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INTERDEPENDENCE BETWEEN POLLUTION AND FISH RESOURCE HARVEST POLICIES*

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Abstract

This study presents a bio-economic model in which the dynamics of a fishery are affected by marine pollution both directly and indirectly. From the optimality analysis it can be seen that as long as a contaminating sector exists near coastal areas the policy on fish resource harvest will be more intense initially (when the environmental situation is better) and less intense in subsequent periods, that is, the fish resource will be managed as if it were a non-renewable resource. It will be also shown that, while the effect of pollution coexists with resource exploitation it cannot be though of the resource stock being in a stationary state, which leads the regulator to adopt a policy whereby the release of pollutants can be better controlled.

Keywords: Fish resources, Marine pollution, Dynamic Programming.

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1. INTRODUCTION.

As it is well known, the sea has always been a great source of multifunctional natural benefits. It provides a habitat for marine flora and fauna, as well as serving as a means of commerce and a dump. Until not too many decades ago, the characteristics that best defined the ocean were its immensity and its fruitfulness. The almost total lack of norms or regulations relating to its uses is therefore not surprising. Today, however, the notion of scarcity characterises marine resources more than ever. At present, the ocean sees itself threatened on at least two fronts; over-fishing and pollution.[1] Insofar as the latter is concerned, it has to be said that the empirical evidence shows that the world's population tends to be concentrated along coastal areas. However, habitual residents, tourists, commercial interests, etc. and marine life compete with each other in ways that are not always compatible. Fisheries in closed and semi-closed seas offer the first basis for an evaluation of the effects of marine pollution as they have witnessed various radical changes in the ecology of water masses, due not only to the effects of fishing but also to the consequences of human pollution (Kahn and Kemp (1985),[9] Conrad and Clark (1987),[3] Cropper (1985)[6]). Some of the sources of marine pollution are constant and, therefore, easily identifiable (built-up urban areas, farms, above all, an excessive use of fertilisers and intensive stock breeding),[2] but others are not,[3] which make their identification more difficult. One of the clearest examples is the Black Sea, into which the rivers of a large part of Europe and Asia flow. The contribution of nutrients from these rivers combines with the fact that the only way to the open sea is through the Bosphorus, which gives rise to high concentrations of nitrates and phosphates. This uncontrolled discharging of nutrients in turn gives rise to what is known as the "eutrophication" of the sea. One of the main consequences of this marine phenomenon is the increase of the extraordinary and dense growth of phytoplankton. Initially, zooplankton species help the development of populations of small pelagic fish, but other invertebrate predators, which have no commercial value whatsoever (the most representative example of a predator is the jellyfish, or medusae[4]).
These invertebrate predators feed on fish larva and if all of this is combined with intensive fishing activity, many fisheries might be forced to close. Knowler et al. (1997),[11] FAO (1996),[8] and, World Resources Institute (1992),[24] describe how medusae populations have brought anchovy fishing in the Black Sea to a situation where the resource is all but exhausted. Other similar examples are to be found in the anchovy fisheries in the Azov and Marmara Seas.

The phenomenon described reveals how marine pollution can affect the dynamics of fish resources not only directly but also indirectly, as, for example, in the case highlighted above, due to the activity of invertebrate predators. As it could be imagined, this is not the only indirect means by which pollution influences fish resources. In this respect, Kahn and Kemp (1983)[9] examine the case of Chesapeake Bay, where the excess of nutrients, herbicides, as well as the erosion of the land, have altered the ecological estuary, causing a reduction in aquatic vegetation, which affects fish resource biomass. For its part, World Resources Institute (1992)[24] points out that numerous fisheries have been indirectly affected by pollution, through the abundant growth of toxic algae which has seriously affected resource biomass. Numerous examples have been studied in the Black Sea, the Baltic, the North Sea, Japan, Hong Kong and others. In general, Caddy and Griffiths (1996)[1] affirm that if it is indeed true that the general productivity of coastal and continental seas normally increases with the drainage of nutrients, above a certain level of drainage, it is more than doubtful that fisheries' net profit will be positive. On the other hand, the direct effect of pollution on resources, as Collins, Stapleton and Whitmarsh (1998)[4], among others, affirm, is no less important.

Given the importance that all these indirect means of transmitting pollution have with regard to fishery development, from an economic point of view, adopting any policy regarding investment or disinvestment in fish resources which does not in some way incorporate the indirect influence of pollution might not be the optimum one. However, a problem that stands out when considering the environmental pollution fish resources, or other renewable resources, have to bear is the joint nature of the problem. It will be quoted here some previous studies; for example, McConnel and Strand (1988)[13] introduce a parameter in the resource growth function, which represents the quality of the water. They assume that improvements in water quality will increase biomass growth, as is true also of fishing activity profits. Other studies, such as those by Swallon (1989)[22] and Olsen and Shortle (1996)[15] and Tahvonen (1991)[23] present various joint models. Swallon (1989)[22] presents a partial equilibrium analysis of inter-relationships between the production of renewable resources, in particular fish resources and the development of a coastal area (tourism, urban activity, etc.). Development alters the environment in a continuous way, which could put the viability of fishing industries in danger. Olsen and Shortle (1996)[15] present a model in which both resource stock as well as pollution are stochastic. They analyse the additional factors that uncertainty introduces into the structure of the optimality conditions for the resource and pollution stock. The article is based on the model presented by Tahvonen (1991)[23] in conditions of certainty.

In this study, it is shown how the fact of considering the indirect effect that pollution has on resources alters the different resource harvest policies and nutrient release, as well as, how it is not possible to reach a stationary state as long as such inter-relationships between pollution and fish resources last. With this aim in mind, in particular, it has been chosen as an indirect means of transmitting pollution that which occurs by means of invertebrate predators, as it has been proven that this is one of the most aggressive environmental means of transmitting pollution, to the extent it is the reason why many fisheries have been exhausted.

The study is structured as follows. In section 2, it is set out a joint bio-economic model which allows for the incorporation of both the direct and indirect effects of pollution on fish resources. The direct effect is shown in the model through the incorporation of a nutrient stock movement equation and the indirect effect through the introduction of a movement equation for invertebrate predator stock whose biomass is introduced into the fish resource growth function. In this section, use is made of the Dynamic Programming instrument in order to obtain the optimality conditions both for the resource stock as well as the nutrients. Section 3 shows how it is not possible to talk of a stationary situation as long as the influence of the stock of predators on the dynamics of the evolution of the resource stock persists. It is presented the policies that the regulator should apply in order to tend towards said stationary situation. Lastly, the main conclusions and scope or extensions of the study are set out.

2. A JOINT FISHING MODEL.

The aim of this section is to present a joint bio-economic model. By "joint" it is meant that, it incorporates the management of two sectors simultaneously, that is, a contaminating sector and a fishing sector. It is then assumed that the sea can be subjected to several uses simultaneously, a habitat for fish resources and an outlet exploited commercially[5], although the compatibility of both activities will only be possible for certain levels of nutrient discharge.

2.1 The basic model.

Below, it will be set out the processes that are introduced into the model in order to describe the evolution of the stocks considered, which are the fish resource stock, the predator stock and the pollution stock. Beginning with the first of these, a typical fishery model would describe the evolution of the resource stock from period to period by means of a biomass net growth function, which depends on the stock of the resource and a harvest function. However, in this study it will be considered (following Knowler et al. (1997)[11]) that the growth of the stock might depend on other factors, such as the presence of certain pelagic predators whose biomass is a nutrient stock function (the predator stock is precisely the variable which it is used to link the contaminating sector and the fishing sector).
The movement equation which describes the evolution of the fish resource stock is as follows:

$$dX = [F(X,M) - h(t)]dt, \tag{1}$$

Where:
X: fish resource stock;
F: biomass growth function;
M(Z): pelagic predators' stock, which in turn depends on the stock of nutrients in the sea, *Z*. This stock is given the letter M because they are usually medusae.
h(t): harvest rate. $0 \le h \le h_{\max}$; Where $h_{\max}$ represents the maximum harvest capacity.

Note equally that by introducing the predator stock in the resource growth function the influence of "chronic" pollution is being considered, that is, a scenario in which a continuous and not episodic discharge of nutrients is being considered.[6]

The resource growth function, *F(X;M)*:
The hypothesis usually accepted since Schaefer's studies in 1957 is that the biomass grows in time in accordance with a logistic function or curve in the form of S.[7] From the biomass growth curve it can be deduced the sustainable yield curve, which links the population growth rate to the quantity of fish biomass.
The natural production function is generally assumed (Tahvonen (1991)[23] and Olsen and Shortle (1996)[15]) to be concave in *X* and *M*:

$F_M < 0, F_{MM} < 0 \; For\; all\; of\; M \geq 0,$
$F_{XX} < 0,$
$F_{XX} F_{MM} - (F_{XM})^2 \geq 0,$
$F_{XM} \geq 0.$
$For\; the\; following\; levels\; of\; stock\; resource, 0 < X_{\min} < X_{\max}\; is\; satisfied:$
$F(0, M) = 0,$
$F(X, M) > 0,\; para\; X_{\min} < X < X_{\max},$
$F(X, M) < 0,\; para\; X < X_{\min}\; y\; X > X_{\max}.$

In the following *Figure* it can be seen what effects pollution has on the production function. Considering the predator stock in the resource growth function implies a reduction not only in the maximum capacity of resource the environment can bear but also, the level of stock corresponding to the maximum sustainable production of stock (Kahn and Kemp (1985)[8]).

[*Figure 2.1. Resource growth function*]

Once the properties of the variables that intervene in the process which describes the fish resource stock have been defined, it can be now shown the dynamics of the process which describes the pelagic predators' stock. Its movement equation depends as much on its growth function, which it is assumed to be exponential (Knowler et al. (1997)[11]), of the previous biomass, as on the level of nutrient concentration (phosphates, nitrates,...) in the sea:

$$dM = G(M, Z)dt, \tag{2}$$

where: $G_M < 0$,[9] $G_Z > 0$.

Lastly, it is set out the process which describes the nutrient stock evolution (Plourde and Yeung (1989)[18]):

$$dZ = [P - lZ]dt, \tag{3}$$

where:
P, rate of nutrient release into the environment;
l, rate of nutrient absorption by the environment, constant assumption.[9]

2.2 The regulator's problem

For reasons of simplicity,[10] it is assumed that a regulator who assigns the resources with the aim of maximising the present value of the net instant profit flow deriving both from nutrient discharge (the consequence of industrial activity) and fishing activity exists.

Benefits deriving from nutrient discharge.

May $D(P)$ be the function that covers the net instant profits[11] as a result of nutrient discharge into the environment, P being the added emission rate.

The marginal emission profit, D_P is positive[12] in a determined interval $(0,I)$ and negative for emission rates which exceed level I. The marginal profit is downward, $D_{PP}<0$.

Profits deriving from fishing

The net instant profit from fishing is obtained from the difference between the profit for the consumers and the cost of the harvest.

The properties of both functions are defined as usually defined in traditional studies (Tahvonen (1991),[23] McConnel and Strand (1988),[13] Olsen and Shortle (1996)[15]).

May $B(h;Z)$ be the profit function, which depends on the quantity harvest and consumed (h) and the nutrient stock (Z).[13] In this function, it is considered that the nutrient stock Z affects the quality of the resource.

It is assumed that:

$$B_h > 0, B_{hh} < 0, B_Z < 0, B_{hZ} < 0,$$
$$B_{ZZ} \leq 0 \ and \ B_{hh}B_{ZZ} - (B_{hZ})^2 \geq 0.$$

Let $C(h;X)$ be the function for the total harvest costs, which depends on the quantity harvested (h) and the resource stock biomass (X).

It is assumed that:

$$C_h > 0, C_{hh} > 0, C_X < 0, C_{hX} < 0,$$
$$C_{XX} \geq 0 \ and \ C_{hh}C_{XX} - (C_{hX})^2 \geq 0.$$

The regulator's optimum plan.

The optimum plan that maximises the present value of the net instant profit flow is written as follows:

$$\begin{aligned}
&V = Max_{\{h,P\}} \int_0^\infty \exp(-rt)\left[B(h,Z) - C(h,X) + D(P)\right]dt, \\
&s.t. \\
&dX = \left[F(X) - h(t)\right]dt, \\
&dM = G(M,Z)dt, \\
&dZ = \left[P - lZ\right]dt, \\
&X(0) \geq 0, \\
&M(0) \geq 0, \\
&Z(0) \geq 0, \\
&h(t) \geq 0,
\end{aligned} \tag{4}$$

where r is the social discount rate (which, in this context of certainty, as a proxy measure, it is used the rate of return on a risk-free interest asset) and t = 0 the initial moment. *V(X;M;Z)* is the fishery's social value function.

Note that the problem posed has two control variables, the harvest rate (*h*) and the nutrient emission rate (*P*), and three state variables, the resource stock (*X*), the predator stock (*M*) and the nutrient stock (*Z*). Malliaris and Brock (1982),[12] Kamien and Schwartz (1991)[10] show how the following differential equation, known as Bellman's equation (alternatively the Optimum Control Theory can be used), is obtained.

$$rV(X,M,Z) = Max_{\{h,P\}}\begin{Bmatrix} B(h,Z)-C(h,X)+D(P)+V_X\left[F(X,M)-h\right] \\ +V_M G(M,Z)+V_Z\left[P-\lambda Z\right] \end{Bmatrix}. \quad (5)$$

From this equation, it is obtained the implicit equation for the fish resource stock and the pollution stock.

2.3 The fishing sector

By maximising expression (5) with respect to the harvest rate it is obtained the following optimality condition (assuming that the optimum harvest rate satisfies the following range $0 \le h \le h_{\max}$):

$$V_X = B_h - C_h \quad (6)$$

The term V_X in the condition above is the marginal value or shadow price of the resource stock. The $B_h - C_h$ difference reflects the marginal profit from consuming the resource less the marginal harvest cost. If the level of emission is optimum, the fishery is perfectly competitive and the property rights are properly defined and so V_X can be interpreted as the marginal resource income.[14]

The process for the second control variable takes place in the same way; maximising expression (5) with respect to the emission rate a second optimality condition is obtained:

$$V_Z = -D_P \quad (7)$$

V_Z represents the marginal value or shadow price of the pollution stock. This condition implies that the marginal emission cost equals the marginal emission profit. If the pollutant industry is perfectly competitive and the resource optimally managed, then $-V_Z$ could be interpreted as an optimum emission tax.[15]

Once the optimum harvest and emission levels have been obtained, h^* *and* P^*, they are replaced in (5) and a difference is made with respect to *X*:

$$rV_X = [B_h - C_h - V_X]\frac{\partial h^*}{\partial X} + [D_P + V_Z]\frac{\partial P^*}{\partial X} - C_X + F_X V_X + \\ + [F - h^*]V_{XX} + [P^* - \lambda Z]V_{XZ} + GV_{MZ}. \tag{8}$$

In order to simplify this equation, note that:

$$dV_X = V_{XX}dX + V_{XZ}dZ + \frac{1}{2}V_{XXX}dX^2 + V_{XXZ}dXdZ + \frac{1}{2}V_{XZZ}dZ^2 + V_{XM}dM \\ + \frac{1}{2}V_{XMM}dM^2 + V_{XXM}dXdM + V_{XZM}dZdM. \tag{9}$$

Replacing (1), (2) and (3) in (9), the result is:

$$dV_X = V_{XX}[F(X,M) - h]dt + V_{XZ}[P - \lambda Z]dt + V_{XM}G(M,Z)dt, \tag{10}$$

dividing by dt, the instant change in the marginal stock value is obtained:

$$\frac{dV_X}{dt} = V_{XX}[F(X,M) - h] + V_{XZ}[P - \lambda Z] + V_{XM}G(M,Z) \tag{11}$$

Lastly, the implicit equation for the fish resource stock is obtained by replacing in (8) the value of $\frac{dV_X}{dt}$, as well as, conditions (6) and (7). This equation is no more than the modified version of the familiar "*golden rule*" for the renewable resource sector in general and of traditional studies on the fishing industry in particular.

$$r = \frac{\frac{dV_X}{dt}}{V_X} + F_X(X,M) - \frac{C_X}{V_X}. \tag{12}$$

Interpreting this equation, the right side represents the profits from not harvesting a unit of resource in relation with their value if it is indeed harvested (V_X). These profits are made up of the rate of change in the marginal stock value $\left(\frac{dV_X}{dt}\right)$, the change in stock productivity (F_X) and the changes in the total fishing cost (C_X). The left side represents the opportunity cost of keeping a marginal unit of the resource and not harvesting it.

Reviewing the assumptions adopted for the growth function as well as for the cost function, and by considering the neo-classical theory (Clark (1976)[2]), the equation obtained can be interpreted in terms of the well-known rule of marginal productivity of the capital theory$\left(F_X = r\right)$: as long as the cost of fishing increases at the same time as the level of stock $\left(\frac{dC(X)}{dX} < 0\right)$ decreases. Therefore, in the optimum stock level X^*, the marginal productivity of the resource will be less than *r*: $F_X < r$.

The effect of pollution in the optimality condition.

The optimum stock which derives from said optimality condition is different to that derived from traditional studies. The marginal resource productivity is declining thus, if the social discount rate does not vary, a greater stock productivity will be demanded from the model proposed in such a way that the modified golden rule continues to be satisfied. That is, the optimum resource stock is now less than this of the traditional studies, $X_P^* < X^*$ (by X_P^* it is denoted the optimum stock when the effect of pollution is introduced) and so, the harvest rate is now greater. This idea will be explained in detail in *section 3*.

However, it will now be considered the possibility that the fishery regulator maintains the same level of harvest. In this case, the social discount rate would have to be lower for the new context proposed, that is, the cost of the opportunity to keep a unit of the resource and not harvest it is now lower.

2.4 The pollution sector

Similarly to the development described above for the fishing sector, below it is obtained the optimality condition for the pollutant stock.

Firstly, the optimum levels h^* *and* P^* are replaced in (5), and differentiating with respect to *P*:

$$\begin{aligned} rV_Z &= B_Z + \left[B_h - C_h - V_X\right]\frac{\partial h^*}{\partial Z} + \left[D_P + V_Z\right]\frac{\partial P^*}{\partial Z} + \left[F(X,M) - h^*\right]V_{XZ} \\ &\quad - lV_Z + G(M,Z)V_{MZ} + \left[P - lZ\right]V_{ZZ} + G_Z(M,Z)V_M , \end{aligned} \qquad (13)$$

in order to simplify this equation, note that:

$$dV_Z = V_{ZZ} dZ + V_{ZX} dX + \frac{1}{2} V_{ZZZ} dZ^2 + V_{ZXZ} dXdZ + \frac{1}{2} V_{ZXX} dX^2 + V_{ZM} dM$$
$$+ \frac{1}{2} V_{ZMM} dM^2 + V_{ZZM} dZdM + V_{ZXM} dXdM. \qquad (14)$$

Below, it is replaced (1), (2) and (3) in (14):

$$dV_Z = V_{ZZ} [P - \lambda Z] dt + V_{ZX} [F(X, M) - h] dt + V_{ZM} G(M, Z) dt. \qquad (15)$$

Lastly, it is obtained the implicit equation for the pollutant stock replacing in (13) the value of $\frac{dV_Z}{dt}$ as well as conditions (6) and (7):

$$rV_Z = dV_Z + B_Z - \lambda V_Z + G_Z V_M,$$

dividing by V_Z and reorganising the terms, it is obtained:

$$D_P = -\frac{1}{r + \lambda} [dV_Z + B_Z + G_Z V_M] \qquad (16)$$

The left side of the above equation represents the marginal emission profit while the right side represents the costs deriving from an increase in the pollutant stock. Note that these costs can be divided up into:

- the rate of change in the marginal value of the pollutant stock (dV_Z).
- the reduction in the consumption profit caused by a reduction in the quality of the fish resource, in turn the consequence of an increase in the pollution level (B_Z).
- the reduction in the fishery's social value function as a consequence of the increase in pelagic predators, in turn the consequence of the increase in the pollution level $(G_Z V_M)$.

Interpreting the implicit equation obtained it can be seen that the contaminant company increases its marginal emission costs with respect to the model presented in traditional studies. Likewise, the worse the environmental situation (more pollution and consequently a greater stock of predators), the greater such marginal emission costs will be. In this way, if contaminating companies were perfectly competitive the emissions would be controlled more, raising the emission taxes, as has been commented on above.

It should be noted that a condition of optimality for the third state variable introduced into the model, the pelagic predators' stock is not obtained, as it is not controlled by the regulator and, therefore, no control variable is associated with it. This stock has no commercial value whatsoever, although its inclusion in the model is undoubtedly interesting, as it has been seen.

3. THE STATIONARY STATE.

In this point, it will be seen what implications the introduction of the predator stock into the resource growth function in the stationary state. It should be borne in mind that with the interactions proposed between the fishing sector and the pollution sector, neither $X = X_P^*$ nor $Z = Z_P^*$ imply a stationary state except when, as it will be analysed below, the predator stock growth function is zero, $G = 0$. This is something usually overlooked in practice and which can lead to a non-optimal management of resources.

3.1 The fishing sector.

Below, it is set out the structure of the efficient harvest rate which derives from the optimality condition (12). Firstly, said equation in the stationary state can be written as follows:

$$rV_X = F_X V_X - C_X \tag{17}$$

Differentiating this equation and using (1) and (2) it is obtained (Implicit function theorem):

$$h = F(X, M) + \frac{F_{XM} V_X}{F_{XX} V_X - C_{XX} + (F_X - F)(-C_{hX})} G. \tag{18}$$

This harvest rate can be expressed as:

$$\begin{aligned} &h = F(X, M) + xG \\ &where: x \equiv \frac{F_{XM} V_X}{F_{XX} V_X - C_{XX} + (F_X - F)(-C_{XX})} > 0. \end{aligned} \tag{19}$$

Observe that, the harvest rate exceeds the resource growth function, $h > F(.)$ itself. So, while a contaminating sector (and so, predator stocks) exists near coastal areas and, unless the predator stock is permanently zero, the resource will be harvested faster than without the contaminating sector. This result is not only surprising but furthermore Swallon (1990)[22], among other authors, corroborates that this result usually emerges from the empirical evidence in fisheries today.

If the growth function of the predator stock were zero, $G = 0$; the result given in traditional studies would be obtained, that is, the harvest rate would be equal to the resource growth. However, is should not be forgotten that the fish resource growth function, when the effect of pollution is not considered, *F(X);* and when it is, *F(M;X)*, should satisfy the following (assuming that although $G = 0, M > 0$):

$$F(M, X) < F(X)$$

Thus, when it is considered the indirect effect that pollution has on fishing resources and so that, the predator stock should be incorporated into the resource growth function, $X = X^*$ in condition (17) a stationary state is not implied. Therefore, if it were considered that in the stationary state the harvest rate should be equal to the growth function as has been habitual in traditional studies the resource would not be being managed optimally. In this way, it can be concluded that the contaminating emissions accelerate the rhythm of resource extraction (if the social discount rate is not modified) as it was analysed in *section 2.3*. That is, as long as industrial development exists in coastal areas, the resource will be harvested as quickly as possible.

In order to better understand this management policy, it should be borne in mind that it is reasonable to think that the company will obtain more profit by extracting a greater quantity of the resource initially, when the environmental situation is better (that is, less pollution and less predators) than later, when the environmental situation could become worse (if the industrial development continues).

To understand (19) better note that, the slope of X_P^* is given by the positive coefficient of G in (18). Then, the rate of predator stock growth represents the rate at which the manager harvests the resource in excees due to the industrial activities. The management optimizes the fish stock but, at a new level different from the traditional studies.

With the aim of being able to derive a possible harvest policy that the regulator would implement if trying to lead the dynamics of the fishery towards a stationary state, it has to be first analysed the results that derive from the contaminant sector.

3.2 The contaminant sector

Below, it is obtained the efficient contaminant emission rate that corresponds to the resource harvest rate. In order to do so, as above, it will be differentiated equation (16) in the stationary state and use (1) and (3):

$$P = \frac{G_Z V_{MX}}{B_{ZZ} + G_{ZZ} V_M + G_Z V_{MZ}} \left[h - F(X, M) \right] + IZ. \qquad (20)$$

This flow can be rewritten as follows:

$$
\begin{aligned}
&P = V\left[h - F(X, M)\right] + lZ, \\
&where: \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (21) \\
&V \equiv \frac{G_Z V_{MX}}{B_{ZZ} + G_{ZZ} V_M + G_Z V_{MX}} > 0.
\end{aligned}
$$

It can be observed that this emission rate, $Z=Z_P^*$ in (16) does not imply a stationary state and that, the result of traditional studies, an emission rate equal to the environmental absorption rate is not now satisfied. Now, the emission rate does not only depend on the environmental absorption rate itself, l, but on other variables related to the fishing sector, that is, both on the harvest rate, h, as well as on the fish resource growth rate, $F(.)$.

It is shown that in a pollution scenario such as the one described, the efficient harvest rate is greater than the growth resource, $h > F(.)$, which gives rise to emission rates higher than the environmental absorption rate, $P > lZ$. Besides, the first term of P in (21), $V[h - F(X, M)]$ is positive and represents the additional development due to the fact of being the efficient harvest rate clearly greater than the sustainable harvest, $F(.)$. This circle brings about that the worse the environmental situation (a greater emission of nutrients) the greater the intensity with which the resource is harvested, so the exploitation of the resource being accelerated before the environmental situation continues to worsen.
Thus, the coastal zone development contributes to social welfare but also irreversibly contributes to generation the more and more predator stocks and so, contributes to irreversibly deplete the environmental basis for fishing resources.

In this face of such a panorama, it is worth asking what the management that the fishery regulator ought to implement should consist of, in order to tend towards a stationary situation. Given the interpretation carried out for the optimality condition (16), for a competitive contaminant market, the regulator controls the emission of nutrients more with the aim of reducing pollution levels. By reducing pollution levels the stock of predators will reduce too and, looking at condition (18), the harvest rate will be lower and lower. If this harvest deceleration policy is maintained until the stock of predators in the environment is reduced to zero, $G=0$; then obviously there would be a convergence to the stationary state, satisfying the results of traditional studies, that is, harvest rate equals vegetative growth, $h = F(X, M)$ and emission rate equals environmental absorption rate, $P = lZ$.
Under this kind of policy the situation given by $X_P^* < X^*$ is not maintained indefinitely in time and, although initially a more of the resource is harvested than in traditional studies without pollution considerations, subsequently the opposite will happen.

This result is even more interesting if it is compared with the results that Perman, Ma and McGilvray (1996)[17] have reviewed for the management of non-renewable resources. These authors show how the damage functions considered in studies on non-renewable resources are associated with the damage deriving from the very extraction of the resource. Thus, the greater the resource extracted (and the less the resource stock that remains after extraction), the greater the environmental damage. The consideration of these damage functions in the management of the non-renewable (and non-replaceable) resources brings with it the determining of a resource extraction policy more intense initially and less intense in subsequent periods.
Note, the policy of investment and disinvestment in the resource proposed for managing the fishing resource stock in situations of environmental pollution, such as the one described, is similar to that which would be adopted if the resource were not renewable and did not have replacements. This result should not surprise us if it is though that, introducing the predator stock, which has an impact on the quantity of the resource, can often exhaust the resource even when it is renewable, so that in reality although the nature of the resource is renewable it should not be managed as such but as if it were a non-renewable resource under this kind of pollution sceneries.

Thus, it can be concluded, as it is set out above, that adopting a harvest policy that is more intensive initially and less intensive in subsequent periods, as if it were a non-renewable resource, is encouraged under a pollution scenery.

4. CONCLUSIONS AND SCOPE OF THIS STUDY.

This study aims to underline the importance today of adequately controlling the industrial development of contaminating activities that are carried out near coastal areas. If it is indeed true that such development is presently necessary and that it contributes to the well-being of society insofar as the generation of income is concerned, it should also be underlined that in the same way it implies an irreversible loss of well-being in that in time it could bring about the exhaustion of fish resources. In particular, fisheries in closed and semi-closed seas have borne witness in recent years to an excessive discharge of nutrients the effect of which on the water masses is varied. Thus, for example, in some seas this excess of nutrients can cause a reduction in aquatic vegetation and, in other cases, such excess has been translated into an uncontrolled increase in toxic marine algae, phenomena which have affected resource biomass in numerous fisheries. In the same way, and given the huge importance that it is having, the study has paid special attention to the eutrophication phenomenon, the main consequence of which is the development of populations of pelagic predators which have no commercial value whatsoever and which feed on fish larvae. The joint effect of these predators and policies of over-fishing have led many fisheries, like the Black Sea anchovy fishery mentioned herein, to extinction.

Thus, the bio-economic model presented intends to regulate the fishing sector and the pollution sector in such a way that the main activities of these sectors can be carried out simultaneously in time and space without generating irreversible environmental externalities. Using Dynamic Programming it has been able to obtain the optimality conditions for the fish resource and for the nutrients. From the former, it is deduced that the optimum resource stock is less in this scenario with respect to traditional studies, that is, while a contaminating sector exists near coastal areas the resource will be harvested as quickly as possible, as long as it is considered that the cost of the opportunity to keep a unit of the resource and not harvest it is the same. However, if the latter were to take a downward trend, then it might be possible to maintain the same harvest policy. Having said that, from an analysis of the stationary state it can be deduced that said optimum stock does not imply a stationary state and that it will not be reached as a result of the interactions between both sectors by means of the predator stock. However, the regulator could tend towards and reach such state by reducing the harvest rate. This policy can be achieved when it is possible to reduce contaminant emissions, and considering the results deriving from the nutrient stock optimality condition, the marginal emission costs being greater, if the contaminating sector were perfectly competitive, emissions would be controlled better and therefore be reduced. Thus, in time, adopting a resource harvest policy that is more intensive initially and less intensive in subsequent periods is encouraged, as the company obtains greater profit extracting more of the resource initially (when the environmental situation is more favourable) and less in subsequent periods. Furthermore, it should be underlined that under this policy the fish resource would be managed as if it were a non-renewable (and irreplaceable) resource. It should be borne in mind that it is reasonable to think that introducing the predator stock which has an impact on the quantity of the resource can often exhaust the resource even when it is renewable, so that in reality although the nature of the resource is renewable it should be managed as such but as if it were a non-renewable resource.

Lastly, it is worth mentioning the scope of this study, which has centred on the optimum management of a fishery bearing in mind the influence of negative biological externalities on the fish resource (through pollution, directly and indirectly). However, the empirical evidence shows that fisheries are managed in the presence of both biological and dynamic externalities, also called international externalities. Cross-border pollution is one of the most important examples of this kind of problem. It should not be forgotten that the activities of one country can harm the environment of another. These types of considerations are important as the non-cooperation between regulators in a situation of international externalities implies carrying out inefficient resource management (Copeland (1989)[5]).

On the other hand, the analysis has been carried in conditions of certainty. it could be, however, immediately extended such analysis to include conditions of uncertainty. Olsen and Shortle (1996)[15] show how such uncertainty could be introduced in the processes that describe the resource stock and pollution dynamics by means of Wienner processes, while Sundaresan (1984)[21] proposes a Wiener-Poison mixed stochastic process for the resource stock. Insofar as the profit function is concerned, it could be considered that both the resource price as well as the operating costs were stochastic, as Datta and Mirman (1998)[7] suggest.

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1. The economic conceptualisation of pollution is that it is an externality. For example, a fishery's production depends on the level of use of the production factors (the so-called fishing effort), but is also influenced by the production decisions that, for example, the paper mill situated upriver takes (Romero (1997)[19]).

2. Of special concern is the question of the transfer of nutrients from land systems to marine systems. Phosphorous is an important ocean component from domestic and industrial waste the environmental transport of which is usually aquatic. It is estimated that human activities have provoked an approximately five-fold increase in nitrogen taken from the rivers into the sea and, with respect to phosphorous, the increase in four-fold, if the take the history of the Rhine as an example. It has been estimated that the total annual amount of phosphorous taken into the sea is around 0.59 Tmol (1 Teramole equals 31 million tons).

3. There are a large number of marine contamination sources; although, undoubtedly, one of the most important is the discharge of nutrients (phosphates, nitrates and silicates). World Resources Institute (1992)[24] provides a detailed analysis of these sources and their different effects on aquatic life, among which it would be underlined sediment discharge, organic matter, heavy metals, toxic chemical products, etc.

4. The Black Sea medusae (Aurelia Aurita and Mnemiopsis Leidyi), and more recently the ctenophora, have driven the anchovy population there to a critical situation. The biomass of these exotic medusae is in function with different environmental factors, including some nutrients (Mutlu et al. (1994)[14]. Other fisheries, such as the Azov Sea and Marmara sea fisheries have also been seriously affected by this kind of invertebrate.

5. Understand it to be a dump exploited commercially by coastal industries which dump their waste or use the sea as a source of cooling, marine mining, tourism, coastal aquaculture, coastal transport. All these activities generate a huge discharge of nutrients. (FAO (1996)[8]).

6. Collins, Stapleton and Whitmarsh (1998)[4] show that depending on whether the pollution is "continuous" or "episodic", its effect on the dynamics of resource exploitation will vary.

7. In a logistic-type growth curve, the underlying idea is that growth is slow when the quantity of biomass increases, but that said increases begin to decrease if the quantity of biomass continues increasing, due to environmental elements.

8. The relationship between the predator biomass and the nutrient stock is exponential (Knowler et al (1997)[11]). Thus, a small amount of nutrients will produce a boom in the predator biomass, affecting negatively and to a great extent the resource considered. This is why in seas such as the Black Sea these predators have driven the anchovy population close to extinction.

9. This absorption rate is, in fact, not constant, as if the environment is more contaminated it might be lower. It will also vary as a consequence of climatic conditions.

10. The study does not include an explicit analysis of the solution in the case of the competitive exploitation of the resource. However, as it is known (see, for example, Olsen and Shortle (1985)[15]), competitive behaviour implies the same solution as that dealt with in this study if a fish resource exploitation tax that simulates the shadow price of the resource is established.

11. These profits could include the value of the increase in farming production, the consequence of using fertilisers or pesticides as well as, for example, the reduction of the costs necessary for municipal purification treatments, etc.

12. The general productivity of coastal and continental seas normally increases with the draining of nutrients, but above a certain level of drainage it is more than doubtful that the profit for the fisheries will be positive (Caddy and Griffiths (1996)[1]).

13. The nutrient stock appears in the profit function under the assumption that the quality of the harvestes as perceived by the consumers varies inversely with respect to the nutrient concentration. McConnell and Strand (1988)[13] show how this consumer perception is not irrational: fish resources are an important transmitter of disease.

14. In a free access situation, V_X could be interpreted as an optimum harvest tax. In this situation, the fishing vessels would continue to go into the fishery until all the income had been dissipated, $B_h - C_h = 0$; in order to avoid this, a tax is introduced before such a situation is reached.

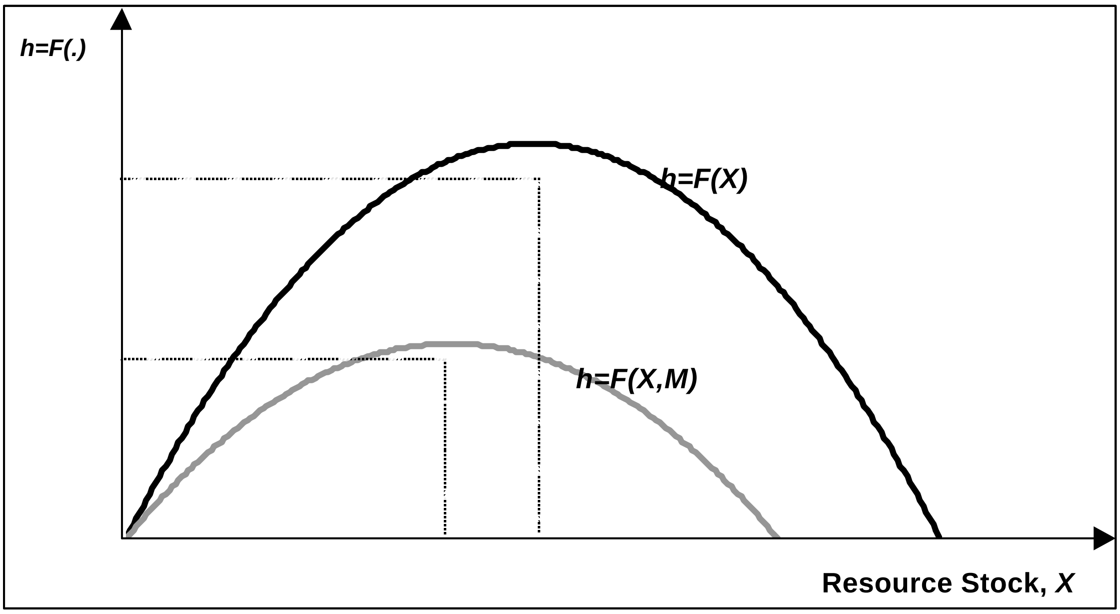
15. Take a sole contaminating company. Firstly, the "private net margin profit", PNMP, are defined. The contaminator will incur a series of expenses in order to carry out the contaminating activity and will receive profits in the form of income; the difference between the income and the expenses is denominated "private net profit". The PNMP is no more than a marginal version of this net profit, that is, the extra profit from changing the level of "activity" into an emission unit.

EMC being the "external" marginal cost, that is, the value of the extraordinary damage caused by pollution from economic activity. Such damage, pollutant emissions, are represented in direct relation with the output level. The optimum level of externality can be found in the intersection of the two curves.

Given that the curves are marginal, if they are represented graphically the areas under them are total magnitudes. The social objective is the maximisation of the total sum of profits minus the total sum of costs; in this respect, Pearce and Turner (1995)[16] among others, show that there is an optimum level of pollution, in which PNMP = EMC is satisfied so that the social objective is complied with.

Illustrations.

Figure 2.1. *Resource Growth Function.*



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