which characterizes the steady state solution pair (x^*,h^*).

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