Vol. 5: 335–344, 2008
doi: 10.3354/esr00140

ENDANGERED SPECIES RESEARCH
Endang Species Res

Printed December 2008
Published online November 17, 2008

Contribution to the Theme Section 'Fisheries bycatch: problems and solutions'

Gear-selectivity-based regulation in a mixed fishery

Raúl Prellezo[1,*], M. C. Gallastegui[2]

[1]AZTI-Tecnalia, Marine Research Division, Txatxarramendi Ugartea z/g, 48395 Sukarrieta, Spain
[2]Dpto. de Fundamentos del Análisis Económico I, Universidad del País Vasco-EHU, Lehendakari Agirre 83, 48015 Bilbao, Spain

ABSTRACT: In this paper we analyze the optimal management of a mixed fishery where the harvest is composed of a target and a bycatch species. In contrast to other studies, we have included the selectivity of the fishing gear as a control variable. The fishery is regulated by means of total allowable effort and with 2 different systems of total allowable catch (TAC): an aggregated and a disaggregated TAC. The main result obtained is that in an aggregated TAC program, the selectivity level and the decision to discard depend only upon the marginal profits of both species, but that in the case of a disaggregated program, other factors such as gear selectivity have to be taken into account.

KEY WORDS: Mixed fisheries · Fishing gear selectivity · Bycatch · Harvest quotas

INTRODUCTION

Even though biological status is currently assessed separately for single species and total allowable catch (TAC) is mainly related to single species, fisheries are normally composed of many different species. Real world data show that fleets typically capture target species as well as bycatch species. Indeed, there is some evidence that the proportion of bycatch to target species has increased as the availability of classic target species has decreased and fleets have begun to look for a new way of obtaining extra returns. For instance, the Basque otter trawl fleet, which historically targeted hake, has turned to a multi-species harvesting regime in the last 10 yr (Marillas et al. 2008).

This implies a change in inter-species selectivity, i.e. the conjunction of processes determining the changes in the probability of harvesting different individuals from the target species. Apart from changing the target species, fishermen also use this selectivity shifting as a way of obtaining an extra return, harvesting non-targeted species with the same gear. Unfortunately, there are some cases where the bycatch is composed of species with low or null commercial value. For example, some seagulls captured by surface fishing gears have neither a commercial nor a non-negligible existence value. On the other hand, we can think of some bycatch species with a great existence value, such as the dolphins captured in driftnets by a fleet targeting tuna; except in certain markets, these dolphins have no commercial value. Finally, there are other species of commercial value but without a specific fleet targeting them. For example, the horse mackerel in the Basque Country has been a bycatch of a Basque fleet targeting other species.

Although in the above examples the bycatch belongs to a different species, this is not always the case. Sometimes the bycatch belongs to the same species as the target but is composed of non-mature individuals. Apart from this, it is also possible to think of a single species that is divided into 2 biologically independent sub-species (e.g. anglerfish, which can be properly classified as white anglerfish and black anglerfish). Given the lower landings of black anglerfish it could be considered a bycatch.

All of these characteristics (and any combination thereof) can comprise what is known as a mixed fishery. In such a fishery, the main determinant of multiple species harvesting and of the bycatch is selectivity of the fishing gear, i.e. the effectiveness of a specific fishing gear as a function of any characteristic of the exploited individuals, such as size, age (intra-species selectivity) or even species (inter-species selectivity). This implies that the control of this selectivity is one

*Email: rprellezo@suk.azti.es

of the most important ways to regulate these fisheries. In this context, the problem emerges when in a mixed fishery the fishing gear is not able to select exactly the target fish resources and this generates an important bycatch. This possibility conditions the management of the fishery as well as the effect of regulations. Managers have to take into account that 2 or more different species (or age cohorts in the case of intra-species selectivity) are being harvested, or at least that a bycatch exists, when deciding how to regulate the fishery.

Fishing policy can be divided in 2 main areas: effort (inputs) and harvest (output) regulations. In this article it is assumed that the input control is based upon a system of limited entries of vessels, while the output control is based upon the implementation of TAC. It is important to note that these types of regulation are extensively used in the common fishery policy (CFP).

The introduction of TAC can be implemented in many different ways. We analyze 2 of them — the first based upon an aggregated quota in both species (many target species, a target and a bycatch), the second based upon a disaggregated TAC, one for each species. Even though there are other types of quotas (for instance a value-based quota, Copes 1986, Turner 1996, 1997), these 2 systems are the most commonly adopted due to their simplicity. It is important to note that we ignore the political[1] and efficiency[2] problems that all of these quota systems can generate.

Given all these different possibilities for the value of the bycatch, and as opposed to Boyce (1996), our analysis is based on the implications that a change of the fishing gear (or more specifically, of the fishing gear selectivity) can have on a mixed fishery. We want to show that when a fishery is managed by means of TAC the capacity of the fishing gear to select only the target resource acquires real significance.

METHODS

Basic model description. Our model looks at a regulated mixed fishery exploited by a single fleet. There is a constraint on the potential number of vessels entering the fishery, hence the fleet is composed of $n \le N$ vessels, where N is the maximum number of vessels allowed to fish. While it is clear that nearly all fisheries are being exploited by several heterogeneous fleets, the interaction between fleets responds more to a dynamic context (McKelvey 1983) than to a static one. In a dynamic context there are some other effects, such as the changes in the benthic substrate on which most of the marine species depend (Lleonart et al. 1996) or the species interdependence through competition and predation (Clark 1990). Hence, for simplicity, the fleet in our model is assumed to be homogeneous. The exploitation of the fishery is focused on a single target species and a bycatch. While such a simplification may limit the results obtained, some fisheries are managed in such a way (the case of some fisheries in the Gulf of Alaska) (Boyce 1996). Furthermore, in some cases the bycatch and the target are the same species, where juvenile or non-mature individuals are harvested along with mature ones.

We use h_j to denote the target harvest d^{-1} for vessel j, and $b(h_j,\alpha)$ to denote the bycatch of this vessel (d^{-1}) as a function of the target harvest. We assume that this function is positive and increases with the output of the target species in a non-decreasing way, therefore we hold that $b_h(h_j,\alpha) > 0$ and that $b_{hh}(h_j,\alpha) \ge 0$ for all positive h_j. We can think of a functional form such as:

$$b(h_j,\alpha) = \alpha h_j^{\beta} \quad (1)$$

where β stands for the elasticity of the bycatch with respect to the target species. The functional form of β is:

$$\beta = \frac{h}{b(h,\alpha)} b_h(h,\alpha) \quad (2)$$

When $\beta = 1$, we are in the case $b_{hh}(h_j,\alpha) = 0$; hence, the ratio of bycatch to target species is independent of total harvest. On the other hand, when $\beta > 1$, we assume that $b_{hh}(h_j,\alpha) > 0$ and the ratio will increase with total harvest[3].

Parameter α is a positive constant that represents the selectivity level of the fishing gear. From Eq. (1) we can see how a higher α implies a higher level of bycatch; note that $b_\alpha(h_j,\alpha) > 0$ for any $h_j > 0$. In this case, we talk about a lower selectivity level of the gear. It is also natural to assume that a zero bycatch is only possible with zero output of the target species, $b(0,\alpha) = 0$. In other words, even if the existing fishing gears differ on their selectivity levels, they are not able to capture solely the target species; hence, the capacity to improve the selectivity of the fishing gear is limited. This implies that $\alpha_0 > 0$[4]. On the other

[1]One of the limitations of implementing a fixed TAC on one species is the existence of reticence to reduce the TAC even when there is evidence of a deterioration in the stock (Walters & Pearse 1996)

[2]The implementation of a TAC may prevent biological over-fishing but fail to prevent economic over-fishing (Munro & Scott 1985, Grafton 1996)

[3]The case $0 < \beta < 1$ implies that the ratio of bycatch to target decreases when total harvest increases. Since this is unlikely, we do not analyze it

[4]Following Turner (1996), if $\alpha_0 = 0$ we hold that the harvest technology satisfies the ‘perfect control of harvest composition’ property, while if $\alpha_0 > 0$, it will exhibit ‘imperfect control of harvest composition’

hand, we also assume the existence of a maximum level of α, denoted by α_∞.

A change in selectivity level does not necessarily imply a different fishing gear, nor even a change in fishing technology. Sometimes, a small change in fishermen's behaviour implies a different selectivity level. For example, among other factors, checking the fishing nets more regularly allows the undesired harvest a chance to escape from death.

Let us define the variable profits (d^{-1}) obtained from harvesting the target species by vessel j as $\pi_j(h_j, \alpha, p_1)$, where p_1 is the market price (€ $fish^{-1}$) of the target species (which we have omitted, as price of the target species is not a decision variable). We assume that these benefits increase with the total harvest in a decreasing way, i.e. $\pi_j(0,\alpha) = 0$, $[(\partial\pi_j(h_j,\alpha)/\partial h_j] > 0$ for all $h_j \geq 0$, and $[\partial^2\pi_j(h_j,\alpha)/\partial h_j^2] < 0$ for $h_j > 0$.

We assume that there is no direct cost in changing the selectivity level, but it is possible that this change affects the profits obtained from the target species. If fishing of the target species is done with greater care, it may increase harvesting costs. For example, if the driftnets are checked more frequently the cost generated will be imputed on the target species. In this sense we assume that a worse selectivity increases the returns obtained from the target species but in a detrimental decreasing way, i.e. $[\partial\pi_j(h_j,\alpha)/\partial\alpha] \geq 0$, for all $\alpha \geq 0$, and $[\partial^2\pi_j(h_j,\alpha)/\partial\alpha^2] < 0$ for $\alpha > 0$. We also assume that

$$\frac{\partial^2\pi_j(h_j,\alpha,p_1)}{\partial\alpha\partial h} = 0 \quad (3)$$

Sometimes a change in the selectivity level will not affect the returns obtained from the target species. One example is a cost-free variation in the fishing gear, such as the use of a different bait. In this case we will assume that $\partial\pi_j(h_j,\alpha)/\partial\alpha = 0$.

Using the previous definitions and given a fishing season length of T (days), a p_2 price[5] (€ $fish^{-1}$) for the bycatch and a fixed cost[6] of k (€ $vessel^{-1}$), returns for the whole season to vessel j are:

$$v_j = T[(\pi_j,\alpha) + \delta p_2 b_j(h_j,\alpha)] - k, \ i = 1,\ldots,N \quad (4)$$

where, $\delta p_2 b_j(h_j,\alpha)$ stands for the returns for vessel j (d^{-1}) obtained from the bycatch. The parameter δ allows us to discriminate the cases where the bycatch has a market, an existence value, or a null value for the society. When the bycatch has a market value we hold that $\delta = 1$ and profits obtained from it are $p_2 b_j(h_j,\alpha)$. When the bycatch has an existence value ($\delta = -1$) we subtract that value from total profits. For simplicity we assume that the existence value is equal to the market price, but it could be higher or lower. When the bycatch does not have a value this term will vanish and total profits will be just those obtained from the harvest of the target species.

TAC on total harvest. There are several systems capable of limiting the harvest. One of the most important is the establishment of TAC on the harvested species. In the European Union (EU) this is based on previous estimates of the natural state of the resources and on the economic and technical features involving each fishery. But when facing a mixed fishery[7] there are other problems for the implementation of TAC, since even if it should be individually computed for each species taking into account (among other factors) the biology and the geographical location, in many cases the limits are based on total harvest (including target and bycatch species) extracted from the fishery[8]. In these cases the quota imposed by the regulatory agency takes the form:

$$\bar{S} \geq S(h_j,\alpha,T,n) = Tn[h_j + b(h_j,\alpha)] \quad (5)$$

where $\bar{S}$ is the total TAC, and T is the season length needed by n vessels to satisfy the imposed quota bounded on its extension by a physical limitation (T_{max}) (Clark 1990), in such a way that:

$$T \leq T_{max} \quad (6)$$

The social planner problem: If we assume the existence of a supranational authority aiming to maximize the value that society obtains from the fishery, the objective function of this authority can be expressed as:

$$V = Tn[\pi_j(h_j,\alpha) + \delta p_2 b_j(h_j,\alpha)] - kn \quad (7)$$

Given Eqs. (4) & (5), and the non-negativity constraints of the variables h, n and T, the Lagrangian for this problem is:

$$L = V + \lambda\{S - Tn[h_j + b(h_j,\alpha)]\} + \tau(T_{max} - T) + \eta_1(\alpha - \alpha_0) + \eta_2(\alpha_\infty - \alpha) + \phi h + \theta n + \psi T \quad (8)$$

where λ, τ, φ, θ and ψ, are the Lagrange multipliers corresponding to Eqs. (5) & (6) and the non-negativity of the variables, h, n and T, respectively, whereas η_1 and η_2 correspond to the constraints imposed on the selectivity level ($\alpha \geq \alpha_0$ and $\alpha \leq \alpha_\infty$).

[5]Both p_1 and p_2 are assumed to be strictly positive

[6]For simplicity we assume that variable costs do not exist

[7]Note that we are only reflecting the case when more than one species is being harvested by a single gear

[8]These kinds of limitations are more commonly used in single-species fisheries and when the bycatch is composed of non-mature individuals of the same species, although for simplicity they are also used in multi-species fisheries. This could be the case of the anglerfish presented in the 'Introduction'

Assuming that the social planner chooses the optimal h, n, T and the selectivity level of the fishing gear[9] (α), the first order conditions for the problem are[10]:

$$\frac{\partial L}{\partial h} = \{\pi_h(h,\alpha) + \delta p_2 b_h(h,\alpha) - \lambda[1 + b_h(h,\alpha)]\}Tn + \phi = 0, \quad h \geq 0, \phi \geq 0, h\phi = 0 \tag{9}$$

$$\frac{\partial L}{\partial n} = \{\pi(h,\alpha) + \delta p_2 b(h,\alpha) - \lambda[h + b(h,\alpha)]\}T - k + \theta = 0, \quad n \geq 0, \theta \geq 0, n\theta = 0 \tag{10}$$

$$\frac{\partial L}{\partial T} = \{\pi(h,\alpha) + \delta p_2 b(h,\alpha) - \lambda[h + b(h,\alpha)]\}n - \tau + \psi = 0, \quad T \geq 0, \psi \geq 0, T\psi = 0 \tag{11}$$

$$\frac{\partial L}{\partial \alpha} = [\pi_\alpha(h,\alpha) + b_\alpha(h,\alpha)(\delta p_2 - \lambda)]Tn + \eta_1 - \eta_2 = 0, \quad \eta_1 \geq 0, \alpha \geq \alpha_0, \eta_1(\alpha - \alpha_0) = 0, \eta_2 \geq 0, \alpha_\infty \geq \alpha, \eta_2(\alpha_\infty - \alpha) = 0 \tag{12}$$

The interpretation of the equations is straightforward. Eq. (9) indicates that, for any positive harvest, its level will be chosen in such a way that the marginal profits $\pi_h(h,\alpha)+\delta p_2 b_h(h,\alpha)$ will equal the marginal scarcity rents on both species, $\lambda[1+b_h(h,\alpha)]$. This condition, $[1+b_h(h,\alpha)]Tn = S_\alpha(h,\alpha,T,n)$, takes into account that a unit increase in the harvest rate leads to an increase in total output of $[1+b_h(h,\alpha)]Tn$ units. Eq. (10) indicates that when $n > 0$, total profits vessel^{-1}, net of scarcity rents of both species and over the entire fishing season, will equal the entry cost of a new vessel (k). Eq. (11) shows how if $T > 0$, the value of an increase of the season length (τ) should equal the total profits, net of scarcity rents of the whole fleet per unit of time. Finally Eq. (12) implies that the selectivity level will be chosen comparing the returns obtained from each unit of the bycatch species (δp_2) and the scarcity rent of both species (λ). Hence $[b_\alpha(h,\alpha)]Tn = S_\alpha(h,\alpha,T,n)$, takes into account that when the selectivity level is increased by 1 unit, total output is increased by $[b_\alpha(h,\alpha)]Tn$ units.

The social planner has to obtain the optimal values for the control variables, keeping in mind different possible values of δ. Since the first-order conditions[11] in Eqs. (9) to (12) depend on the selectivity of the fishing gear, we start the analysis by considering optimal selectivity.

Optimal selectivity: The optimal selectivity is derived from Eq. (12), which can be solved for λ, obtaining:

$$\lambda = \left[\frac{\eta_1 - \eta_2}{Tnb_\alpha(h,\alpha)} + \frac{\pi_\alpha(h,\alpha)}{b_\alpha(h,\alpha)} + \delta p_2\right] \tag{13}$$

According to Eq. (13), the value of λ depends on δ, p_2 and η.

Proposition 1: When the bycatch has a positive or a null value to society, the total TAC is captured. However, when the bycatch has an existence value this does not necessarily happen (see Appendix 1 for proof).

Proposition 1 shows the way in which it is optimal to capture as much as possible when the harvest (target or bycatch) does not reduce benefits. It shows that the selectivity level will be used as a way to harvest the species (target or bycatch) with the highest marginal profit. We can see it by solving Eqs. (9) & (13), obtaining:

$$\eta_1 - \eta_2 = \{[\pi_h(h,\alpha) - \delta p_2]\Omega(h,\alpha,T,n) - \pi_\alpha(h,\alpha)\}Tn \tag{14}$$

where $\Omega(h,\alpha,T,n) = S_\alpha(h,\alpha,T,n)/S_h(h,\alpha,T,n)$ takes into account that an increase in the selectivity level has a different effect on the total output compared to an increase in the harvest rate. This term weighs the difference between the marginal profits of both species $[\pi_h(h,\alpha) - \delta p_2]$. The term $\pi_\alpha(h,\alpha)$ shows that a lower selectivity implies higher profits, and finally, $\eta_1 - \eta_2$ is the difference between the shadow prices of the constraints imposed on the selectivity level (it is important to observe that if $\alpha_\infty > \alpha_0$, η_1 and η_2 cannot be simultaneously positive).

First assume that the bycatch has a null value ($\delta = 0$). Looking at Eq. (14) we see how the social planner has to compare the marginal profits of the target species $\pi_h(h,\alpha)$ with the reduction in harvesting costs due to the use of a lower selectivity level $\pi_\alpha(h,\alpha)$. Hence, if $[\pi_h(h,\alpha)]\Omega(h,\alpha,T,n) > \pi_\alpha(h,\alpha)$, it will be necessary to use the best selectivity possible; in this case it is necessary that $\eta_1 > 0$, so that $\alpha^* = \alpha_0$. This implies that only if the change in profits due to an increase in the harvest rate (relative to the increase in the total harvest derived from it) is higher than the change in the profits due to an increase in the selectivity level (relative to the increase in the total harvest derived from it), we will have to use the best possible selectivity. On the other hand, if

[9] The variable that the social planner can choose in this problem is not the fishing gear, which normally is fixed. The social planner could impose any rule that could improve the selectivity level, e.g. increasing or decreasing net size. Additionally, the existence of a regulation on the number of vessels entering the fishery gives the planner the possibility of selecting only those vessels that use fishing gear with the desired selectivity. Ward (1994), in a somewhat different context, analyses the effects of a gear modification proposed to reduce bycatch and discarding. This implies a straightforward selectivity modification and a cost derived from this change

[10] α and h stand for the partial derivatives selectivity level and harvest rate, respectively

[11] Assuming that $\pi_{hh}(h_j,p_1) + \delta p_2 b_{hh}(h_j,\alpha) < 0$, Eq. (7) is quasi-concave in T, n, h and α. This, plus the quasi-convexity of the constraints involved in the maximization, ensure sufficiency for the Kuhn-Tucker conditions. Therefore, second-order conditions for maximum are satisfied

$[\pi_h(h,\alpha) - p_2]\Omega(h,\alpha,T,n) < \pi_\alpha(h,\alpha)$, the optimal selectivity will be $\alpha^* = \alpha_\infty$, the worst possible selectivity. Finally, if $[\pi_h(h,\alpha)]\Omega(h,\alpha,T,n) = \pi_\alpha(h,\alpha)$, the optimal selectivity cannot be defined using only Eq. (14) since in this case $\eta_1 = \eta_2 = 0$, which in turn implies that $\alpha_0 \leq \alpha^* \leq \alpha_\infty$.

Now assume that the bycatch can be sold in the market ($\delta = 1$). The selectivity level will be chosen in the same way, but taking into account the positive returns from the bycatch. It implies (see Eq. (14) that a worse selectivity allows, apart from a lower harvesting cost, a positive return from the harvested bycatch (p_2). Now, if $[\pi_h(h,\alpha) - p_2]\Omega(h,\alpha,T,n) > \pi_\alpha(h,\alpha)$, it will be necessary to use the best possible selectivity, i.e. $\alpha^* = \alpha_0$. This implies that a higher marginal profit for the target species than for the bycatch is necessary but not sufficient. In the opposite case, $\pi_h(h,\alpha) \leq p_2$, the optimal selectivity is $\alpha^* = \alpha_\infty$.

In both cases it is convenient to observe that the selectivity level depends crucially upon β. Thus, a higher β implies a higher effect of the selectivity on the total harvest $[b_\alpha(h,\alpha)]$ and a higher probability of having a selectivity level of the type $\alpha^* = \alpha_0$.

Proposition 1 also shows that when the bycatch has an existence value $\delta = -1$ the total TAC is not necessary fulfilled. This will be the case when even the highest selectivity level ($\alpha^* = \alpha_0$) is not enough to compensate the existence value of the bycatch harvested ($-p_2$), or when $\alpha^* > \alpha_0$ does not sufficiently reduce the harvesting costs $[\pi_\alpha(h,\alpha)]$ to compensate for this existence value. On the other hand if the total TAC is fulfilled, we will have to add the marginal profits of both species and compare them with the costs of increasing the selectivity.

When a TAC for both species is implemented, Eq. (14) shows how the optimal selectivity is determined comparing the marginal profits of both species. It is straightforward that Eq. (14) has to be computed for the optimal harvest rate that will be obtained later on.

TAC for each species. When the characteristics of the fishery are such that the regulatory agency is able to implement a TAC for each species (i.e. the species can be easily differentiated, as in the case of the anchovy and the mackerel) the harvest constraints are given by the maximum harvest rate allowed for each one, that is:

$$\bar{S}_1 \geq S_1(h_j,T,n) = Tnh \tag{15}$$

$$\bar{S}_2 \geq S_2(h_j,\alpha,T,n) = Tnb(h,\alpha) \tag{16}$$

where $\bar{S}_1$ and $\bar{S}_2$, stand for the maximum quotas for the target species and the bycatch, respectively. In order to simplify the comparison with the case previously studied, we assume that the total TAC is the same, i.e. $\bar{S}_1 + \bar{S}_2 = S$. Finally, when a disaggregated TAC is established, it becomes necessary to take into account which constraint is binding.

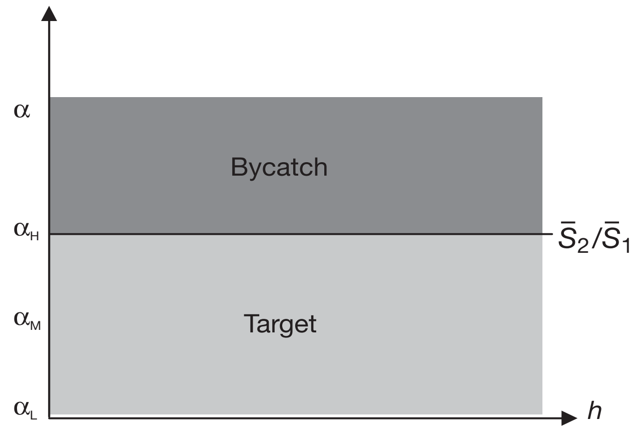

Fig. 1. Changes in constraints for different selectivity (α) levels (low, medium and high; L, M, H, respectively) and the relationship with the ratio of the bycatch to the target species quotas ($\bar{S}_2/\bar{S}_1$) when $\beta = 1$

Binding constraints: The ratio between the bycatch and the target will be determined by the expression $b(h,\alpha)/h$, such that if n vessels harvest during T days, the total bycatch is $Tnb(h,\alpha)$, whereas the target harvest is Tnh. Hence, the relevant constraint for a fixed harvest rate is:

$$\frac{b(h,\alpha)}{h} \frac{>}{<} \frac{\bar{S}_2}{\bar{S}_1} \tag{17}$$

In the case $b(h,\alpha)/h > \bar{S}_2/\bar{S}_1$, the relevant constraint is the TAC corresponding to the bycatch, whereas, in the opposite case $b(h,\alpha)/h < \bar{S}_2/\bar{S}_1$, the relevance switches to the TAC of the target species.

Case $\beta = 1$: We should remember that in this case the rate of the bycatch to the target species is independent of the harvest rate. Hence $b_{hh}(h,\alpha) = 0$ and Eq. (17) changes to:

$$\alpha \frac{>}{<} \frac{\bar{S}_2}{\bar{S}_1} \tag{18}$$

Eq. (18) implies that the binding constraint depends only on the selectivity level of the fishing gear and not on the harvest rate such that, if selectivity is low enough (a high α), we have $\alpha > \bar{S}_2/\bar{S}_1$ and the bycatch TAC becomes relevant, while if the selectivity level is high (a low α), we have $\alpha < \bar{S}_2/\bar{S}_1$ and the target species TAC is then relevant.

Given the selectivity level of the fishing gear, one of the TACs will not be relevant in the analysis, except in the case where $\alpha = \bar{S}_2/\bar{S}_1$.

Fig. 1 shows how, in this case, the binding constraints area depends on the $\bar{S}_2/\bar{S}_1$ ratio; if the TAC of the bycatch is increased, the area of this constraint will be reduced and vice versa. If the optimal α coincides with α_H, for a given $\bar{S}_2/\bar{S}_1$ ratio the bycatch constraint will be relevant; if it coincides with α_L the target species constraint will be relevant; and if it coincides with α_M both constraints will be relevant.

Case β > 1: In this case the ratio of bycatch to target grows with h[12], hence $b_{hh}(h,\alpha) > 0$, and the change in the relevant constraint is a function of the selectivity level and of the target species harvest. If we suppose that β = 2, Eq. (17) changes to:

$$\alpha h \frac{\geq}{<} \frac{\bar{S}_2}{\bar{S}_1} \qquad (19)$$

Now both constraints are relevant, since it is possible to switch from one to the other, changing the harvest rate or the selectivity level.

The area for each restriction is now given not only by the ratio $\bar{S}_2/\bar{S}_1$, but also is affected by the $b(h,\alpha)/h$ straight line. So if we fix the ratio $\bar{S}_2/\bar{S}_1$, the determination of the binding constraint will be given just by the $b(h,\alpha)/h = \alpha h$ straight line and the fishing gear selectivity level will determine the slope of this straight line. Fig. 2 shows 3 different values of h for 3 different levels of selectivity. As we hold that $\alpha_{H2} > \alpha_{M2} > \alpha_{L2}$, the corresponding harvest rates will be ordered as $h_H < h_M > h_L$. The area where the bycatch constraint is binding is reduced as a more selective fishing gear is used.

Once the constraints are understood, we can tackle the social planner problem with the objective of maximizing the value that society obtains from the fishery. The first-order conditions are equivalent to the previous case, although now each species has its own shadow price (λ_1 and λ_2, corresponding to the target and the bycatch, respectively; see Appendix 2).

When a TAC for each species is implemented, we don't know which TAC is going to be fulfilled first, therefore we find 2 different cases, depending on which TAC is reached first.

Binding TAC for bycatch: Let us suppose that for any $\alpha \geq \alpha_0$ the TAC of the bycatch is binding, whereas that of the target is not, i.e. $\lambda_1 = 0$ and $\lambda_2 > 0$. Hence, as in the previous case, we can obtain the condition that determines optimal selectivity:

$$\eta_1 - \eta_2 = \{[\pi_h(h,\alpha) - \delta p_2]\Omega_2(h,\alpha,T,n) - \pi_\alpha(h,\alpha)\}Tn \qquad (20)$$

where $\Omega_2(h,\alpha,T,n) = S_{2\alpha}(h,\alpha,T,n)/S_{2h}(h,\alpha,T,n)$ takes into account that an increase in the selectivity level has a different effect on the total bycatch in comparison to an increase in the harvest rate. Eq. (20) is almost the same condition as the one obtained in the case of an aggregated TAC (Eq. 14) when the society assigns a null value to the bycatch (δ = 0). Note that since the target TAC is not binding, we do not have to take into account the different effects of selectivity and harvest rate on total output, but the effect that they have on the total bycatch captured. Hence, since there is a TAC for each species, the increase in the total output due to an extra unit of the harvest rate can be divided into 2 effects: one in the bycatch quantity and one in the target quantity. Since only the bycatch constraint is binding, in Eq. (20) only this effect is taken into account — $\Omega_2(h,\alpha,T,n)$ in Eq. (20), instead of $\Omega(h,\alpha,T,n)$ in Eq. (14).

Corollary 1: When the TAC of the bycatch is binding, the value that the society assigns to the bycatch does not affect the optimal selectivity.

This results from the fact that once the bycatch constraint is binding (for any selectivity level), the manager cannot change his/her behavior in order to alter the profits obtained from these catches. From this point of view, the only way to increase profits is to improve the selectivity level (a lower α).

When the bycatch constraint is binding, the social planner has to improve the selectivity level to capture a greater quantity of the target species, which always gives a positive return. But this improvement could increase the cost of harvest and, if the latter effect is higher, the decision will be to not capture more target species through a change in selectivity. Therefore the optimal selectivity is decided in the same way as in the case of an aggregated TAC when δ = 0.

Binding TAC for the target species: When only the TAC for the target species is binding, $\lambda_1 > 0$ and $\lambda_2 = 0$. In this case the selectivity level is one that makes both constraints binding, when δ = 1 or δ = 0. This is so because it is always positive to obtain more of the bycatch species.

When δ = 0, a lower selectivity implies a lower cost of harvesting the target species; when δ = 1 we have the

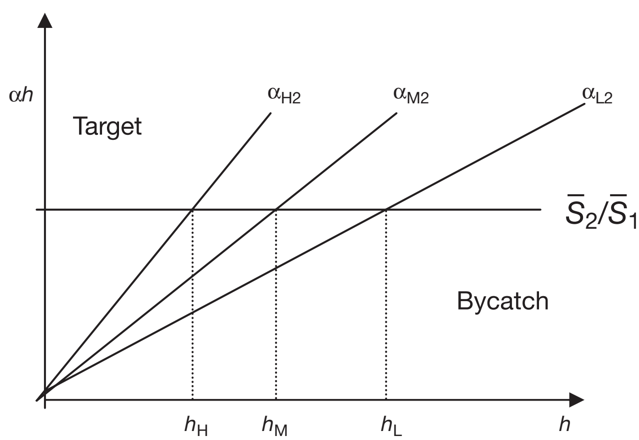

Fig. 2. Changes in constraints for different selectivity (α) levels (low, medium and high; L, M, H, respectively) and the relationship with the ratio of the bycatch to the target species quotas ($\bar{S}_2/\bar{S}_1$) when β = 2

[12] $$\frac{d(b/h)}{dh} = \frac{b_h(h-b)}{h^2} > 0$$

same effect plus the fact that the bycatch gives positive returns.

In terms of selectivity, we see that when $\beta = 1$, the optimal selectivity level is $\alpha^* = S_2/S_1 = \alpha_M$ (note that this only holds if $\alpha_{min} \in [\alpha_0,\alpha_\infty]$; Fig. 1), independent of the harvest level; when $\beta > 1$, however, the optimal selectivity level will depend on the optimal harvest rate ($h^{D^{**}}$), i.e. $\alpha^* = S_2/(S_1 h^{D^{**}}) = \alpha_{M2} h^{D^{**}}$ (note that this only holds if $\alpha_{M2} h^{D^{**}} \in [\alpha_0,\alpha_\infty]$; Fig. 2). On the other hand, if the bycatch has an existence value ($\delta = -1$), the condition determining optimal selectivity is:

$$\eta_1 - \eta_2 = [p_2 b_\alpha(h,\alpha) - \pi_\alpha(h,\alpha)]Tn \qquad (21)$$

Hence, it is necessary to compare the negative returns of harvesting a species with an existence value $[p_2 b_\alpha(h,\alpha)]$ with the possibility of decreasing the cost of harvesting the target species due to a lower selectivity level $[\pi_\alpha(h,\alpha)]$. If this existence value is greater than the cost saving due to the use of a lower selectivity, i.e. $p_2 b_\alpha(h,\alpha) > \pi_\alpha(h,\alpha)$, $\eta_1 - \eta_2$ becomes positive and the highest selectivity will be used, i.e. $\alpha^* = \alpha_0$. In the opposite case, $p_2 b_\alpha(h,\alpha) < \pi_\alpha(h,\alpha)$, the optimal selectivity should be $\alpha^* = \alpha_\infty$.

RESULTS

Fishing season length, harvest rate and number of vessels

In the previous sections we have analyzed the way in which the optimal selectivity is determined. We now consider the fact that selectivity choice is not independent and that it depends on some other variables that influence it. The social planner controls simultaneously the selectivity, the fishing season length, the harvest rate and the number of vessels entering the fishery.

Fishing season length

The optimal election of this variable can be summarized thus:

> Proposition 2: The optimal fishing season length will be $T^* = T_{max}$, for both TAC systems (see Appendix 3 for proof).

Proposition 2 is derived from the assumption regarding the cost of increasing the fishing season length. For convenience, we have assumed that this cost is zero because if we assume a fixed cost f of increasing the season length, we will have to compare it with the fixed cost per vessel k in such a way that if $k = f$, they will be perfect substitutes and if $k < f$ the optimal number of vessels will be N (the maximum number of vessels) and T^* will depend on this N. Hence, since this cost is zero, it follows that harvest can be increased at a zero cost by means of increasing season length. Consequently, $T^* = T_{max}$. It is important to note that this result is independent of the selectivity of the fishing gear.

Optimal harvest rate

The harvest rate determines not only the target species captured but also, through the selectivity level, the amount of the bycatch. When $\beta = 1$, from the first-order conditions, we obtain that for any TAC system the optimal harvest will be determined by:

$$\frac{k}{T_{max}} = \pi(h,\alpha) - \pi_h(h,\alpha)h \qquad (22)$$

where $\pi(h,\alpha) - \pi_h(h,\alpha)h$ are the profits d^{-1} net of scarcity rent of the target species. From Proposition 2 we know that k/T_{max} is constant, so the optimal harvest will increase with selectivity. When $\beta > 1$ the optimal harvest rate depends on the TAC system. If an aggregated TAC is implemented from the first-order conditions we determine the optimal harvest rate to be given by:

$$\frac{k}{T_{max}} = \pi(h,\alpha) - \pi_h(h,\alpha)\frac{S(h,\alpha,n)}{S_h(h,\alpha,n)} + \frac{\delta p_2 \Gamma(h,\alpha)}{S_h(h,\alpha,n)} \qquad (23)$$

where $\Gamma(h,\alpha) = b(h,\alpha) - b_h(h,\alpha)h$, and $\delta p_2 \Gamma(h,\alpha)$ is the change in the bycatch value as the amount of the target changes[13].

This condition implies that if $\delta = 0$ or $\delta = 1$, the relationship between the optimal harvest rate and the selectivity level is the same as that when $\beta = 1$. But when the bycatch has an existence value, it could occur that a lower selectivity implies a higher optimal harvest rate. The former can be explained by the fact that a higher amount of the target may increase the value of the bycatch.

When a disaggregated TAC is implemented, we have 2 conditions, depending on which constraint is binding:

$$\frac{k}{T_{max}} = \pi(h,\alpha) - \pi_h(h,\alpha)\frac{S_1(h,n)}{S_{1h}(h,n)} + \frac{\delta p_2 \Gamma(h,\alpha)}{S_{1h}(h,\alpha,n)} \qquad (24)$$

when the target constraint is binding[14], and

---

[13] Where $S_h(h,\alpha,n) = \dfrac{S_h(h,\alpha,n)}{Tn}$

[14] Where $S_{1h}(h,\alpha,n) = \dfrac{S_{1h}(h,\alpha,n)}{Tn}$

$$\frac{k}{T_{\max}} = \pi(h,\alpha) - \pi_h(h,\alpha)\frac{S_2(h,n,\alpha)}{S_{2h}(h,n,\alpha)} \quad (25)$$

when the bycatch constraint is binding, though Eqs. (23) to (25) collapse to Eq. (22) when $\delta = 1$. Eqs. (24) & (25) imply almost the same result as Eq. (23), but taking into account the binding constraint. Hence, the effect that a selectivity level change has on them is the same as in the case where a TAC is implemented on both species, but note that Eq. (25) does not depend on δ.

Optimal fleet size

When it is optimal to use the entire TAC, we can use Eqs. (5), (15) & (16) to obtain the optimal fleet size:

$$n^{*A} = \frac{S}{T_{\max}[h^{*A} + b(h^{*A},\alpha^*)]} \quad (26)$$

$$n^{*D} = \frac{S_2}{T_{\max}[b(h^{*D},\alpha^*)]} \quad (27)$$

$$n^{**D} = \frac{S_1}{T_{\max} h^{*D}} \quad (28)$$

where n^{*A}, n^{*D} and n^{**D} stand for optimal fleet size when an aggregated and disaggregated TAC are implemented. The differences between n^{*D} and n^{**D} depend on whether the target or the bycatch constraint is binding.

From Eqs. (26) to (28) we obtain that the optimal fleet size depends inversely upon the optimal selectivity level and the optimal harvest rate (although selectivity does not appear explicitly in Eq. (28), the harvest rate depends inversely on it).

Comparison of both systems

In the preceding sections 2 different ways of implementing a TAC system have been considered. The first is based upon an aggregated TAC on the target and the bycatch species, while the second implements a TAC for each species separately. In order to compare them it is necessary to take into consideration some features.

Since we have assumed that $\bar{S}_1 + \bar{S}_2 = S$, it is obvious that any optimal harvest rate that can be obtained with a disaggregated quota can also be achieved with an aggregated quota. Consequently, profits obtained by society are always higher than or equal to an aggregated quota as opposed to a disaggregated quota. To examine this, note that Eqs. (8) & (A1) (see Appendix 1) only differ on the quota constraints, but as $\bar{S}_1 + \bar{S}_2 = S$, any harvest obtained from Eq. (A1) could be reached through solving Eq. (8).

In an aggregated quota system, selectivity is just a tool to harvest more of the species with the highest marginal profit. If we compare the cases of aggregated vs. disaggregated TAC, when the price of the bycatch is low enough, the amount of target species harvested is beyond $\bar{S}_1$, with the quota corresponding to when a disaggregated TAC is implemented. On the other hand, if the price for the bycatch species is high enough, that species' capture will be beyond $\bar{S}_2$, the quota corresponding to when a disaggregated TAC is implemented. It could happen that the target harvest could equal $\bar{S}_1$ and the bycatch $\bar{S}_2$, but this would be just a matter of luck.

Normally these quota constraints are based on previous estimates of the state of the resource, therefore what we get in a disaggregated TAC system is a perfect harvest composition (i.e. the target harvest is equal to $\bar{S}_1$ and the bycatch to $\bar{S}_2$), but if we compare the disaggregated to the aggregated TAC system, we lose in social value, at least if $\bar{S}_1$ and $\bar{S}_2$ do not change with time.

The optimal selectivity level when an aggregated TAC is implemented is always a corner solution — α_0 or α_∞; depending on the marginal profits of the species and when a disaggregated program is implemented, the S_1:S_2 ratio determines which constraint is binding and implies an upper bound for the optimal selectivity level (α_M or α_{M2} in Figs. 1 & 2, depending on the value of β) that can be lower than α_∞. In an aggregated quota system the limits are given by α_0 and α_∞. This result implies that the total quota can be composed mainly of the most profitable species, thus leaving the less profitable ones almost unexploited.

DISCUSSION

The harvesting of non-targeted species is sometimes desirable as a way to commercially exploit the resource in question, but fishermen have incentives to discard the bycatch when it cannot be sold. The reason is that regardless of whether this harvest could be penalized (existence value) or not, it normally generates a cost (for instance, because the hold may be full), so the decision of fishermen is usually to discard it. The main problem of these discards is that when fish are pulled to the surface too quickly and in a high level of biomass, the harvest is unable to survive the pressure. Consequently, if it is returned to the sea, the fish will normally be dead (Parfit 1995). These discards are a worldwide problem (FAO 1997, ICES 1998); marine mammals, birds and some fish are species under this kind of pressure.

Discarding is the tool to avoid imperfect control of harvest composition. If we assume a profit-maximizing fisherman, discarding allows the possibility of obtaining the highest harvest rate of the high-value species.

In the fishing literature this effect is known as high grading.

We can also have the opposite case, i.e. discarding of the higher-value species. This can happen if we take into account that it is beneficial to decrease the selectivity level. If discarding is not costly it can be optimal to decrease the selectivity level and discard both the low-value bycatch as well as the high-value bycatch (low grading). Since low grading is less likely to occur, we analyze only high grading. Therefore the question can be posed as follows: When does the low-value bycatch have a chance of being landed?

It is obvious that an aggregated TAC implies high grading, since what fishermen want is to fulfill the quota with the higher-value individuals. In the case of a disaggregated TAC being implemented, a low-value bycatch has a chance of being landed only when the target constraint is binding. If the bycatch can be sold in the market in this case, fishermen will discard it, since once the target TAC is fulfilled, discarding will only reduce the benefits. But when the bycatch has an existence or a null value it will be fully discarded (when the bycatch has a null value we can include a hold constraint to make discarding optimal).

Where a shipboard monitoring program does not exist (and this is what normally occurs, as these programs are expensive), quota systems rather than the amount harvested will regulate the amount of fish landed. This implies that internalizing the value of the low-value species becomes impossible. But as pointed out by Anderson (1994), in a fishery with a homogeneous[15] fleet, if the fishing gear selectivity is known by the regulatory agency, discarding can be avoided just by requiring that for any landed unit of the target species the appropriate amount of bycatch must be landed as well; in case of non-compliance, the quota balance should be accordingly reduced. The selectivity level should be determined outside commercial observation, for example by scientific experiments, in order to avoid giving fishermen incentives to lie to regulators about gear selectivity levels.

If the selectivity is fixed (and $\beta = 1$), there are no differences between an aggregated and a disaggregated TAC when a landing monitoring program is implemented. But we have shown how this selectivity choice is different depending on the TAC system. Hence, this program to reduce discarding will only be optimal if it takes into account the fact that the selectivity level should be optimally defined, i.e. it should take into account that different TAC systems imply different optimal selectivity levels.

[15]Anderson (1994) also examined the case of heterogeneous vessels facing a hold constraint

CONCLUSIONS

We have analyzed a mixed fishery regulated through inputs and outputs, taking into account that even in single-target fisheries total output is composed of many species and thus it is important to regulate the pressure level on stock. Optimal management of these kinds of fisheries is also affected by the different types of bycatch harvested. There are certain species that can be sold in the market but there are some others that cannot. Even if it is necessary to internalize the cost of species with existence value, the possibility of discarding, together with the cost of onboard monitoring programs, makes this difficult.

Discarding may occur in both aggregated and disaggregated TAC systems. In order to reduce discards, programs that imply controlling the amount landed are effective. But since these programs are based on the selectivity level of the fishing gear, the manager should control it optimally.

The main finding of this paper is that the optimal control will be influenced by the TAC system in use. Thus we have shown that when an aggregated TAC is applied, the optimal selectivity level will always be a corner solution. With a disaggregated TAC the optimal selectivity level is not necessarily a corner solution.

The stylized model used in this article does not take into account many important aspects, such as the hold constraint, or the heterogeneity of the fleet. It represents a valid approach however, as it allows an analysis of the manner in which the selectivity level should be calculated and consequently the way in which the programs for achieving it should be implemented.

LITERATURE CITED

Anderson LG (1994) An economic analysis of high grading in ITQ fisheries regulation programs. Mar Resour Econ 9: 209–226

Boyce JR (1996) An economic analysis of the fisheries bycatch problem. J Environ Econ Manag 31:314–336

Clark CW (1990) Mathematical bioeconomics. The optimal management of renewable resources, 2nd edn. John Wiley & Sons, New York

Copes P (1986) A critical review of the individually transferable as a device in fisheries management. Land Econ 62:278–291

FAO (1997) Examen de la pesca y la acuicultura en el mundo. FAO, Rome. www.fao.org/docrep/003/w3265s/w3265s02.htm

Grafton RQ (1996) Individual transferable quotas: theory and practice. Rev Fish Biol Fish 6:5–20

ICES (1998) Report of the working group on fishing technology and fish behaviour. ICES, Copenhagen

Lleonart J, Silvani L, Fernandez-Cuevas I, Gual A (1996) La crisis pesquera Española: un enfoque ecológico, la situación del mundo. Lester R. Brown, Barcelona, p 401–433

Marillas A, Prellezo R, Garmendia E, Escapa M, Gallastegui

C, Ansuategi A (2008) Multidimensional and intertemporal sustainability assessment: a case study of the Basque trawl fisheries. Fish Res 91:222–238
McKelvey R (1983) The fishery in a fluctuating environment: coexistence of specialist and generalist fishing vessels in a multipurpose fleet. J Environ Econ Manag 10:287–309
Munro GR, Scott AD (1985) The economics of fisheries management. In: Kneese AV, Sweeney JL (eds) Handbook of natural resource and energy economics, Vol 2. Elsevier Science, Amsterdam, p 623–676
Parfit M (1995) Diminishing returns: exploiting the ocean's bounty. Nat Geogr Nov 1995:2–37
Turner MA (1996) Value-based ITQ's. Mar Resour Econ 11: 59–69
Turner MA (1997) Quota-induced discarding in heterogeneous fisheries. J Environ Econ Manag 33:186–195
Walters C, Pearse PH (1996) Stock information requirement for quota management systems in commercial fisheries. Rev Fish Biol Fish 6:21–42
Ward JM (1994) The bioeconomic implications of a bycatch reduction device as a stock conservation management measure. Mar Resour Econ 9:227–240

Appendix 1. Proof of Proposition 1

From Eqs. (9) to (12) we obtain $\lambda > 0$ when $\delta = 1$ or 0, but when $\delta = -1$ it could happen that $\lambda \geq 0$ and so the total allowable catch (TAC) is not necessarily binding.

Appendix 2. The social planner problem for a disaggregated TAC

Given the value obtained by society from the fishery (Eq. 7), the previously explained constraints, Eqs. (6), (15) & (16), and the non-negativity of the variables h, n and T, the Lagrangian of this problem is:

$$L = V + \lambda_1[S_1 - Tnh] + \lambda_2[S_2 - Tnb(h,\alpha)] + \tau(T_{\max} - T) + \eta_1(\alpha - \alpha_0) + \eta_2(\alpha_\infty - \alpha) + \phi h + \theta n + \psi T \quad \text{(A1)}$$

where λ_1 and λ_2 are the Lagrange multipliers corresponding to Eqs. (15) & (16). The social planner chooses the same variables as in the case of an aggregated TAC, so the first order conditions are:

$$\frac{\partial L}{\partial h} = [\pi_h(h,\alpha) + \delta p_2 b_h(h,\alpha) - \lambda_1 - \lambda_2 b_h(h,\alpha)]Tn + \phi = 0, \quad h \geq 0,\ \phi \geq 0,\ h\phi = 0 \quad \text{(A2)}$$

$$\frac{\partial L}{\partial n} = [\pi(h,\alpha) + \delta p_2 b(h,\alpha) - \lambda_1 h - \lambda_2 b(h,\alpha)]T - k + \theta = 0, \quad n \geq 0,\ \theta \geq 0,\ n\theta = 0 \quad \text{(A3)}$$

$$\frac{\partial L}{\partial T} = [\pi(h,\alpha) + \delta p_2 b(h,\alpha) - \lambda_1 h - \lambda_2 b(h,\alpha)]n - \tau + \psi = 0, \quad T \geq 0,\ \psi \geq 0,\ T\psi = 0 \quad \text{(A4)}$$

$$\frac{\partial L}{\partial \alpha} = [\pi_\alpha(h,\alpha) + b_\alpha(h,\alpha)(\delta p_2 - \lambda_2)]Tn + \eta_1 - \eta_2 = 0 \quad \text{(A5)}$$

$$\eta_1 \geq 0,\ \alpha \geq \alpha_0,\ \eta_1(\alpha - \alpha_0) = 0,\ \eta_2 \geq 0,\ \alpha_\infty \geq \alpha,\ \eta_2(\alpha_\infty - \alpha) = 0 \quad \text{(A6)}$$

Appendix 3. Proof of Proposition 2

Eqs. (10) & (11) will only be compatible for $\tau > 0$ since they imply that $k/T = \tau/n$ for k, T and $n > 0$. Thus, if $\tau > 0$, $T^* = T_{\max.}$ Similar reasoning can be followed using Eqs. (A3) & (A4), which leads to $T^* = T_{\max}$ for both TAC systems.

Editorial responsibility: Clement Tisdell, Brisbane, Australia

Submitted: October 15, 2007; Accepted: September 9, 2008
Proofs received from author(s): November 5, 2008