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Modelling the Taxation of Overexploited Open-Access Fisheries

BY

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Abstract.–GATTO M. and GHEZZI L., 1990. Modelling the taxation of overexploited open-access fisheries. *In*: Dynamical Models in Biology, R. Arditi (ed.). *Mém. Soc. vaud. Sc. nat. 18.3*: 213-225.
The paper aims at identifying the effects exerted by a tax levy on an overexploited and previously unregulated fishery. The analysis is carried out by means of a dynamic model, which includes the fish stock, the harvesting effort and the price for fish as state-variables; attention is focused on the roles played by both the demand elasticity and the open access externality. According to the analysis, the standard results provided by the received microeconomic theory are remarkably modified. In the long run a higher amount is sold at a lower price regardless of demand elasticity.

Résumé.–GATTO M. et GHEZZI L., 1990. Modélisation de la taxation de pêcheries surexploitées à accès libre. *In*: Modèles dynamiques en biologie, R. Arditi (dir.). *Mém. Soc. vaud. Sc. nat. 18.3*: 213-225.
Ce travail cherche à identifier les effets de la taxation d'une pêcherie surexploitée et précédemment non réglementée. L'analyse est accomplie au moyen d'un modèle dynamique qui comprend le stock de poisson, l'effort de pêche et le prix du poisson comme variables d'état. L'attention est portée sur les rôles joués par l'élasticité de la demande et par la liberté d'accès à la pêcherie. Selon cette analyse, les résultats standards de la théorie microéconomique traditionnelle sont considérablement modifiés. Sur le long terme, du poisson plus abondant est vendu à un prix inférieur indépendamment de l'élasticité de la demande.

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1. INTRODUCTION

Since the classical work by GORDON (1954) the unavoidable overexploitation of fish stocks in unregulated fisheries has been perceived as a major threat not only to the survival of many species but also to the profitability of the fishing industry. The received doctrine suggests several regulatory methods to overcome the inefficiency of the open-access fishery; they can be roughly grouped into *normative non-exclusive instruments* (total catch quotas, place and gear restrictions), *exclusive fishing rights* (licenses, allocated catch quotas) and *financial disincentives* (taxes, royalties, subsidies cuts).

Normative methods have the advantage of avoiding depletion without withdrawing a share of the fishery rent. Their effectiveness however relies on the existence of costly organizations performing both monitoring and enforcement tasks (see SUTINEN (1985) for a theoretical analysis of the problem). Considerable costs can thus preclude the implementation of these systems, especially in the case of countries dealing with rising national debts. On the other hand, by restricting access to a few fishermen, *exclusive fishing rights* prevent the phenomenon of excess capacity but also pose a difficult problem of fairness.

To *taxes* is generally ascribed the drawback of depriving the fishermen of part of the fishery rent to the benefit of society at large. On the other hand, the advantage is considerable in terms of simplicity and inexpensiveness of implementation.

This paper analyzes in a novel way the bulk of scattered results concerning the effects of taxes on an open-access fishery. Although the case of a variable price for fish is treated extensively in the literature, the demand for fish is generally assumed to be infinitely elastic in the works where account of taxes is taken (ANDERSON 1977, CLARK 1976, 1985). This hypothesis is now relaxed to effectively cover the issue of whether taxes fully or at least partially affect the market price for fish.

More specifically, a dynamic model of an unregulated fishery is introduced in section 2. Fish stock, harvesting effort and the price for fish appear as state-variables in a framework where, in contrast with the prevailing practice, price movements are supposed to be faster than the ones of the other state-variables. After performing a stability analysis, the sensitivity of equilibria is checked against changes in the features of both the demand for fish and the harvesting efficiency. Furthermore, the long term evolution of the overexploited fishery is shown to be related to some topological properties of the model isoclines.

The role played by taxes relative to demand elasticity is considered in section 3. At first a static analysis is carried out that compares the long run price with the one ruling before the levy. A result is obtained whereby a long run decrease in price occurs irrespectively of demand elasticity. Short run effects are also highlighted by means of a dynamic analysis.

2. THE FISHERY MODEL

Wide acceptance has been gained by the work of SMITH (1968, 1969), who devised a dynamic version of the commercial fishery model pioneered by GORDON (1954) and SCHAEFER (1957). The model we use in this paper might be considered as an extension of that of Smith and it is given by the following equations

$$\frac{dx(t)}{dt} = F(x(t)) - h(t) \tag{1}$$

$$\frac{dE(t)}{dt} = k[p(t)h(t) - cE(t)] \tag{2}$$

$$\frac{dp(t)}{dt} = m[G(h(t)) - p(t)] \tag{3}$$

where t is time, x is the fish population biomass, E denotes the fishing effort, p is the market price for fish, $F(x)$ is the natural growth rate, h represents the harvesting (or catch) rate, $G(h)$ is the «inverse» demand curve, k and m are suitable reaction coefficients, c is the constant cost of effort[1]. In the sequel reference will also be made to $g(p)$, the demand curve, which is the inverse function of $G(h)$.

We assume that

– $F(x)$ is concave[2] positive only on the open interval $(0, K)$, and vanishing at 0 and K (the so-called environmental carrying capacity);

– the production function is of the Schaefer type: $h = qxE$, where q is the catchability coefficient;

– $G(h)$ monotonically decreases with h while the relating total revenue function $G(h)h$ exhibits decreasing marginal return. For the sake of simplicity, $G(h)$ is further supposed to possess elasticity which does not increase with h.

When drawing the pictures hereafter presented, $F(x)$ and $G(h)$ have been supposed to be logistic and linear respectively. Needless to say, the

[1]This implies the usual assumption that the supply of effort is infinitely elastic.

[2]Depensation and critical depensation cases are therefore ruled out. [Depensation is defined and discussed, e.g. by CLARK (1976, p. 108-113).]

main conclusions emerging from the current analysis are not affected by this selection. Noticeable differences from Smith's specifications are

– as the demand for fish is not assumed to be infinitely elastic, equation (3) has been added to explain price movements;

– E does not represent the number of standard vessels operating in the fishery (the capital invested), but is rather a suitable measure of labor. This is consistent with the case of many commercial fleets, the vessels of which harvest several different populations without relying exclusively on one stock. Entry and exit from any fishery become therefore short-term events.

System (1), (2), (3) is a general model of fishery which can be specialized to include the case of the backward bending «supply» curve (ANDERSON 1973, COPES 1970). That model rests on the assumption that price changes very slowly with respect to the dynamics of fish biomass and fishing effort. Mathematically this amounts to requiring that the dynamics of price, as described by equation (3), is very slow when compared with the ones of the fish stock and the harvesting effort, given by equations (1) and (2) respectively. Such equations can therefore be equilibrated, thus obtaining the backward bending «supply» curve. Following the standard procedure, the long term equilibrium can then be identified by intersecting such a locus with the demand curve in the (p, h) space.

We take the opposite and, in our opinion, more realistic viewpoint that price variations occur on a shorter time scale than the ones of x and E. More specifically, we assume that market clears, namely that price instantaneously adjusts so that catch is always completely sold

$$p(t) = G(h(t)) \ .$$

Equations (2) and (3) are then replaced with

$$\frac{dE(t)}{dt} = k[G(qx(t)E(t))qx(t)E(t) - cE(t)] \tag{4}$$

and the fishery dynamics is consequently explained by equations (1) and (4) only. Thus the present approach and the one relying on the backward bending «supply» curve stem from different «fast-slow dynamics» hypotheses. Both approaches share the same long term equilibria, but, in our opinion, the former allows a more correct evaluation of the transients, which for long-lived, slowly growing species may well last one or two decades. It is worthwhile to remark that BERCK (1981) also assumed that market clears but he disregarded the role played by the effort dynamics.

Having introduced the various assumptions concerning the fishery model, we now proceed to the analysis of its main features. The economically significant equilibrium states lie on the intersections of the $dx/dt = 0$ isocline

$$E = \frac{F(x)}{qx} \tag{5}$$

with the non-trivial $dE/dt = 0$ isocline branch

$$E = g(\frac{c}{qx})\frac{1}{qx} \; . \tag{6}$$

Since $F(x)$ is concave, the right-hand side of (5) is a decreasing function of x. To each point lying on the curve defined by equation (6) there corresponds a catch rate h such that $h = g(c/qx)$ (remember that $g(p)$ is the demand function). Consequently, the catch rate h increases with x as the price p per unit of harvested biomass equals the unit cost of production (c/qx). It follows that the right-hand side of (6) is increasing with x or unimodal, since it varies as $g(p)p$, the total revenue as a function of price. In particular, demand elasticity exceeds unity where the right-hand side of (6) is rising, equals unity where it is maximum and is lower than unity where it is decreasing.

Let us further define h_{MSY} as the maximum sustainable yield and h_{MR} as the catch rate that would grant the maximum revenue $h_{G(h)}$, if this rate were sustainable. h_{MSY} can be thought of as a measure of bio-technical efficiency whereas a unitary demand elasticity corresponds to h_{MR}, which relates to the concept of economic efficiency.

As the character of the fishery actual equilibrium point varies according to the relationship between maximum sustainable yield and demand elasticity, the cases $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$ and $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ are given distinct examinations. To enhance comprehension, isocline patterns are outlined. Moreover, both the equilibrium relationships between total revenue and effort and total cost and effort are considered; the sketching of the former relies on ANDERSON (1973).

The isocline patterns concerning the case $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$ are portrayed in fig. 1a.

Along any of the dotted hyperbolas, in the sequel referred to as iso-catch lines, catch rate h is constant. Point V marks the equilibrium of the exploited fishery; it can be shown that it is stable and generally a focus. Throughout the paper this kind of equilibrium, which corresponds to a demand elasticity exceeding unity, will be referred to as type I.

In fig. 1b this equilibrium is depicted as the intersection between the total revenue and the total cost curve. Had the effort cost c taken another value, the equilibrium point would have remained of type I while shifting along

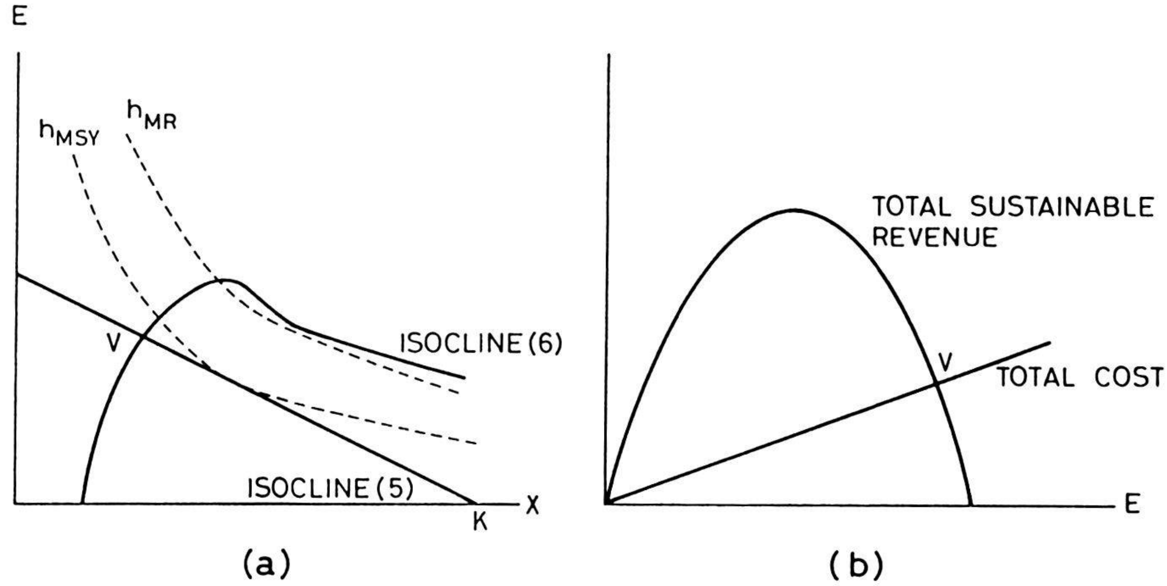

Figure 1.–Finding the equilibria of the fishery model (1), (4) in the case $h_{\text{MSY}} \leq h_{\text{MR}}$ (the demand for fish is elastic); (a) isocline patterns; (b) total revenue and total cost versus effort.

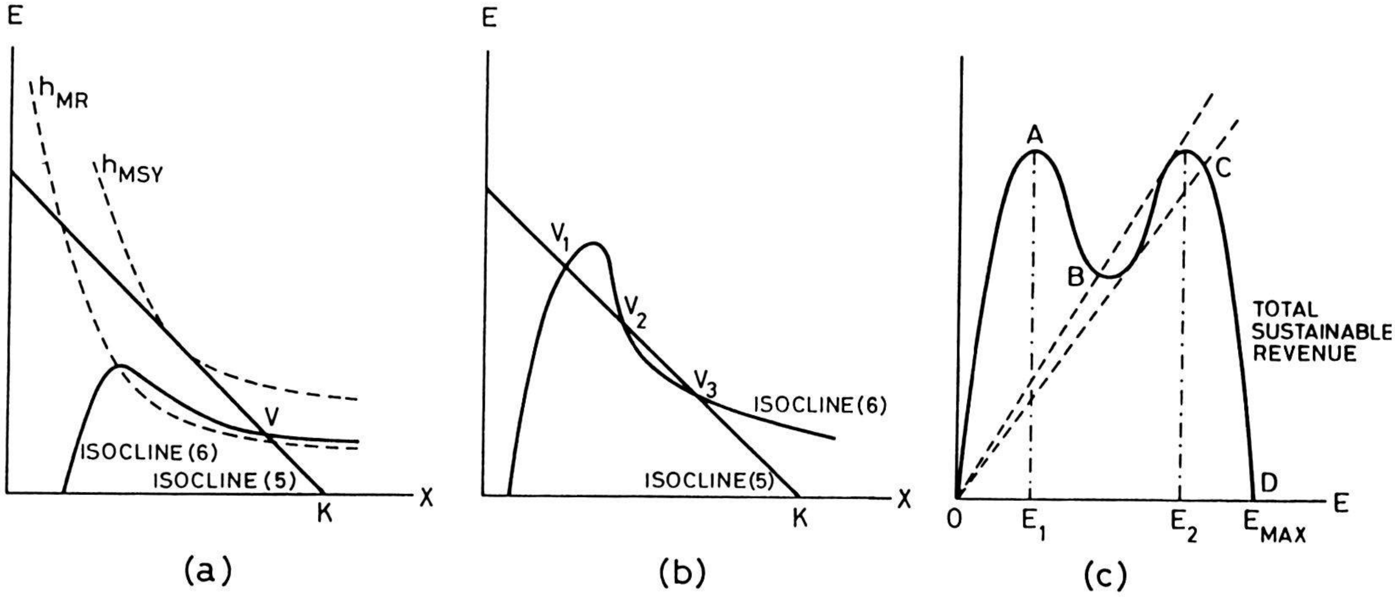

Figure 2.–Finding the equilibria of the fishery model (1), (4) in the case $h_{\text{MSY}} > h_{\text{MR}}$ (the demand for fish is inelastic); (a) isocline patterns (not heavily exploited fishery); (b) isocline patterns (overexploited fishery); (c) total revenue and total cost versus effort.

the isocline (5). Notice that the same result would hold if price for fish were assumed to be constant. This is not unexpected, because unimodal total revenue curves correspond to infinitely elastic demand curves as well as to fairly elastic ones.

On the contrary, when $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ the total revenue curve possesses two maxima, as depicted in fig. 2c; further, demand is elastic when $0 \leq E \leq E_1$ and $E_2 \leq E \leq E_{\mathrm{MAX}}$.
The existence of one or more equilibrium points and their characters therefore depend on the value of the effort cost c. If the cost curve cE intersects the revenue curve within either sector 0A or sector CD there is one non-trivial equilibrium state only, which is still of type I. If the intersection otherwise occurs in sector AB, where demand elasticity is lower than unity, it is readily proved that the resulting equilibrium, from now onwards labelled as type II, is a stable node. The corresponding isocline patterns are portrayed in fig. 2a, where point V marks the equilibrium state.

The further and more intricate occurrence concerns a triple intersection in sector BC, where two stable equilibria are separated by a saddle point. A possible outcome is depicted in fig. 2b, where point V_1 is a type I equilibrium, point V_2 is a saddle point and point V_3 is a type II equilibrium. Whether the actual equilibrium is either point V_1 or point V_3 hinges on the past history of the fishery.

As we are concerned with the case of an unregulated and intensively exploited fishery, the intersection between the total revenue and total cost curves can be safely assumed to occur in sector CD. As a matter of fact, the transition from underexploitation to overexploitation generally derives from changes in the features of the economic environment. Basically, these amount to shifts in the demand curve, which are induced by increases in consumers' income, as well as to increases in the harvesting efficiency, as a consequence of technological improvements.

In terms of the present model, the first event implies an upward shift of the total revenue curve; if it is of the double maximum type, a catastrophic jump can occur. This issue has been covered by (CLARK 1976), who considers the intersections between a given backward bending «supply» curve and a slowly varying demand curve (see especially his fig. 5.20, p. 156). Demand changes also entail the shift of isocline (6) with respect to isocline (5)[1].

[1]The whole process can be summarized as follows (and readily checked by sketching the isocline patterns). Let us assume that the incipient condition coincides with an equilibrium of type II. Subsequent shifts of isocline (6) generate the appearance of another equilibrium state, which then splits into a saddle point and a type II equilibrium. Following further shifts of isocline (6), the saddle point moves then towards the current equilibrium state, which still remains of type II. Meanwhile the other equilibrium state enters the type I class. The catastrophic jump eventually occurs when the saddle point reaches the current equilibrium state, vanishing with it.

The same rationale applies to the case of technological improvements, which «squeeze» horizontally the total revenue curve. The relating comparative statics exercise is dealt with, e.g. by ANDERSON (1977, p. 47-50) in the case of an infinitely elastic demand but the extension to the variable price case is straightforward. Technological improvements modify the specifications of both isoclines (5) and (6) of the isocatch hyperbolas as well.

3. THE EFFECTS OF TAXES

In the present section the effects exerted by a proper tax policy on an overexploited and previously unrestricted fishery are examined. This issue is treated extensively by ANDERSON (1977, p. 174-183) and CLARK (1985, p. 157-174) but the case of a variable price for fish is only incidentally approached. Berck's analysis (BERCK 1981) takes the matter into account, yet it does not consider the role played by both demand elasticity and effort dynamics. Although the case of a tax per unit of landed fish is usually considered in the received doctrine, nevertheless the current analysis is carried out in terms of a tax rate T imposed on the selling price as such policy can be more easily implemented.

The regulating authority goals may be different, sometimes even conflicting. However, when considering the problem from the consumers' point of view, h_{MSY} as equilibrium catch rate may become a reasonable target, since the corresponding market price for fish is minimum. Being aware of the criticism surrounding the concept of the maximum sustainable yield as a management tool (LARKIN 1976), we stress that it is used here as a benchmark only. In fact, as pointed out previously, the current analysis is chiefly concerned with the central albeit seldom explored issue of whether a significant part of the tax rate would ultimately be loaded on demand either in the short or in the long run.

Equation (4) is restated here to allow for the tax rate T

$$\frac{dE(t)}{dt} = k[(1-T)G(qx(t)E(t))qx(t)E(t) - cE(t)] \,. \tag{7}$$

Isocline branch (6) is then replaced with

$$E = g\left[\frac{c}{(1-T)qx}\right]\frac{1}{qx} \,. \tag{8}$$

To each point lying on the curve defined by equation (8) there still corresponds a catch rate h such that the price p per unit of harvested biomass equals the relating cost of production, now suitably modified to allow for the tax rate. As equation (8) differs from equation (6) only in the parameter $(1-T)$ and in a suitable rescaling of the x axis, it retains the same features depicted in the previous section. It can also be easily checked that any increase of the tax rate T moves isocline (8) downwards in the state space. A similar shift is exhibited by the curve relating total revenue to effort at equilibrium since from the supply point of view the tax rate imposition amounts to a shrinkage of demand and consequently of total revenue.

To get a deeper insight into the effects exerted by the levy on the equilibrium set, the tax rate T is given the appearence of a slowly varying parameter in the analysis to follow. The fishery is supposed to be at first heavily overexploited, so that the current equilibrium state (4) of system (1) is of type I, as pointed out in the previous section. Given that neither h_{MSY} nor h_{MR} are affected by tax imposition[1], the two cases $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$ and $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ are topologically the same as those considered in Section 2; consequently, they are given separate examination. The former is depicted in fig. 3 while the latter is portrayed in fig. 4; in both pictures, still referring to a demand curve of the linear kind, point V_{OLD} marks the starting equilibrium while V_{MSY} is the equilibrium that grants the maximum sustainable yield.

If $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$, the total revenue curve does not change its shape when T is increased; therefore, the actual equilibrium is always of type I.

If $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$, the new equilibrium is either of type I or of type II depending on the value of T. In particular, the actual equilibrium is at first of type I but it turns to type II when T exceeds a certain value. Two basic events may then occur, that depend on $D = h_{\mathrm{MSY}} - h_{\mathrm{MR}}$ being small or large. If D is small, either no bifurcation occurs as T is increased or two bifurcations take place, that corresponds to a *fold catastrophe*. If the equilibrium transformed by the second bifurcation is labelled as V_{BIF}, the inequality $E_{\mathrm{MSY}} < E_{\mathrm{BIF}}$ holds (see fig. 4a). On the other hand, if D is large, two bifurcations occur but the catastrophic jump is now such that $E_{\mathrm{MSY}} > E_{\mathrm{BIF}}$ (see fig. 4b).

From the regulating authority point of view these facts imply that

- if $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$ (see fig. 3a) the current equilibrium state can be shifted toward the one granting the maximum sustainable yield by means of a careful tuning of T;
- if $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ and D is small, V_{MSY} can still be achieved by a proper selection of the tax rate T to be levied (see fig. 4a again);
- if $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ and D is large, the hysteresis exhibited by the model rules out the possibility of a straight convergence to the target, which can

[1]In fact, the total revenue curve is such that either the only maximum (when $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$) or the two maxima and the local minimum (when $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$) correspond to fixed values of effort regardless of tax rate T.

however be achieved by means of a time-varying tax policy. For instance, a suitable tax rate could be levied to shift the equilibrium state to point $V_{\rm BIF}$; as soon as point $V_{\rm BIF}$ has been approached the tax rate should be reduced to shift back the equilibrium point toward point $V_{\rm MSY}$ (see fig. 4b again).

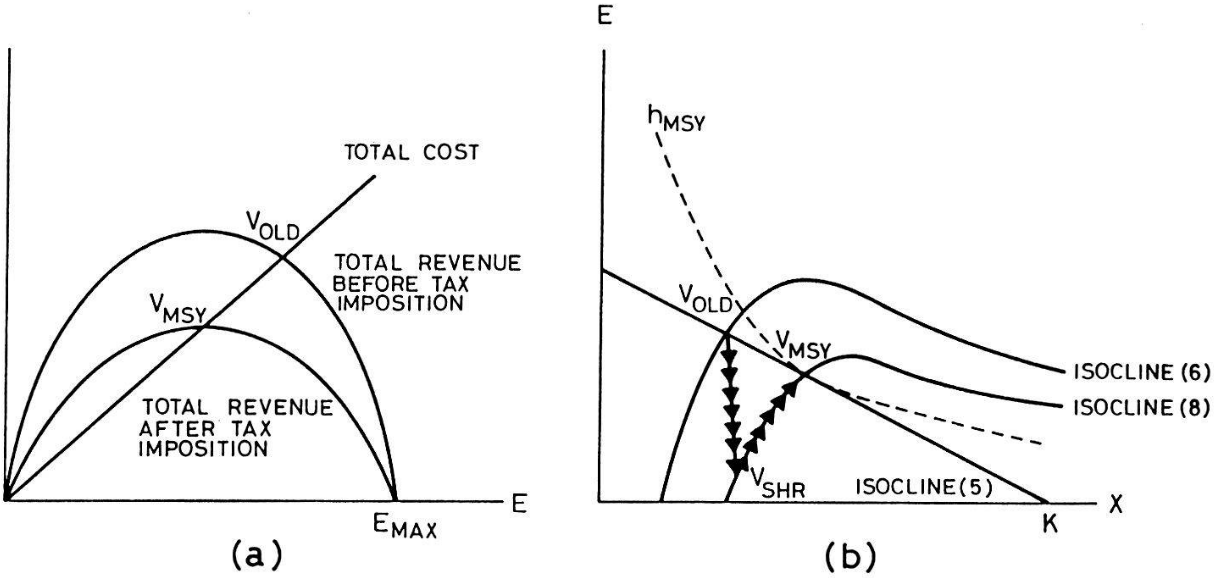

Figure 3.–Analyzing the effects of a levy in the case $h_{\rm MSY} \leq h_{\rm MR}$ (the demand for fish is elastic); (a) the shift of the total revenue curve; (b) the isocline shift and the approximate trajectory toward the new equilibrium.

In comparative statics terms, the change induced by the tax levy can be qualitatively subsumed as follows, *regardless of the actual relationship between* $h_{\rm MSY}$ *and* $h_{\rm MR}$

$$x_{\rm MSY} > x_{\rm OLD};\; E_{\rm MSY} < E_{\rm OLD};\; h_{\rm MSY} > h_{\rm OLD};\; p_{\rm MSY} < p_{\rm OLD}\,.$$

Turning now our attention to transients, the analysis becomes straightforward if the dynamics of the fish stock, given by equation (1), is assumed to be slower than the one of effort, as described either by equation (4) or (7)[1]. Further, when considering the case $h_{\rm MSY} > h_{\rm MR}$, D is supposed to be small, in order to avoid technical complexities. The solid arrows in fig. 3b and 4c mark the approximate trajectories joining $V_{\rm OLD}$ to $V_{\rm MSY}$. In the short run, effort and catch rate slump in both cases, consequently raising the price for fish, but in the long term the harvesting rate exceeds the corresponding initial value whereas the price for fish is lower than that prevailing in the unregulated context. The basic features of the transient

[1]The diversion to other fisheries of labor previously devoted to the harvest of a particular stock is supposed to rapidly occur according to profitability. From this point of view, it is thus reasonable to expect that this event takes place on a smaller time scale than the one of the fish stock dynamics.

hinge again on demand elasticity. If $h_{\mathrm{MSY}} \leq h_{\mathrm{MR}}$ (fig. 3b) fishermen' short term reaction is sharper but it is then offset by an even wider long term adjustment. If $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ (fig. 4c) the incipient reaction as well as the subsequent adjustment process are less pronounced[1].

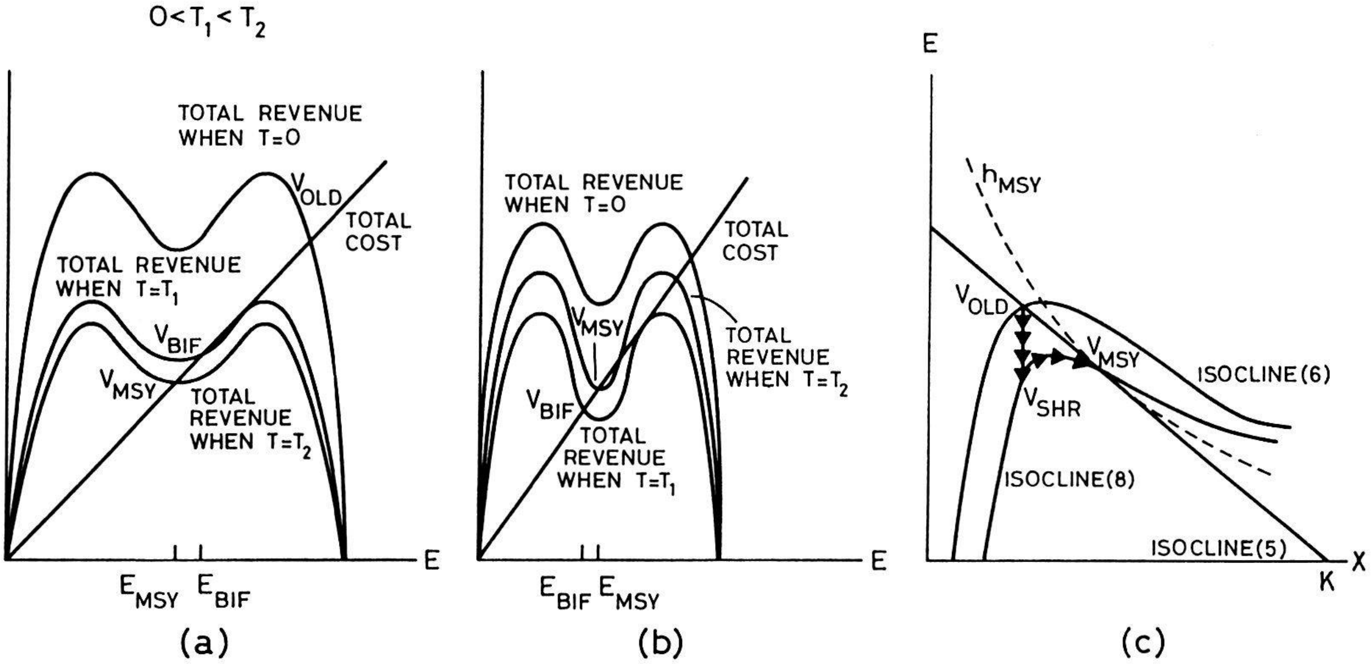

Figure 4.–Analyzing the effects of a levy in the case $h_{\mathrm{MSY}} > h_{\mathrm{MR}}$ (the demand for fish is inelastic); (a) the shift of the total revenue curve (the demand for fish is fairly inelastic); (b) the shift of the total revenue curve (the demand for fish is very inelastic); (c) the isocline shift and the approximate trajectory toward the new equilibrium.

The economic rationale underlying the whole process can be so explained. As shown in the previous section, the equilibrium of an unregulated fishery is such that

$$p_{\mathrm{OLD}} = \frac{c}{q x_{\mathrm{OLD}}} .$$

When the tax is levied, this equality no longer holds

$$p_{\mathrm{OLD}} < \frac{c}{(1-T) q x_{\mathrm{OLD}}} .$$

To set a new balance between revenue and cost, fishermen reduce at first their effort; harvest is then decreased, so that a smaller amount of fish is

[1]In both cases the temporary shrinkage of effort is likely to be less sharp in the real world, as fishermen behavior is also affected by the expectations they hold on future developments.

sold at a higher price than previously. At point V_{SHR} (see fig. 3b and 4c), where the economic equilibrium is temporarily restored, the full tax is added to the price

$$p_{\mathrm{SHR}} = \frac{p_{\mathrm{OLD}}}{1-T} \, .$$

In the short run, demand is consequently burdened with the full tax; for a given tax rate, the more elastic the demand the larger the magnitude of the supply fall. However, the subsequent recovery by the fish stock gives rise to an up-turn: the increase in supply rate, due to the reduction progressively occuring in the harvesting cost, is such that final price p_{MSY} is smaller than the initial one p_{OLD}.

4. Final Remarks

Standard microeconomics theory claims that when a tax is levied on goods sold in a purely competitive market the burden is loaded on demand only if it is unelastic.

The analysis carried out in the present paper suggests that, in the case of a fishery, the presence of an externality remarkably modifies the aforementioned result. The imposition of a suitable tax rate generally stirs a supply slump and a consequent rise of the price for fish in the short run, but considerable efficiency gains are subsequently induced by the ensuing recovery of the previously overexploited stock. Supply therefore grows again and the burden due to the tax is then more than offset in the long run irrespectively of demand elasticity, which however affects the features of the transients.

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