Fishing technology and optimal distribution of harvest rates*

Marta Escapa and Raúl Prellezo†

April 1999, Preliminary

Abstract

In this paper we analyze the optimal management of a joint ownership fishery exploitation model where agents use different fishing gears. As opposed to other works, we consider a model in which the fishing technology affects resource's growth not only through the harvest function, but also through the natural growth rate of the resource. The main objective is to capture the evidence that some fishing gears alter the habitat of the resource, and may alter the natural growth rate of the resource.

The main result we obtain is that, when the natural growth of the resource is altered by the fishing technology, the optimal stock is not independent of how harvest quotas are distributed among the agents. Thus, in this context, a fishing policy that determines, first, the optimum stock and, secondly, decides on how to distribute the harvest among the different agents will not be efficient.

Keywords: Fisheries Regulation, Fishing Gear's Selectivity, Quota Sharing.

JEL: Q20, Q22, Q28

*We thank M.C. Gallastegui for her helpful comments. Financial support from grants UPV/EHU 035-321-HB070/96, GV HU-1998-133 and Gobierno Vasco PI95/13 is gratefully acknowleged. All errors are our own responsability.

†Dpto. de Fundamentos del Análisis Económico, Universidad del País Vasco-EHU, Lehendakari Agirre, 83, 48015, BILBAO, Spain. e-mail: jepesgam@bs.ehu.es, etdprigr@bs.ehu.es.

1 Introduction

There is considerable world-wide concern about the negative effects that the exploitation of fishing resources is having on the equilibrium of the marine ecosystem. And even though it is not easy to quantify the effect, it certainly does depend, among other things, on the technology or fishing gear used to harvest the resource. Thus, for example, some fishing gears alter the habitat of the resource by changing the quantity of the existing foodstuff, or even by modifying the composition according to types and sizes of natural communities or by altering the recruitment rate of the resource (Lleonart et al. 1996). In this case, it can be asserted that the fishing technology employed can affect the natural growth rate of the resource. In fact, there is a tendency to differentiate between fishing gears as a function of their selectivity, that is, according to their capacity to influence negatively the natural growth of the resource in terms of a reduction of its recruitment rate. Some of the current conflicts in relation with fishing resources are due precisely to the existence of several agents, who use different fishing gears and compete for the same resource[1].

However, a common practice in the economic literature on fishing resources has been to assume that the fishing activity affects the net growth of the resource solely through the harvest rate, whereas the natural growth rate is a function of the resource's own biomass and of the environmental conditions of the sea. These conditions are usually assumed stable and constant. Some recent research holds that joint exploitation when using different technology affects the harvest function (Garza Gil 1998, Gutiérrez and Da Rocha 1998) but not the natural growth function. On the other hand, some papers where fishing technology's selectivity has been taken into

[1] The "tuna war" between the Basque and French fleet in the Gulf of Biscay, is just an example. The Basque fleet uses gears such as boulters, "curricanes" or live fodder, which are much more selective than the large driftnets used by the French fleet.

account, only consider the bycatch generated in a multispecific fishery (Boyce 1996, Turner 1997, Ward 1994).

In this paper we analyze the optimal management of a fishing resource , taking into account that the natural growth function depends on the fishing technology employed. Concretely, we include in the growth function a variable that depends on the selectivity level of the technology and this affects the intrinsic growth rate of the resource[2]. We assume that the resource is exploited by two agents or countries that use different technologies, thus, the natural growth function depends not only on the selectivity level of the technology used by each agent, but also on the harvest share they obtain.

The principal aim of the paper is to analyze how the optimal stock of the resource depends on the way in which the fishing quotas are distributed among the countries. In order to do this, firstly, we have compute the optimal stock and harvest rate assuming that the fishing quotas are determined exogenously; secondly, we have obtained the optimal stock and harvest shares that maximize the discounted net flow of the fishery.

The former case reflects how the Common Fishing Policy of the European Community (CFP) operates; it is based on the assignment of a fixed percentage (quota) of the Total Allowable Catch (TAC) to each State Member. The TACs are determined annually for each specie whereas the shares each country has in these TACs have remained fixed for years according to the Relative Stability Principle. The main result we obtain is that, when quotas are given, the optimum stock is not independent of how the harvest is shared amongst the agents if these agents use fishing gears with different selectivity level. Therefore, in these cases the current design of the CFP is not efficient since this policy determines the quotas and the harvest rate (TAC) separately without taking into account that they are not independent.

The paper is structured in the following way. In section 2 the basic model is presented and the basic assumptions are explained. In section 3

[2]The vegetative growth rate of a resource approaches to the intrinsic growth rate when the population tends to zero.

the stock and the optimum harvest are calculated when the allocation of the quotas is determined exogenously. In section 4 the same analysis is carried out but assuming that the technologies differ in their selectivity level and generate different unit harvest costs. Section 5 determines the optimum stock and quotas simultaneously. Finally, section 6 summarizes the main results obtained.

2 The basic model

We consider a joint ownership fishery exploitation model. To simplify, we assume that only two countries (or agents) exploit the resource. We denote Country 1 and Country 2's harvest shares as $\alpha = \frac{h_1(t)}{h(t)}$ and $(1-\alpha) = \frac{h_2(t)}{h(t)}$, respectively, where $h(t)$ is the total harvest rate.

It is common to assume that the natural growth function of the resource takes the form $F(x) = rx(1-\frac{x}{K})$[3], where k, r and x stand for the carrying capacity or maximum biomass size, the intrinsic growth rate and resource's stock or biomass, respectively. Our aim is to introduce in this function the effect that the different fishing technologies have on the natural growth of the resource. Firstly, we define $\gamma_i \geq 1$ as a parameter that measures the selectivity level of the technology used by country i. If country i uses a technology which doesn't affect the natural growth of the resource (a very selective technology), γ_i takes the unit value. But if country $i's$ technology affects, in a negative way, the natural growth of the resource (non selective technology), γ_i will be greater than unity. Secondly, we take into account that the effect of the fishing technology on the growth of the resource also depends on the percentage of harvest caught with that technology. In order to introduce these two effects in the growth function, we define a variable, θ, which depends on the selectivity level of the fishing technology used by each country and on the harvest shares in the following way

$$\theta(\gamma_1, \gamma_2, \alpha) = 1 - \alpha\gamma_1 - (1-\alpha)\,\gamma_2; \quad \theta \leq 0.$$

[3]This is the logistic function, first proposed by P.F.Verlhust in 1838.

Finally, we define $\widetilde{r} = r + \theta$ as the observed growth rate of the resource.

Taking into account the previous definitions, the equation that describes the natural growth of the resource in our model can be written as

$$G(x, \theta) = [r + \theta]\, x \left[1 - \frac{x}{K}\right], \tag{1}$$

It must be noted that as long as $\theta \leq 0$[4], the observed growth rate of the resource ($\widetilde{r}$) will always be lower than or equal to the intrinsic growth rate (r), in such a way that $G(x, \theta) \leq F(x)$, $\forall x$. Should be noted that parameter θ appears in the natural growth function of the resource in order to reflect that this growth depends on the harvest technology.

The net growth of the resource or population dynamics will be described by the following equation

$$\frac{dx}{dt} = G(x, \theta) - h(t). \tag{2}$$

The harvest function for each country is assumed to be linear in the rate of its fishing effort $(L_i(t))$[5] and in the stock $x(t)$, so that

$$h_i(t) = qL_i(t)x(t) \qquad i = 1, 2, \tag{3}$$

where q is the catchability coefficient, which is supposed to be constant and equal for both countries.

We shall also assume that both countries face a world demand for the harvested fish which is infinitely elastic, and that the effort input supply functions are also infinitely elastic. We denote the unit cost of fishing effort by a and the price of fish by p. Country $i's$ total cost of fishing effort is equal to $aL_i(t)$, and, by equation (3), the unit cost of harvesting can be expressed as

[4]When $\gamma_1 = \gamma_2 = 1$ the observed growth rate ($\widetilde{r}$) and the intrinsic growth rate (r) meet, as long as $\theta = 0$. But if $\gamma_1 > 1$ or $\gamma_2 > 1$, θ will be negative for all $\alpha \geq 0$ and $\widetilde{r}$ will be lower than r.

[5]As usual, we suppose that the effort variable is an index that adds all the inputs used to capture the resource (capital and labor).

$$c(x) = \frac{a}{qx}. \tag{4}$$

3 Optimum stock when harvest shares are given

In this section we consider that the harvest shares obtained by each country (α and $(1-\alpha)$) are exogenously determined by a supranational authority and that they are time invariant[6].

The objective functional for each country is its discounted net cash flow from the fishery which can be expressed as

$$vp_1 = \int_0^\infty e^{-\delta t} \alpha \left[p - c(x)\right] h(t) dt, \tag{5}$$

$$vp_2 = \int_0^\infty e^{-\delta t} \left(1-\alpha\right) \left[p - c(x)\right] h(t) dt, \tag{6}$$

where $\delta > 0$ is the discount rate.

We are interested in the optimal harvest rate for each country but, previously, it is necessary to obtain the optimal equilibrium biomass. Let us suppose that there exists a supranational authority who chooses the stock that maximizes the sum of the present value of the revenues obtained from the fishery by both countries, that is

$$\begin{aligned} vp = \int_0^\infty e^{-\delta t} \left[p - c(x)\right] h(t) dt \\ s.t. \quad & \\ \tfrac{dx}{dt} &= G(x,\theta) - h(t), \\ x(t) &\geq 0, \\ h(t) &\in \left[h_{\min}, h_{max}\right], \end{aligned} \tag{7}$$

where $vp = vp_1 + vp_2$.

The Hamiltonian of this problem is

[6] As mentioned in the introduction, this assumption corresponds to the Common Fisheries Policy (CFP) applied by the European Union.

$$H = e^{-\delta t}\left[p - c\left(x\right)\right]h(t) + \lambda(t)\left(G(x,\theta) - h(t)\right), \tag{8}$$

where $\lambda(t)$, the costate variable, is the shadow price of the resource discounted back to $t = 0$. The first order conditions of the problem are

$$\frac{\partial H}{\partial h} = 0 = e^{-\delta t}\left[p - c\left(x\right)\right] - \lambda(t), \tag{9}$$

$$\frac{d\lambda}{dt} = -\frac{\partial H}{\partial x} = e^{-\delta t}c'\left(x\right)h(t) - \lambda(t)G_x(x,\theta), \tag{10}$$

$$\frac{\partial H}{\partial \lambda(t)} = \frac{dx}{dt} = G(x,\theta) - h(t). \tag{11}$$

Solving equations (9), (10) and (11), we obtain that the optimal stock in the steady state, x^*, must satisfy the following condition

$$\delta = G_x(x^*,\theta) - \frac{c'\left(x^*\right)G(x^*,\theta)}{\left[p - c\left(x^*\right)\right]}. \tag{12}$$

This condition implicitly determines the optimal equilibrium biomass, x^*, and it differs from the usual modified Golden Rule equation, because the yield on the marginal rate investment (r.h.s.) depends on parameter θ, and therefore the fishing technology and harvest shares of the countries. In fact, both the resource's marginal productivity, $G_x(x^*,\theta)$, and the marginal stock effect, $\frac{c'(x)G(x,\theta)}{[p-c(x)]}$, will decrease if the selectivity level of the countries' fishing technology decreases or if the harvest quota of the less selective country increases.

As proven by Munro (1979), we know that when the natural growth function of the resource does not depend on the differences between countries, the stock and the optimal harvest are independent of the distribution of fishing quotas among the countries. However, equation (12) shows that if the fishing technology affects the natural growth of the resource, then the stock as well as the optimal harvest are not independent of the distribution of harvest among the countries.

Solving equation (12) for x^*, we get

$$x^* = \frac{K}{4}\left[1 - \frac{\delta}{(r+\theta)} + \frac{a}{pqK} + \sqrt{(1 - \frac{\delta}{(r+\theta)} + \frac{a}{pqK})^2 + \frac{8\delta a}{(r+\theta)pqK}}\right]. \tag{13}$$

Following Clark (1990), we define the following dimensionless variables

$$Z = \frac{a}{pqK} \quad and \quad \rho = \frac{\delta}{(r+\theta)},$$

where Z is described by Mesterton-Gibbons (1993) as an "inverse efficiency parameter" (it is equal to the open access biomass level) and ρ is known as the bionomic growth ratio. Making use of these definitions, equation (12) can be rewritten as

$$x^* = \frac{K}{4}\left[1 - \rho + Z + \sqrt{(1-\rho+Z)^2 + 8\rho Z}\right]. \tag{14}$$

This equation shows how the optimal equilibrium biomass depends on the effect that the fishing technology and harvest shares have on the natural growth of the resource. Besides, the optimal harvest also depends on the fishing technology used by the countries, as long as in the steady state $h^*(t) = G(x^*, \theta)$.

This implies that the supranational authority, who determines the harvest shares, should take into account that two different distributions may imply a different optimum biomass and, as a consequence, a different optimal harvest rate. The following propositions show how the sharing of quotas affects the optimal biomass and profits obtained from the fishery.

Proposition 1

If the fishing technology of country 1 is more (less) selective than the one of country 2, the greater (smaller) the share of country 1 is, the greater (smaller) the optimal equilibrium biomass will be. That is

$$\gamma_1 \lesseqqgtr \gamma_2 \Rightarrow \frac{dx^*}{d\alpha} \gtreqqless 0.$$

Proof*:* See the Appendix.

Proposition 2

If the fishing technology of country 1 is more (less) selective than the one of country 2, the greater (smaller) the share of country 1 is, the greater (smaller) the profits obtained from the fishery will be. That is

$$\gamma_1 \lesseqgtr \gamma_2 \Rightarrow \frac{d\pi^*}{d\alpha} \gtreqless 0.$$

Proof*:* See the Appendix.

These propositions show that the equilibrium biomass and the profits obtained by the society from the fishery will be higher when there is a rise in the quota of the country with the most selective technology. On the other hand, it becomes obvious that the optimal biomass doesn't depend on the quota sharing when both countries are identical ($\gamma_1 = \gamma_2$).

We shall next use a numerical example to illustrate these results. Let us suppose a fishery where $r = 1.2$, $K = 1.500.000$ tones, $q = 0.0000025$, $\delta = 0.1, a = 400.000$ ptas./fishing days and $p = 200.000$ ptas./Ton. Besides, it is assumed that the fishing technology of country 1 is very selective, $\gamma_1 = 1$. First, we consider that both countries receive an egalitarian share ($\alpha = 0.5$) in order to calculate how the changes in the fishing technology of country 2 (from $\gamma_2 = 1$ to $\gamma_2 > 1$) affect the optimal biomass, optimal harvest and revenues from the fishery. Table 1 shows that for $\gamma_1 < \gamma_2$, the egalitarian distribution implies that the optimal biomass and harvest and total benefits in the steady state decrease as long as the negative effect of the fishing gear of country 2 increases. If this negative effect is strong enough, it may cancel the intrinsic growth rate of the resource and reduce its productivity to zero, thus, the optimal solution would be to lead the resource to its extinction.

(Insert Table 1)

We now assume that $\gamma_1 = 1$ and $\gamma_2 = 1.15$ and allow the harvest shares to vary. In Table 2 we show how changes in the harvest shares affect the optimal biomass, the optimal total harvest and the observed growth rate ($\tilde{r}$).

(Insert table 2)

It can be observed that if the quota of the most selective country decreases, the observed growth rate falls, and this implies a reduction of optimum biomass and total harvest.

In this section, we have analyzed how optimal biomass depends on the sharing of the quota among countries, but assuming that the selectivity of the fishing technology only affects the natural growth function. In the following section, we take into account that the unit effort cost also depends on the selectivity level of the fishing gear.

4 Optimum stock when quotas sharing is given and harvesting costs differ between countries

It seems natural to think that differences in the selectivity level of fishing gears will generate different unit effort costs. In this paper we assume that differences in the harvesting cost are due to differences in the unit cost of the fishing effort[7]. Thus, we define unit harvesting costs for each country as

$$c_i(x) = \frac{a_i}{qx} \qquad i = 1, 2, \tag{15}$$

where a_i is country i's unit price of fishing effort and q is the catchability coefficient.

[7]Fishing gears that differ in their selectivity level may also imply a different catchability coefficient or may require different intensity of inputs, capital and labor. These are some of the reasons that may explain the differences in unit harvesting costs.

As in the previous section, we assume that the quota sharing is given so that the planner will determine the optimal stock maximizing the following objective functional

$$vp = \int_0^{\infty} e^{-\delta t} \left[\alpha \left[p - c_1(x) \right] + (1-\alpha) \left[p - c_2(x) \right] \right] h(t) dt \tag{16}$$

subject to the same restrictions of problem (7) in the previous section. From the first order conditions, we obtain the following equation which implicitly determines the optimal stock of the resource

$$\delta = G_x(x^*, \theta) - \frac{\left[\alpha c_1' \left(x^* \right) + (1-\alpha) c_2' \left(x^* \right) \right] G(x^*, \theta)}{\left[p - \left(\alpha c_1 \left(x^* \right) + (1-\alpha) c_2 \left(x^* \right) \right) \right]}. \tag{17}$$

Solving this equation for x^*, we obtain

$$x^* = \frac{K}{4} \left[1 - \rho + Z' + \sqrt{(1 - \rho + Z')^2 + 8\rho Z'} \right], \tag{18}$$

where $Z' = \frac{\alpha a_1 + (1-\alpha) a_2}{pqK}$ and $\rho = \frac{\delta}{(r+\theta)}$.

Once again, we reach the result that the optimal stock depends on how optimal harvests are shared between both countries although now the "inverse efficient parameter" (Z') also depends on the quota sharing as long as the unit cost harvesting differs between countries. Equation (18) shows that the share of optimal harvest affects the optimal biomass, x^*, through ρ and through Z', in such a way that now the effect of quota sharing on the optimal stock will depend on what the differences between the countries are with respect to the selectivity of their fishing technology and their unit harvesting cost. As long as

$$\frac{dx^*}{d\rho} < 0,$$

$$\frac{dx^*}{dZ'} > 0,$$

$$\frac{d\rho}{d\alpha} = \frac{\delta}{(r+\theta)^2} (\gamma_1 - \gamma_2) \gtreqless 0 \Leftrightarrow \gamma_1 \gtreqless \gamma_2,$$

and

$$\frac{dZ'}{d\alpha} = \frac{a_1 - a_2}{pqK} \gtreqless 0 \Leftrightarrow a_1 \gtreqless a_2,$$

the sign of $\frac{dx^*}{d\alpha}$ may be positive or negative depending on whether $\gamma_1 \lesseqgtr \gamma_2$ and $a_1 \gtreqless a_2$. In order to determine the sign of $\frac{dx^*}{d\alpha}$, we have to consider the following different cases:

Case	Differences between countries	$\frac{d\rho}{d\alpha}$	$\frac{dZ'}{d\alpha}$	$\frac{dx^*}{d\alpha}$
(1)	$\gamma_1 > \gamma_2, \quad a_1 > a_2$	$+$	$+$	?
(2)	$\gamma_1 > \gamma_2, \quad a_1 < a_2$	$+$	$-$	$-$
(3)	$\gamma_1 < \gamma_2, \quad a_1 > a_2$	$-$	$+$	$+$
(4)	$\gamma_1 < \gamma_2, \quad a_1 < a_2$	$-$	$-$	?

In cases (1) and (4), the differences between the countries are such that assigning a higher quota harvest to country 1 may have a positive or a negative effect on the optimal biomass, whereas in cases (2) and (3) the optimal biomass increases if country 1 receives a higher quota harvest[8].

In the first case, if the harvest quota of country 1 increases, the optimal biomass may increase or decrease because two opposite effects arise[9]. On the one hand, country 1 has the less selective technology ($\gamma_1 > \gamma_2$), and an increase in his quota (α) implies a reduction of the growing rate of the resource, and, as a result, the equilibrium biomass tends to be lower. On the other hand, country 1 has the highest harvesting cost ($a_1 > a_2$) and an increase in his quota implies a higher "inverse efficient parameter" ($\frac{dZ'}{d\alpha} > 0 \Leftrightarrow a_1 > a_2$) and optimal biomass tends to be higher ($\frac{dx^*}{dZ'} > 0$). Therefore, the final effect of an increase in the harvest quota of country 1 will depend on the degree of the differences between the selectivity of the fishing gear and the harvesting unit cost. In table 3, this ambiguous effect is shown.

[8] When both countries use a technology with the same degree of selectivity ($\gamma_1 = \gamma_2$) and they have different unit harvesting costs ($a_1 \neq a_2$), the optimal biomass will be higher if the percentage of the country with the highest unit cost increases.

[9] The fourth case is similar to the first case as two opposite effects arise again when the quota share of country 1 increases.

(Insert table 3)

It can be observed that given a certain difference in the selectivity of the fishing technology, optimal biomass may increase or decrease with the harvest quota of country 1 depending on how great the differences in unit harvesting costs between the countries are.

In the second case, if country 1 receives a higher quota harvest the optimal biomass will decrease. On the one hand, as in the first case, country 1 has the less selective technology ($\gamma_1 > \gamma_2$) and an increase in his quota (α) implies a reduction of the optimal biomass. But on the other hand, country 1 has now the lowest harvesting cost ($a_1 < a_2$), and an increase in his quota implies a lower "inverse efficient parameter" ($\frac{dZ'}{d\alpha} < 0 \Leftrightarrow a_1 < a_2$), in such a way that the optimal biomass tends to be lower ($\frac{dx^*}{dZ'} > 0$). Therefore, the final effect of an increase in the harvest quota of country 1 is a reduction of the optimal biomass[10].

Since optimal biomass is not independent of how optimal harvest is shared among countries, the planner should simultaneously determine optimal quotas and optimal biomass. This problem will be looked into the following section.

5 Joint determination of optimal biomass and harvest quotas

The results obtained in the previous section show that given the assumptions of our model, the optimal stock is not independent of how the harvest quotas are shared out. The aim of this section is to analyze the joint determination of the optimal stock and the fishing quotas. We assume that these quotas must be strictly positive for both countries as we want to consider a situation in which there is not possibility of restricting the access of a country to the

[10]Following a similar reasoning, it can be explained why in the third case optimal biomass increases as country 1's harvest quota increases.

resource[11].

The social planner's aim is to maximize the discounted net cash flow from the fishery, subject to the same restrictions as in the previous section. The share is not now given and, therefore, we will have two control variables rather than one. For simplicity, we consider each country's harvest as the control variables, $h_1(t)$ and $h_2(t)$[12], in such a way that the objective functional can be expressed now as

$$vp = \int_0^\infty e^{-\delta t} \left[(p - c_1(x))\, h_1(t) + (p - c_2(x))\, h_2(t) \right] dt. \tag{19}$$

The Hamiltonian of this problem can be written as

$$H = e^{-\delta t} \left[[p - c_1(x)]\, h_1(t) + [p - c_2(x)]\, h_2(t) \right] + \lambda(t) \left(G(x,\theta) - h_1(t) - h_2(t) \right) \tag{20}$$

and the first order conditions are

$$\frac{\partial H}{\partial h_i} = 0 = e^{-\delta t} \left[p - c_i(x) \right] + \lambda(t) \left(G_{h_i}(x,\theta) - 1 \right) \qquad i = 1, 2, \tag{21}$$

$$\frac{d\lambda}{dt} = -\frac{\partial H}{\partial x} = e^{-\delta t} \left(c_1'(x)\, h_1(t) + c_2'(x)\, h_2(t) \right) - \lambda(t) G_x(x,\theta), \tag{22}$$

$$\frac{\partial H}{\partial \lambda(t)} = \frac{dx}{dt} = G(x,\theta) - h_1(t) - h_2(t). \tag{23}$$

As equation (21) shows, we must now take into account the effect of the harvest rate of each country on the natural growth of the resource. This effect is measured by the term $G_{h_i}(x,\theta)$, which is the derivative of the natural growth function (1) with respect to the harvest rate of each country and is equal to

[11] If we allow that the whole quota go to just one country, the other should be compensated in a proper way. This could be done by side payoffs, but these are not always wellcome by countries because of socioeconomic aspects linked with the population involved in fishing activities.

[12] The same result will be obtained if we consider the total harvest rate, $h(t)$, and the share, α, as the control variables.

$$G_{h_i}(x,\theta) = \theta_{h_i} x \left[1 - \frac{x}{K}\right] \quad where \quad \theta_{h_i} = \frac{h_j(t)}{h^2(t)}\left(\gamma_j - \gamma_i\right). \tag{24}$$

As can be observed, the effect that the harvest of each country has on the natural growth of the resource will be different depending on the selectivity degree of the technology of each country and on how the harvest is shared between both of them. Besides, if $\gamma_i \neq \gamma_j$, this term will always be positive for one country and negative for the other.

If we solve the first order conditions (21), (22) and (23) ($h(t) = G(x^*, \theta)$), we obtain the following modified golden rule for the optimal biomass in the steady state

$$\delta = G_x(x^*, \theta) - \frac{\left[\frac{h_i}{h} c_i'(x^*) + \frac{h_j}{h} c_j'(x^*)\right] G(x^*, \theta)\left(1 - G_{h_i}(x^*, \theta)\right)}{p - c_i(x^*)}. \quad i, j = 1, 2 \tag{25}$$

When the social planner computes the optimal stock, he/she equals the ratio of marginal revenue to the effect that the fishing activity of both countries has on the natural growth rate. Each possible share of total harvest implies a different effect upon the marginal growth rate, and so, a univocal determination of the optimal biomass (x^*) and the harvest shares (h_1^* and h_2^*) is not possible. However, taking into account that we are interested in an interior solution in the feasible space with positive quotas for both countries, we can determine some necessary conditions that ought to be satisfied.

Solving the first order condition (21) for $i = 1, 2$, we have that

$$\frac{[p - c_1(x)]}{1 - G_{h_1}(x,\theta)} = \frac{[p - c_2(x)]}{1 - G_{h_2}(x,\theta)}. \tag{26}$$

Condition (26) states that the optimal control requires that the ratio between marginal revenues and the harvest effect of each country on the natural growth rate should be equal for both countries. As long as $G_{h_i}(x,\theta)$ and $G_{h_j}(x,\theta)$ always have opposite sign, it is necessary to guarantee that both be, in absolute value, lesser than one, in order to satisfy equation (26).

Lemma 1

For the existence of a steady state in the interior of the feasible control space, a necessary condition is that $G_{h_i}(x,\theta) \in \mid (0,1) \mid$ and this implies that

$$(\gamma_i - \gamma_j)\frac{h_i^*}{h^*} < \widetilde{r} \qquad \forall \quad \gamma_i > \gamma_j. \tag{27}$$

Proof*:* See the Appendix.

If $\gamma_i > \gamma_j$, then we have that $(\gamma_i - \gamma_j)\frac{h_i^*}{h^*} > 0$ and therefore $\widetilde{r} > 0$. In other words, this lemma states that the negative effect of the selectivity of the fishing gear on the natural growth rate cannot be so high as to cancel the growth of the resource.

Lemma 2

If country 1's fishing technology is more (less) selective than country 2's, i.e., $\gamma_1 < \gamma_2$ $(\gamma_1 > \gamma_2)$, an interior solution requires that

$$a_1 > a_2 \quad (a_1 < a_2).$$

Proof*:* See the Appendix.

This lemma states that a necessary condition to achieve an optimal interior solution is that the country with the least selective technology must have the lowest unit harvesting cost. We can therefore conclude that, when both countries have identical unit harvesting costs but a different selectivity fishing technology, the optimal solution cannot imply positive quotas for both countries.

In the previous section we have distinguished four cases with different possible asymmetries between countries, in terms of a_i and γ_i. The next table shows in which of those cases the optimal harvest quota for each country will be positive.

Case	Differences between countries	Percentage Country 1	Percentage Country 2
(1)	$\gamma_1 > \gamma_2, \quad a_1 > a_2$	0	1
(2)	$\gamma_1 > \gamma_2, \quad a_1 < a_2$	$[0,1]$	$[0,1]$
(3)	$\gamma_1 < \gamma_2, \quad a_1 > a_2$	$[0,1]$	$[0,1]$
(4)	$\gamma_1 < \gamma_2, \quad a_1 < a_2$	1	0

As can be seen in this table, an interior solution may be optimal in two of the cases, that is, when the least selective country has a lower unit harvesting cost than the other.

We have obtained necessary conditions for an interior solution to the problem, but they are not sufficient to guarantee that there exist an interior solution. This can be observed in the following numerical example. Let us use the fishery example in section 3 to show that the least selective country should have a certain cost advantage to make a positive quota for both countries optimal. We take as given the countries' selectivity fishing technology, ($\gamma_1 = 1$, $\gamma_2 = 1.15$) and the unit effort cost of country, $a_1 = 400.000$ ptas./ fishing day. Besides, we consider a fixed target biomass[13], $x^* = 1.1305 \times 10^6$, which is the optimum when the shares are given. Using equation (26) we compute the optimal harvest quotas for the different unit harvesting cost of country 2.

(Insert table 4)

Table 4 shows the range of the unit effort cost of country 2 for which there exists a positive share for both countries. For a given difference between countries in the selectivity of the fishing technology, we find that the quota of the least selective country rises as long as its unit cost of harvesting goes

[13]We consider a given biomass which is obtained from Table 2. We should remember that a univocal determination of harvest shares and optimal biomass is not possible, due to the existing interaction between them.

down. Besides, if its cost advantage is high enough, the optimal policy implies a corner solution where only the least selective country exploits the resource.

We can thus conclude that, when the social planner tries to simultaneously determine optimal stock and optimal harvest shares, an interior solution will be optimal only for certain asymmetries between countries. Besides, the planner would only be able to determine for each quota sharing its corresponding optimal biomass, or vice versa, solving conditions (26) and (25) simultaneously.

6 Conclusions

The fact that certain fishing gears or fishing technologies may affect the resource's natural growth rate negatively seems fairly straightforward. However, in the economic literature on fishing resources, it has always been assumed that the natural growth of a resource is a function of its own biomass and of the sea's environmental conditions, and these are considered to be stable and constant.

In this paper we analyze the optimal management of a fishery where the natural growth function for the fishing resource depends on the fishing technology employed. We have included in the growth function a variable which depends on the selectivity level of the fishing gear and which affects the resource's intrinsic growth rate. Concretely, it is supposed that the natural growth function depends not only on the selectivity level of the technology, but also on the harvest share obtained with that technology.

First, we determine the optimal stock and harvest under the assumption that there exists a supranational authority which determines the fishing quotas exogenously. And this is the way in which the Common Fisheries Policy (CFP) acts, that is, it assigns to each State Member the right to fish a fixed percentage (quota) of the Total Allowable Catches (TAC) which is determined for each specie annually. The principal result obtained is that the optimum stock is not independent of how the harvest is shared among the agents. Therefore, the current CFP cannot be efficient if the fishing technologies of the State Members do not have the same level of selectivity. In this case, an optimal CFP should determine the stock and the harvest quotas simultaneously. In this paper, we deal with a first analysis of the implications that this type of policy would entail when both countries, in addition to using different technologies, have different unit harvest costs. We have thus concluded that a solution with positive harvest quotas for both countries will only be optimal for certain asymmetries between countries.

APPENDIX

Proof of Proposition 1

Lets start by checking that $\gamma_{1<}\gamma_2 \Rightarrow \frac{dx*}{d\alpha} > 0$, where x^* is given by equation (15). Taking into account that $\gamma_{1<}\gamma_2 \Rightarrow \frac{d\theta}{d\alpha} > 0$ and given that $\frac{d\widetilde{r}}{d\theta} > 0$ and $\frac{d\rho}{d\widetilde{r}} < 0$, what we now have to prove is that $\frac{dx^*}{d\rho} < 0$. In order to check that $\frac{dx*}{d\alpha} < 0$ when $\gamma_{1<}\gamma_2$, we have also to prove that $\frac{dx^*}{d\rho} < 0$, because in this case $\frac{d\theta}{d\alpha} < 0$.

We have therefore to prove that

$$\frac{dx^*}{d\rho} = \frac{K}{4}\left[-1 + \frac{(1-\rho+Z)(-1)+4Z}{\sqrt{(1-\rho+Z)^2+8\rho Z}}\right] < 0, \tag{28}$$

and this implies that

$$(1-\rho+Z)(-1)+4Z < \sqrt{(1-\rho+Z)^2+8Z\rho}.$$

Having made some operations the previous condition entails that

$$8Z(Z-1) < 0,$$

in such a way that $\frac{dx^*}{d\rho} < 0 \Longrightarrow Z < 1$. In other words, the "inverse efficient parameter" must be lower than one and this condititon is always fulfilled. We can check it by using equation (4) to rewrite Z as

$$Z = \frac{c(x^*)x^*}{pK}, \tag{29}$$

where $x^* < K$, because $\lim\limits_{t\to\infty} x(t) = K$, and $c(x^*) < p$. Therefore, if the fishery is being exploited, then $Z < 1$.

Proof of Proposition 2

In the steady state, profits from the fishery are given by

$$\pi^* = [p - c(x^*)]\ h^*$$

in such a way that

$$\frac{d\pi^*}{d\alpha} = [p - c(x^*)]\frac{dh^*}{d\alpha} - h^*\frac{dc(x^*)}{dx^*}\frac{dx^*}{d\alpha},$$

where

$$\frac{dc(x^*)}{dx^*} = \frac{-a}{q\ (x^*)^2} < 0,$$

$$\frac{dx^*}{d\alpha} \gtreqless 0 \quad \textit{depending on}\ \gamma_1 \lesseqgtr \gamma_2.$$

Then,

$$(-h^*\frac{dc(x^*)}{dx^*}\frac{dx^*}{d\alpha}) \gtreqless 0\ if\ \gamma_1 \lesseqgtr \gamma_2,$$

and if we prove that $\frac{dh^*}{d\alpha} \gtreqless 0$ if $\gamma_1 \lesseqgtr \gamma_2$, we will have proven proposition 2. We know that $\frac{d\widetilde{r}}{d\theta} > 0$ and $\frac{d\rho}{d\widetilde{r}} < 0$ when $\gamma_1 < \gamma_2$. Using the "bionomic growth rate parameter" presented in the main text and taking into account that in the steady state $h = G(x^*, \theta) = \widetilde{r}\ (x^* - \frac{(x^*)^2}{K})$, we obtain that

$$\frac{dh^*}{d\rho} = \frac{d\ \widetilde{r}}{d\rho}(x^* - \frac{(x^*)^2}{k}) + \widetilde{r}\ \frac{dx^*}{d\rho}(1 - \frac{2x^*}{k}) = \frac{\widetilde{r}_\rho}{\widetilde{r}}h^* + x_\rho h_x^* \tag{30}$$

What we now have to prove is that $\frac{dh^*}{d\rho}$ is always negative, hence $\frac{dx^*}{d\alpha}$ and $\frac{dh^*}{d\alpha}$ will be possitive or negative depending on $\gamma_1 \lesseqgtr \gamma_2$. Equation (30) depends on the resource's growth function and on the productivity weighted by $\frac{\widetilde{r}_\rho}{\widetilde{r}} < 0$ and $x_\rho < 0$, and so for $x^* < \frac{k}{2}$, $\frac{\widetilde{r}_\rho}{\widetilde{r}}h^*$ and $x_\rho h_x$ will be negative and, therefore, $\frac{dh^*}{d\rho}$ as well. But it is also known (Munro and Clark 1985) that the optimal biomass in the steady state must be higher than $\frac{k}{2}$.

To see how in this case $\frac{dh^*}{d\rho}$ is negative we will formulate the equilibrium biomass as a proportion of the carrying capacity of the resource $x^* = A^*k$ $(0 < A^* < 1)$. Now equation (30) changes to

$$\frac{dh^*}{d\rho} = -k\ \widetilde{r}\left[\frac{\widetilde{r}}{\delta}\underset{(+)}{A^*(1-A^*)} - \frac{dA^*}{d\rho}\underset{(+)}{(1-2A^*)}\right] \tag{31}$$

To prove that $\frac{dh^*}{d\rho}$ is negative, we have to show that the second term in brackets of equation (31) is lower than the first one equation With this aim, we will have to formulate equation (28) in terms of A^*

$$\frac{dA^*}{d\rho} = \frac{1}{4}\left[-1 + \frac{(1-\rho+Z)(-1)+4Z}{\sqrt{(1-\rho+Z)^2+8\rho Z}}\right] \tag{32}$$

Then, from (32) we know that $\frac{dA^*}{d\rho} \in (-\frac{1}{2}, 0)$, and since we are considering an optimal biomass $x^* > \frac{k}{2}$ it is clear that $A^* \in (\frac{1}{2}, 1)$. The maximum value of $\left|\frac{dA^*}{d\rho}\right|$ is equal to $(1 - A^*)$, in such a way that by equation (31), $\frac{dh^*}{d\rho} < 0$ will occur if

$$\frac{\widetilde{r}}{\delta} A^* > 2A^* - 1$$

And it is easy to show that this condition is always satisfied.

Proof of Lemma 1

When $\gamma_i \neq \gamma_j$, $G_{h_i}(x,\theta)$ and $G_{h_j}(x,\theta)$ have opposite signs, and for the feasibility of condition (26), these both terms must be, in absolute value, lesser than the unity.

In the steady state, we have that $G(x,\theta) = h\,(t)$ and replacing this condition in equation (24) we obtain

$$G_{h_i}(x,\theta) = \frac{h_j}{\widetilde{r}\ h}\left(\gamma_j - \gamma_i\right),$$

and

$$\frac{h_j}{\widetilde{r}\ h}\left(\gamma_j - \gamma_i\right) < 1 \Rightarrow \frac{h_j}{h}\left(\gamma_j - \gamma_i\right) < \widetilde{r}\ \ when \quad \gamma_j > \gamma_i.$$

Proof of Lemma 2

From lemma 1 we know that if $\gamma_2 > \gamma_1$, then $G_{h_1}(x,\theta) \in (0,1)$ and $G_{h_2}(x,\theta) \in (-1,0)$. Therefore, equation (26) requires that

$$p - c_1\left(x\right) < p - c_2\left(x\right),$$

which implies that $a_1 > a_2$, as long as $c_1\left(x\right) = \frac{a_1}{qx}$ and $c_2\left(x\right) = \frac{a_2}{qx}$.

References

[1] Boyce J.R. (1996), *"An Economic Analysis of The Fisheries Bycatch Problem" Journal of Environmental Economics and Management 31*, 314-336

[2] Clark, Colin W. (1990). "*Mathematical Bioeconomics. The optimal management of renewable resources*", 2ª ed., John Wiley & Sons, Nueva York.

[3] Garza Gil, M.D. (1998)."ITQ Systems in Multifleet Fisheries. An Application for Iberoatlatic Hake*", Environmental and Resource Economics* 15, 93-106.

[4] Gutiérrez, M.J. y J.M. Da-Rocha (1998)."The Optimality of the Common Fisheries Policy: A Calibration of the Distortions for the Northen Stock of Hake", mimeo.

[5] Lleonart J, Silvani L, Fernandez-Cuevas I, Gual A, (1996), *"La Crisis Pesquera Española: Un Enfoque Ecológico",* "La situación del Mundo" R. Brown, (apéndice).

[6] Mesterton-Gibbons, M. (1993). "Game Theoretic Resource Modeling", *Natural Resource Modeling 7*, 93-147.

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

[8] Munro, Gordon R and Scott A.D. (1985), "The Economics of Fisheries Management". Handbook of Natural Resource and Energy Economics, Vol II, by A.V. Kneese and J.L Sweeney. Elsevier Science Publisher B.V.

[9] Turner Matthew A, (1997), *"Quota Induced Discarding in Heterogeneous Fisheries" Journal of Environmental Economics and Management 33*, 186-195.

[10] Ward J. M. (1994) *"The Bioeconomic Implicatios of a Bycatch Reduction Device a Stock Conservation Management Measure" Marine Resource Economics* 9, 227-240.

Table 1:
Biomass, harvest and profits when $\gamma_1 = 1$

γ_2	$X(\times 10^6)(1)$	$h(1)$	$\pi(2)$
1	1.1317	3.3344×10^5	1.9546×10^{10}
1.15	1.1305	3.1329×10^5	1.8318×10^{10}
2	1.1194	1.9882×10^5	1.1346×10^{10}
3	1.0584	6.2319×10^4	3.0429×10^9
>3.4	0	-	-

(1) Tones; (2) Pesetas

Table 2:
Biomass and harvest for different shares

α	$X(\times 10^6)(1)$	$\widetilde{r}$	$h\ (\times 10^5)(1)$	$h_1\ (\times 10^5)(1)$	$h_2\ (\times 10^5)(1)$
$\alpha = 1$	1.1317	1.2000	3.3344	3.3344	0
$\alpha = 0.75$	1.1311	1.1712	3.2338	2.4253	0.8084
$\alpha = 0.5$	1.1305	1.1250	3.1329	1.1566	1.5664
$\alpha = 0.25$	1.2990	1.0875	3.0318	0.7579	2.2738
$\alpha = 0$	1.2920	1.0500	2.9310	0	2.9310

(1) Tones

Table 3:
Optimal stock evolution when $\gamma_1(1.2) > \gamma_2(1.1)$ and $a_1(400.000) > a_2$

α	$X(1)$for $a_2 = 376000$	X for $a_2 = 398231$	X for $a_2 = 399000$
0	1.104250	1.128183	1.129010
0.2	1.109044	1.128210	1.128871
0.4	1.113835	1.128222	1.128719
0.6	1.118621	1.128222	1.128554
0.8	1.123404	1.128210	1.128376
1	1.128183	1.128183	1.128183

(1) $(\times 10^6)$

Table 4:
Country's quota for different unit harvesting costs

a_1	a_2	α
400.000	$\geq$ 392.250	1
400.000	390.560	0.75
400.000	387.910	0.5
400.000	383.190	0.25
400.000	$\leq$ 372.460	0