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Optimal Fisheries Management using Transferable Shares of a Convex Tax

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Abstract

In this paper, we propose a fishery control scheme which happens to be first best efficient in the context of a Gordon-Schaefer model where asymmetric information about effort/harvesting costs is present. It is widely acknowledged that in the absence of regulations, competition between vessels leads to a competitive game wherein the outcome is inefficient. We introduce a management scheme that regulates the fishing industry through a convex tax on effort. The shares of this tax can be traded in a market, thus solving problems related to asymmetric information. This can be achieved since heterogeneous fishing firms are individually stimulated to solve the same optimality problem as a social planner would. We apply this model to the Northwest Mediterranean demersal fishery as a case study.

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1 INTRODUCTION

In recent decades, incentive adjusting approaches such as individual catch quotas have become the preferred way of managing fisheries rather than incentive blocking approaches, including effort controls. This is because such instruments may achieve outcomes that are socially efficient. A large number of fisheries are today managed by tradeable quotas (Chu, 2009; Bjørndal & Munro, 2012). With a given vessel quota, harvesters will have incentives to minimise the cost of harvesting. On the other hand, catch quotas might increase the incidence of discarding and misreporting of catches (Kristofersson & Rickertsen, 2009; Catchpole *et al.*, 2005) and they might have negative social effects (Merayo *et al.*, 2018).

Weitzman (2002) proves that landing fees might be superior to quantity controls when the social planner must make decisions in face of inaccurate stock estimates. When, in addition, also economic uncertainty is present, a convex tax on catches might prove to outperform uniform fees (Berglann, 2023). However, Berglann (2023) assumes homogeneous vessels because otherwise the outcome in his model might be inefficient due to different marginal tax rates across firms. The contribution of this paper is to generalise Berglann's work by allowing for heterogenous vessels and, moreover, to show that convex taxation for regulation purposes can turn out to give the first best optimal outcome under asymmetric information about effort costs. Using non-linear instruments for regulation purposes have turned out to be central in studies of static models (Kaplow & Shavell, 2002; Berglann, 2012) and one reason for further investigation here.

Many fisheries worldwide are still managed by input controls. Instruments often include control of the number of vessels (limited entry), days per vessel, technical characteristics and more. There are several reasons for imposing this type of control. One is because individual catch quotas may not function well in multispecies fisheries, e.g. in the tropics, where a very large number of species may be harvested at the same time and where there may be great uncertainty about stock estimates (Squires *et al.*, 2017)[1]. Another reason may be the difficulty of monitoring harvests while one or more aspects of input may be controlled much more easily. Examples include industrial fisheries such as those of the Falkland Islands (Mainardi, 2001) and the Faroe Islands (Jakupsstovu *et al.*, 2007) but also many small-scale fisheries. In the case study we will consider, we will focus on multi-species demersal fisheries in the Mediterranean, which serve as an example of the latter.

[1] There are, however, also multispecies fisheries where individual quotas have been found to function very well. One example is given by the British Columbia groundfish fishery (Bjørndal & Munro, 2012).

First, like Hannesson (2020), we demonstrate consequences of competition in an open fishery. With two or more participants the outcome is inefficient. We find a clearly defined explicit closed-form solutions in the heterogeneous firms' case. As said, we suggest coping with these inefficiencies with a management tool based on convex taxation. An important feature with our proposal is that the resulting payment function will be formed such that the fishers' profits become independent of profits of other participants in the fishery, and, hence, thereby eliminate rivalry between them. The share parameter we specify here can be interpreted as a flexible individual effort quota, which moreover, turns out to be suitable for trading between firms.

Assuming a fixed price in a static setting, a sole owner firm with all fishing rights would opt for the Maximum Economic Yield (MEY) result. This outcome aligns with the preference of the social planner. Our analysis utilise a static Gordon-Shaefer model and assume that asymmetric information about fishing costs is present. Then, when implementing our flexible variant of effort-based quotas, every vessel selects an efficient level of effort. The payment function, in this case, depends on an effort share parameter assigned to vessel i and the effort level it chooses. By allowing for this share parameter to be transferable the problem of asymmetric information is resolved. The effort regulation mechanism might then be interpreted as an individual tax being levied on each vessel that only depends on an individual effort share parameter and of its own aggregated effort during the regulation period. We also derive the scheme in a setting with quantity regulation.

This article is organised as follows: The bioeconomic model and its outcome for the fishery without regulation is developed in section 2. Section 3 introduces the regulation scheme based on combining linear rewards with a total non-uniform tax that can be shared between firms in a way that prevents them from making strategic moves. Section 4 presents empirical results for our case study by applying the model to the demersal fisheries of the Western Mediterranean. The results, and their potential implications, are discussed in the final section.

2 THE MODEL OF COMPETITION IN FISHERIES

In this section, we will develop a bioeconomic model. The starting point is a price-taking sole-owner, as the outcome will be seen to correspond to that of the social planner. This will then be contrasted with fisheries with homogeneous and heterogeneous vessel owners.

Full competition, on the other hand, will result in an outcome that corresponds to open access (Bjørndal & Munro, 2012). Between these extremes we can find an outcome based on an assumption akin to the one used in traditional Cournot model. Here, in a simple one-product economic model each oligopoly firm maximises its profit given that it knows the quantity produced by other firms. In this situation more firms will increase social welfare simply because firms in total will choose to produce more of the good.

In the fishery case the same Cournot-Nash model applies. However, the outcome is the opposite of what is the case for "traditional" industries. Firms in the fishing industry do not choose production but an effort measure such as the number of fishing days at sea (Mainardi, 2001). And, as is well known, without regulation more firms and increased competition implies higher total fishing effort and therefore the fish stock is reduced because of overfishing (Hannesson, 2020). As opposed to the traditional Cournot model, a sole owner here gives the best - while full competition gives the worst - outcome.

Sole owner

In the analysis, we will solve the bioeconomic model for steady state. We will disregard discounting as this will simplify the analysis without having an impact on the results we want to derive. We base the analysis on the static Gordon-Schaefer bioeconomic model (Bjørndal & Munro, 2012, Hannesson & Kennedy, 2005) with $n \geq 1$ independent vessels with equal cost functions. Moreover, steady state means that there is no change in stock size x, i.e.,

$$\frac{\partial x}{\partial t} = F(x) - h(e,x) = 0 \tag{1}$$

where $F(x)$ is the growth function, and $h(e,x)$ is catches given as a function of stock size x and of total effort e. Solving this equation with regard to x, and eliminating the $x = 0$ solution, gives the stock function $x(e)$, where $x'(e) < 0$ as stock declines in effort. With the Schaefer harvest function (Schaefer, 1957), we have

$$h\big(e, x(e)\big) = h(e) = e\,x(e) \tag{2}$$

where we operate with a normalised total effort variable e where catchability of the fishing industry is embedded. Then, further assuming constant price p optimal, total profit π is

$$\pi = \max_e [p\,e\,x(e) - C(e)\,] \tag{3}$$

where total normalised effort costs

$$C(e) = (c/2)e^2 \tag{4}$$

is expressed as a (quadratic) function[2]. This formulation describes the profit in a sole-owner fishery where all fishing rights are held by one firm. The concavity of the function ensures an inner solution to (3). The optimal solution is the well known maximum economic yield (MEY) level. As the social planner optimises the same objective function, the outcome of (3) is efficient.

To find an analytical expression, we use the logistic natural growth equation,

$$F(x) = r\,x\,(1 - x/K) \tag{5}$$

where r is the intrinsic growth rate and K the carrying capacity of the environment. Assuming steady state (1), for $x(e) > 0$, the stock-effort relationship becomes

$$x(e) = K - \frac{K}{r}e \tag{6}$$

The first order condition for solving (3), when (5) is inserted, becomes

$$p\,x(e)\; + \;p\,x'(e)\,e - c\,e \;= p\,K - \frac{2\,p\,K}{r}e - c\,e = 0\,. \tag{7}$$

Substitution of $b = \frac{p\,K}{r}$ and a modified cost parameter $\bar{c} = c\,/b$ gives

$$e_{so} = \frac{r}{2\, +\, \bar{c}} \tag{8}$$

where e_{so} denotes the normalised effort of the price-taking sole-owner.

Homogenous vessel owners

Continuing with the homogeneous case, now with $n \geq 2$ equal firms having the same effort cost function (4) but with a cost parameter that is *n* times higher, $c_n = n\,c$. Each firm i in the fishing industry chooses their total (normalised) effort e_i simultaneously and independently in a one-stage game by maximising its profit given that the firm has knowledge about the sum of effort chosen by other firms. Firm i's profit is maximized as follows

$$\max_{e_i}\left\{\pi_i = p\,e_i\,x\left(e_i + e_j(n-1)\right) - \frac{\mathrm{n}\,c}{2}e_i^2\right\} \tag{9}$$

where e_j is sum of one of the other firm's catch-effort multiplied by the number of other firms, $(n-1)$, and the cost functions for each firm are given by (4). The first order conditions are

$$\frac{\partial \pi_i}{\partial e_i} = x\left(e_i + e_j(n-1)\right) + e_i\,x'\left(e_i + e_j(n-1)\right) - n\,c\,e_i = 0 \tag{10}$$

[2] A quadratic cost function, appropriately scaled, may be viewed to represent vessel capacity constraints and is a perturbation on the more typically employed linear costs. It is here necessary to avoid difficulties in finding closed solutions. For simplicity the linear cost component of the function is ignored. Quadratic cost functions in the fisheries literature are relatively common and have been employed by a number of authors (e.g. Helgesen, 2022; Ibrahim, 2021; Hanson & Ryan, 1998, Koenig, 1984).

for each firm $i = 1, .., n$. Solving (10) with respect to e_i gives firm i's reaction function. Following up by switching index j with i in (10) and solving with respect to e_i gives, with the substitution $b = \frac{K\,p}{r}$ and the modified cost parameter $\bar{c} = c\ /b$

$$e_i = \frac{r}{1 + n(1 + \bar{c})} \tag{11}$$

Total normalised effort is given by $e = n\, e_i$, which when n → ∞ gives the result

$$e = n\, e_i = r/(1 + \bar{c}) \tag{12}$$

which corresponds to the open access solution.

Heterogenous case

Next, we consider the heterogenous case with $n \geq 2$ firms in the fishing fleet having different effort costs functions $c_i(e_i) = \frac{c_i}{2} e_i^2$. All firms $(i = 1, 2, \dots, n)$ choose their total effort e_i simultaneously and independently in a one-stage game by maximising their profit given that each firm i has perfect knowledge about the sum of (normalised) effort chosen by other firms, $\sum_{j \neq i} e_j$ The optimisation problem for firm i is

$$\max_{e_i} \left\{ \pi_i = p\, e_i\, x \left(e_i + \sum_{j \neq i} e_j \right) - \frac{c_i}{2} e_i^2 \right\} \tag{13}$$

First order conditions are

$$\frac{\partial \pi_i}{\partial e_i} = K\, p - e_i \left(c_i + \frac{2\, K\, p}{r} \right) - \left(\frac{K\, p}{r} \right) \sum_{j \neq i} e_j - c_i\, e_i = 0 \tag{14}$$

for firms $i = 1, 2, \dots, n$.

Simplifying using $b = \frac{K\,p}{r}$, the first order conditions (14) become

$$\frac{\partial \pi_i}{\partial e_i} = r\, b - c_i\, e_i - b \left(2\, e_i + \sum_{j \neq i} e_j \right) = 0 \tag{15}$$

for all firms $i = 1, 2, \dots, n$. We further simplify by dividing the left-hand side of (15) by b and by introducing modified cost parameters $\bar{c_i} = c_i\ /b$. Denoting $\beta = (e_1, e_2, \dots, e_n)^T$, and $\alpha = (r, r, \dots, r)^T$, the full set of first order conditions can be rewritten in matrix form $M\, \beta = \alpha$

$$\begin{pmatrix} \bar{c}_1 + 2 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & \bar{c}_n + 2 \end{pmatrix} \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix} = \begin{bmatrix} r \\ \vdots \\ r \end{bmatrix} \tag{16}$$

If the inverse matrix M^{-1} exists, the solution to equation (16) is

$$\beta = M^{-1} \alpha \tag{17}$$

The fishery model (13) replicates the mathematical form used in a model to investigate a Cournot competing manufacturing industry. That implies

Proposition 1.

The equilibrium outputs are given by

$$e_i = r\left(1 - \frac{(1+\bar{c}_i)\left(1+\sum_{j\neq i}\frac{1}{1+\bar{c}_j}\right)}{(2+\bar{c}_i)+(1+\bar{c}_i)\left(1+\sum_{j\neq i}\frac{1}{1+\bar{c}_j}\right)}\right) \tag{18}$$

and profits

$$\pi_i = (1+\bar{c}_i)\,r^2\left(1 - \frac{(1+\bar{c}_i)\left(1+\sum_{j\neq i}\frac{1}{1+\bar{c}_j}\right)}{(2+\bar{c}_i)+(1+\bar{c}_i)\left(1+\sum_{j\neq i}\frac{1}{1+\bar{c}_j}\right)}\right)^2 \tag{19}$$

for all firms ($i = 1, 2, \ldots, n$).

Proof. See Nie *et al.* (2021).[3]

3 THE MODEL OF REGULATED FISHERIES

Eliminating competition in fisheries

Regulation schemes that eliminate competition between firms/vessels in fisheries might require a payment function where fishers' profits are independent of other participants in the fishery. This opens up for the possibility that heterogenous fishing firms can be individually induced to solve the same problem as a price-taking sole owner or a social planner. Each firm can for instance be regulated via a mechanism suggested by Berglann (2023, 2012). Berglann (2012)[4] considers regulation in a static model with negative externalities caused by pollution. We do the same by treating a dynamic fishery model in a steady state.

First, before fishing starts, the planner applies available historical data to estimate values of the parameters K and r in the stock-effort relationship function (6), $x(e) = K - \frac{K}{r}e$. Moreover, for the moment we can also assume that the planner is able to estimate an optimal distribution of share effort quotas parameter denoted s_i. More specifically, this effort shareholding is defined as $s_i = \hat{e}_i/\hat{e}$ where $\hat{e}_i$ is the individual effort quota and $\hat{e}$ is the Total

[3] Nie *et al.* (2021) investigate Cournot competition in a model with *n* firms, each producing the amount e_i, where the production cost function of firm *i* is quadratic $C_i(e_i) = \frac{c_i}{2}e_i^2$ while the inverse demand function is assumed to be $p = a - \sum_{i=1}^{n} e_i$. Profit is given by $\pi_i = p\, e_i - \frac{c_i}{2}e_i^2$. This model has the exact mathematical form as the fishery model (13) we are presenting.

[4] Originally proposed by Loeb and Magat (1979) in the context of regulating the output of a monopoly.

Allowable Effort quota. Moreover $e = e_i/s_i = \sum e_i$ and $\sum s_i = 1$. For instance, if the planner knows there are n equal fishing firms, then the planner set $s_i = 1/n$.

Secondly, these estimations are exposed and published, thereby becoming common knowledge. The purpose of this publication is that these parameter values will be used in the regulation scheme during the forthcoming regulation period. Each firm i in the industry is informed that its revenue for landed fish will not be paid out through regular sale channels. Instead they will be compensated by the regulation authorities by the following reward

$$R_i = p\, e_i\, x(e) \tag{20}$$

where

$$x(e) = x\left(\frac{e_i}{s_i}\right) = K - \frac{K}{r}\frac{e_i}{s_i}. \tag{21}$$

Here e_i is the effective effort chosen by firm i which, for all having optimal s_i's, will reflect total effort as $e = e_i/s_i$. To avoid adaptiation behaviour the planner promises that the K, r and s_i parameters, in (20, 21), will not be updated within the regulation period.

To further illustrate we divide the reward scheme (20, 21) into two parts, a linear part, and a tax part. The linear part

$$l_i = L(e_i) = p\, e_i\, K \tag{22}$$

is derived from the first part of the stock-effort relationship (21). The tax part (of (21)) stems from firm i's share of the total compensation levied on the industry $\theta(e)$ due to the fishing mortality it causes. This tax, of which the optimal form happens to be quadratic in our case with a logistic model, is equal to

$$t_i = T(e_i, s_i) = s_i\, \theta(e_i/s_i) = p\, e_i\ K/r\, (e_i/s_i) = s_i\, p\, K/r\, (e_i/s_i)^2 \tag{23}$$

where the parameter s_i as mentioned above is interpreted as firm i's holding of share effort permits or its allocated share of the total effort e the industry is expected to choose. Note that the above interpretation of s_i might be a little misleading. It is only a parameter in the individual tax function (23) rather than a unit of permissible effort. It turns out to map into the firm's share of total effort for the firm only if all firms behave optimally. However, in no way does the s_i parameter restrict firm owners from choosing more or less effort than the given share of the total.

If the social planner were in possession of adequate information on every firm i's cost function $C_i(\, e_i) = c_i/2\, e_i^2$ he/she would be able to perfectly foresee the relation between the ex post optimal effort of vessels, and he/she would be able to portion out optimal s_i holdings. As assumed here, however, the planner does not know any of the c_i cost function parameters.

Therefore he/she cannot directly expedite an efficient share distribution. However, the planner can circumvent the information problem. Recall that the tax rate (23) levied upon firm i, $\theta'(e_i/s_i) \ = 2\ p\frac{K}{r}(e_i/s_i) > 0$ which implies that the rate of the tax (23) increases with its argument e_i/s_i. So, for the firm, a higher s_i for constant e_i means that it faces a lower marginal tax and that its total tax bill decreases. Consequently, shares are in demand, and we can presume that the announcement of K and r of the modelled stock function (21) is followed up by an initial allocation of the fixed supply $\sum s_i = 1$ of effort share certificates. This allocation can be effectuated through an auction, or the shares may be given away for free (grandfathering). Subsequently, exchanges may take place in an effort share market. Firm i's holding of s_i is verifiable from a central register at the moment the planner calculates the tax (23) on the realised choices of i's effort e_i.

In this two-stage sequential mechanism, in the second stage firm i chooses effort e_i according to

$$V(s_i) = \max_{e_i} \{\pi_i(e_i, s_i) = L_i(e_i) - T_i(e_i, s_i) - C_i(\ e_i)\} \tag{24}$$

where $V(s_i)$ is the value of share holding s_i. The necessary optimality condition to (24) using (22) and (23) is

$$L_i'(e_i) - C_i'(e_i) = \ \theta_i'(e_i/s_i) \tag{25}$$

which defines $e_i = e_i(\ s_i)$. Since the objective in problem (24) is strictly concave, condition (25) is also sufficient, and the optimum is unique. In our case (25) solves to

$$e_i(\ s_i) = \frac{p\ K\ r\ s_i}{2\ p\ K + c_i\ r\ s_i} \tag{26}$$

while (26) inserted into the value function (24) gives

$$V(s_i) = \frac{(p\ K\ )^2\ r\ s_i}{4\ p\ K\ \ + 2\ c_i\ r\ s_i} \tag{27}$$

Assume there is a sufficient number of fishing firms, each small enough that it is a reasonable approximation to treat them as price-taking agents in the market for shares s_i. In the first stage firm i trades effort shares, solving the decision problem

$$\max_{s_i} \{\ V(s_i) - \mu\ s_i\} \tag{28}$$

where μ is the market-clearing price per unit of s_i. The necessary optimality condition for interior solutions of (28) is $\mu = V'(s_i)$, which, by the Envelope Theorem applied to (24), is equal to

$$\mu = V'(s_i) = \frac{e_i}{s_i}\theta'\left(\frac{e_i}{s_i}\right) - \theta\left(\frac{e_i}{s_i}\right) = \frac{(p\ K\ )^3\ r}{(2\ p\ K + c_i\ r\ s_i)^2} \tag{29}$$

which is positive since all parameters are positive. Since $V''(s_i) < 0$ [5] it follows that the objective in problem (28) is strictly concave. Hence, condition (29) is both necessary and sufficient, and the optimum unique.

Proposition 2. *Suppose the constraint* $\sum s_i \coloneqq 1$ *is perfectly enforced. Then, for all* i, s_i *will be distributed among firms such that consistency is obtained. That is,*

$$e = \frac{e_i}{s_i} \; for \; all \; i. \tag{30}$$

Proof. (Berglann 2012). Let $f_i = e_i/s_i$ (effort per share). Then (29) is expressed as $\mu = f_i \, \theta'(f_i) - \theta(f_i)$ and

$$\frac{d\mu}{df_i} = f_i \theta''(f_i) = \frac{2\, p\, K}{r}$$

Note that from $\partial\mu/\partial f_i > 0$ it follows that the share price is monotonically increasing with f_i. Because μ is constant across firms, firms equate $f_i = f$. If shares sum to unity this implies $f = z$. The desired assertion follows. **QED.**

Equation (29) is the inverse demand function for effort shares for firm i. The demand depends on its chosen level of effort and consistency (30) implies that in equilibrium no firm buys more shares than it needs. Thus, replacing the original fishery income with reward $L_i(e_i) = p\, e_i\, K$ (the first part of (21)) and levying the tax $T_i(e_i, s_i) = s_i \theta(e_i/s_i)$ to compensate for the firm i's share of the total exploitation (23) of the fishery resource implies

Proposition 3. *Together with the proposed reward (22) and tax scheme (23), the enforcement of* $\sum s_i \coloneqq 1$ *eliminates competition in the fishery and encourages each firm to choose their socially efficient effort level that combined also corresponds to Maximum Economic Yield (MEY).*

Usually either effort or catch quotas are used as instruments to limit overfishing. To let what we call the effort (flexible) share quota s_i be an instrument for fisheries management has to our knowledge not before been explicitly proposed in the literature. The catch-effort choice variable e_i can be looked upon as a decision variable that are immune to "effort creep" (Squires *et al.*, 2017).

More specifically, in itself e_i may contain elements that can change over time. For instance, investments in new and improved gear- or search technology usually increase a vessel's ability to catch more fish per day. However, to choose the same level of effective effort

[5] $V''(s_i) = -\theta''\left(\frac{e_i}{s_i}\right)\frac{e_i^2}{s_i^3} = -\frac{2\, c_i\, (p\, K\,)^3\, r^2}{(2\, p\, K + c_i\, r\, s_i)^3}$

e_i for a vessel will then only mean that the vessel must reduce its number of fishing days correspondingly.

The connection with quantity regulation

By changing our proposal through a slight modification of the reward (22) and the tax functions (23) we show that our suggested approach might also be applied for implementing catch quotas. While effort regulation requires the determination of the *K* and *r* parameters of the model, harvest regulation in addition also requires one more parameter. It needs an estimation of the equilibrium stock size denoted $\bar{x}$. The outcome is then akin to an Individual Tradable Quota (ITQ) system where individual harvests for a species might be expected to add up to its Total Allowable Catch (TAC). Since the cost of fishing are better known by fishers than by the planner (asymmetric information), in our case the harvest outcomes might be regarded as ex-post optimal.

Let $\bar{x}$ denote a constant equal to the equilibrium stock size after harvesting as it is estimated, together with *K* and *r,* by the planner and published to become common knowledge. When multiplying e_i in (22, 23) with that constant we aim at a construction where the harvest chosen by firm *i* is equal to $h_i(s_i) = e_i(s_i)\,\bar{x}$. Profits will then be expressed by

$$\bar{\pi}_i(h_i) = \bar{L}_i(h_i) - \bar{C}_i(h_i) - \bar{t}_i = p\,h_i\,K - \tilde{c}_i/2\,h_i^2 - s_i\,p\,K/(r\,\bar{x})\,(h_i/s_i)^2. \qquad (31)$$

where $\tilde{c}_i = c_i/\bar{x}$ is a parameter in the square cost function of harvest. The value of shares becomes (from 27) $\bar{V}(s_i) = V(s_i)\,\bar{x}$ while the share quota price becomes (from 29) $\bar{\mu} = \mu\,\bar{x}$. It follows straightaway[6] from Proposition 3:

Corollary 4. *The proposed reward and tax scheme (31) on firm i's catches, the estimation of the constant* $\bar{x}$ *equal to the expected stock size, together with the enforcement of* $\sum s_i := 1$, *eliminates competition in the fishery and encourages each firm to choose their socially efficient harvest level that combined also corresponds to Maximum Economic Yield (MEY).*

4. THE MEDITERRANEAN DEMERSAL FISHERIES

Mediterranean fisheries are a case in point when it comes to effort or input management. These fisheries are managed by controlling input through effort limitations and technical restrictions, contrary to other EU fisheries that are regulated by catch quotas (output controls) (Lleonart & Maynou, 2003). This fisheries management model was enshrined in the EU Common Fisheries

[6] We here ignore issues related to that the dynamics of the stock might influence firm choices of harvest quantities.

Policy (CFP) as the "Mediterranean specificity" (EU 2006) and has contributed to determine the non-adaptive character of fisheries management in the region (Penas Lado, 2016), that is, fishing effort is not annually revised to meet some specified optimality criterion. The lack of annual revision of fishing effort to match existing fishing opportunities has led to excessive harvest, overcapacity and economic inefficiencies (Vielmini *et al.*, 2017; Gómez & Maynou, 2020). To redress these problems, the EU has established subregional Multi-Annual Plans (MAP) to align fishing effort with fishing mortality at maximum sustainable yield (MSY) for the main fish stocks within a specified time frame, as envisaged in the 2013 reform of the CFP (EU, 2013). For instance, in the Western Mediterranean, the MAP for demersal resources aims at reducing effort with 40% by the end of 2024 compared to actual days for 2016-18 by setting the number of fishing days per fleet segment (COM/2018/0115 final – 2018/050 (COD)).

Thus, the problem of effort shares is very pertinent, particularly in the Mediterranean multi-annual plan (MAP) where the total effort available (days/year) is now being allocated to individual vessels, according to some historical values as "effort shares", s_i. In retrospect the total effort may have been set too high.[7]

The objective of the Western Mediterranean Multi-Annual Management Plan (WM MAP) is to achieve (Fmsy) by 1st January 2025 for the main five target species European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), Norway lobster (*Nephrops norvegicus*), deep-water rose shrimp (*Parapenaeus longirostris*) and red shrimp (*Aristeus antennatus*).

Our case study models demersal fisheries in the NW Mediterranean, focusing on geographical subarea GSA06 (the Mediterranean coast of Spain[8]). Demersal fisheries are exploited mainly by otter bottom trawl (about 80% of demersal landings), with fishing vessels of 14 - 28 m length overall based in 40 fishing harbours and a fleet size of 578 vessels in 2019. Fishing vessels exhibit minimal or no selectivity in their harvesting practices.

The five main stocks that define the policy objective make up 48% of the landings of the demersal fishery, the remainder comes from dozens of other secondary species (see Akbari *et al*., 2021). For this reason and for model simplicity, we are treating the stock as an aggregate here.

The model was parameterised from data for the bottom trawl demersal fishery in GSA 06, available for the period 2008-2016 in STECF (2020) and complemented with data for 2017-2019 obtained by interviews of vessel skippers (Gómez & Maynou, 2020). The parameters of the biological submodel were estimated with ASPIC 7 (Prager *et al.*, 1996) and are given in

[7] Note that we in this section operates with "real effort", i.e., we operate with a catchability coefficient q_i $such\ t$
[8] For fishing areas, see http://www.fao.org/gfcm/data/maps/gsas/en/.

table 1. The combined carrying capacity of the stocks harvested by this fleet is 19,900 tonnes with the instrinsic growth rate estimated at 2.5. This implies that the stock level giving rise to maximum sustainable yield $x_{MSY} = K/2 =$ is 9,950 tonnes with MSY equal to $h_{MSY} = rK/4 =$ 12,473.5 tonnes.

In 2019, the fishing fleet consisted of 578 vessels, each operating between 120 and 190 days, on average 155 days (table 1). Thus, total effort measured in days was 89,590 [9]. Total catches were 10,640 tonnes. Table 1 also gives price, costs and production estimated for 2019. The price of fish is € 9,472.5 per tonne, while total cost per unit effort, with a linear cost function, is € 1,066.70 per day. This includes fuel, labour and other variable costs as well as fixed costs.[10] The total quadratic costs parameter in the table is estimated from linear total costs at the MEY level. [11]

Table 1: Parameters for the NW Mediterranean demersal fishery exploited by otter bottom trawl.

Fleet size (2019)	578	Vessels
Individual effort level (number of fishing days)	120 -190	days / year
Mean individual effort (number of fishing days)	155	days / year
Harvest	10,640	Tonnes
Biological production function (Schaefer model)		
K	19,900	tonnes
R	2.5	
q = 0.00397 (tonne/year)/155 =	$2.56\ 10^{-5}$	tonne/day
Economic parameters		
Price of fish	9,472,5	€/tonne
Total cost per unit effort	1066.7	€/day
Total quadratic costs 1066.7/38021	0.0281	$(€/day^2)$.
Based on STECF (2020); Gómez and Maynou (2020).		

In figure 1 we illustrate total revenue and total costs, both as functions of total effort, for the demersal fishery under consideration, based on the parameters given in table 1 for the estimated aggregate Gordon-Schaefer model. We find that e_{MSY} =48,804 days, e_{MEY}=38,021

[9] Note that in this section the unit of effort is days at sea, while the effort parameter in the sections above, also includes the catchability parameter q, making efficient effort (denoted e_i in sections above) equal to $q_i\ e_i$.

[10] Fuel is estimated at € 240.00/day, labour at € 438.70/day and other variable costs at € 319.00/day, while average fixed costs are € 69.00/day.

[11] Stipulated value from the linear total costs parameter as follows: Marginal total costs are equal for the linear and the quadratic total cost case for e_{MEY}= 38,021 days. I.e. calculated as MC (quadratic) = MC (linear)/ $e_{MEY} = 1066.7\ (€/day)/38021\ \ (days) =\ 0.0281(€/day^2)$.

days and e_{OA}= 62,282 days. This compares to an actual effort of almost 89,590 in 2019. Thus, actual effort is even larger than e_{OA}, This clearly illustrates the need for a reduction in effort.

For 2019, it is seen that the difference between revenues (dot, red) (= € 100.8 million) and costs (dot, blue) (= € 112.6 million) is a negative profit of € 11.8 million. The actual stock level in 2019 is estimated at 4,378 tonnes. This is, however, a disequilibrium situation. Inspection of figure 1 will, however, show that in equilibrium, there will be substantial losses at this effort level (vertical dotted line). In equilibrium, harvest is 3,751 tonnes, stock size 1,635 tonnes and there is a negative profit of € 77.1 million. A situation like this can only be supported by substantial subsidies.

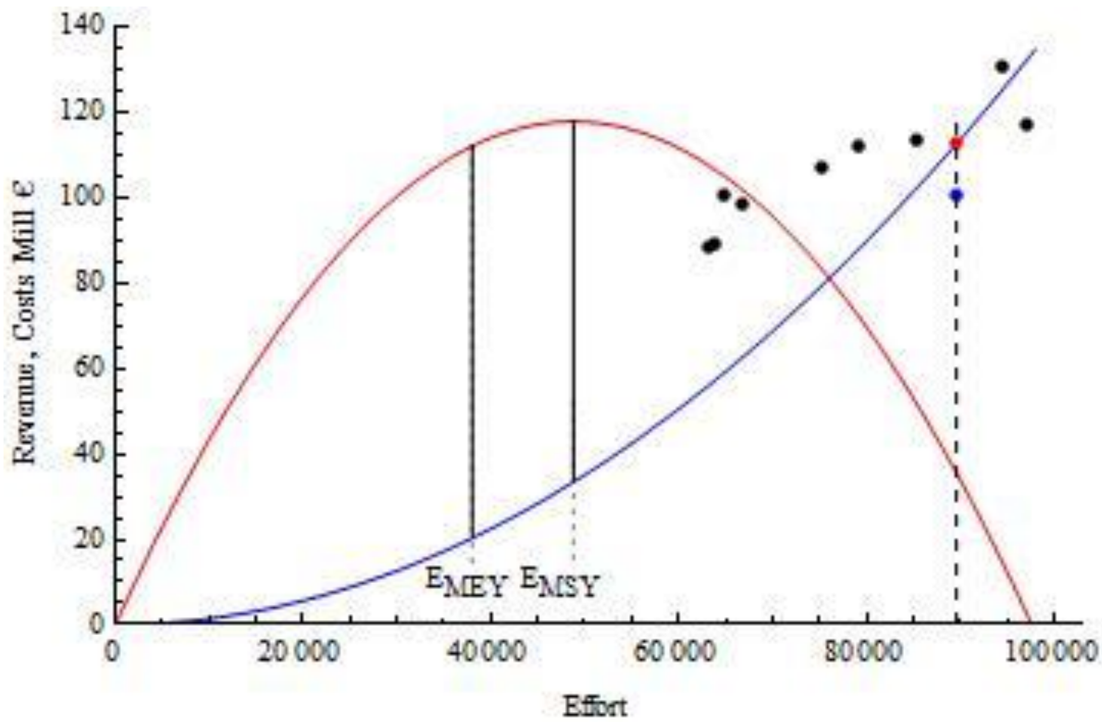

Figure 1: Total quadratic costs (blue curve) and revenues (red curve) as a function of total effort in the single species Gordon-Schaefer model of the NW Mediterranean demersal fishery. The blue and red coloured dots are respectively revenues and costs in 2019. The black dots are observed revenues at observed effort levels from 2008 to 2018.

The various alternatives, in terms of number of vessels, total effort, harvest, stock size and profit are illustrated in Table 2. Scenario 1 is the 2019 status quo situation with a negative profit of € 11.8 mill. but as noted, this is a disequilibrium. The steady state situation is much worse with a negative profit of € 77.1 mill. For the 2019 harvest of 10,640 tonnes to be in steady state, effort per vessel would have to be reduced from 155 to[12] $e_i = 116.6$. In other words, reducing effort with 25% (scenario 2) would be sufficient to obtain the same landings and but with a profit of € 37.4 million which turns around the negative profit to become positive at the present time because of less use of costly effort. Equilibrium stock size in this case is 6,160 tonnes.

Scenario 3 represents the current effort reduction plan to reduce the current effort by 40%. Once equilibrium is reached, this would involve a more than doubling of the stock size to 8,941 tonnes, an annual harvest of 12,310 tonnes and annual profits of € 76.1 million.

Scenarios 4-7 (in Table 2) show the outcomes when a limited number of firms are allowed to participate in the fishery. Scenario 4 and 5 describes the outcome with a fixed price when all fishing rights are held by one firm, respectively in the case when the firm has MEY and MSY objectives. MEY is the social planner's preferred solution. Scenario 6 shows the outcome in the duopoly case, i.e., when the fishery is open and two independent firms $i = 1, 2$ are given the fishing rights. The oligopoly scenarios 7 and 8 have respectively *n=10* (arbitrarily chosen) and *n=578* (2019 fleet size) number of fishing rights in use. In these scenarios (6-8) fishing firms do include their own effort costs in their calculations. Firm i chooses effort determined by equation (11) which is the effort that maximises its equilibrium profit given the sum of effort for all other firms. Scenario 9 shows the full competition or open access case (corresponding to $n \rightarrow \infty$). Here total effort is given by equation (12). In general, we see, for $n \geq 2$, that the solutions will not be efficient.

Table 2: Outcomes for the NW Mediterranean demersal fishery by the otter bottom trawler fleet in GSA06 when each of n vessels maximise its profit given the sum of effort for all other fishers. In alle these cases we calculate with total quadratic costs per unit effort = 0.0281 €/day^2

Scenario		Number of fish rights, *n*	Total effort days	Total harvest tonnes	Stock size tonnes	Total profit mill €
1	Realised (2019)	578	89,590	10,640	1,635	-77.1
2	25% effort reduction	<578	67,395	10.633	6,160	37.4
3	40% effort reduction	<578	53,754	12,310	8,941	76.1
4	MEY	1	38,021	11,830	12,148	91.8
5	MSY	1	48,804	12,438	9,950	84.4
6	Duopoly	2	47,217	12,424	10,273	86.4
7	Oligopoly	10	58,546	11,941	7,963	65.0
8	Fleet size (2019)	578	62,213	11,499	7,216	54.6
9	Full competition	$\rightarrow \infty$	62,282	11,488	7,202	54.4

[12]Solving $h = q\, x(n\, e_i) n\, e_i$ for $n = 578$ with respect to e_i yields $e_i = \frac{Kr \pm \sqrt{Kr(-4h+Kr)}}{2Knq}$ with solutions $e_i = 52.3$ (neglected because below MEY) and $e_i = 116.6$.

Regulating revenues

Homogenous vessels/firms.

With reference to section 3, instead of setting "regular" effort quotas for each vessel/firm equal to a specific number of days, an alternative to achieve optimal total effort can be by regulating individual revenues. These revenues will depend on individual choices of a catch-effort variable, equations (22) and (23), and a share parameter s_i that can be traded in a market. To facilitate comparison within a heterogeneous fleet, we will first apply the scheme to a homogeneous fleet. As shown in Table 3, we then distribute shares equally between those three equal firms.[13] There is no need to trade shares in this case because all firms are equal. Despite this we can calculate the share price from (29). When using equations (22) and (23) and parameter values of Table 1, we recommend a regulation scheme with an outcome at the MEY effort level (Table 2, scenario 4: 38,021 fishing days) as a goal. Then firm i's catch-effort in equilibrium becomes a share s_i of the catch-effort chosen by the sole owner (and social planner). Since $\sum_{i=1}^{n} s_i = s$, we find that the desired MEY outcome is achieved when *s=1* [14]. We can also note that the effective effort e_i multiplied with the stock size $\bar{x}$ in equilibrium is equal to total harvest in tonnes.

Table 3: Outcomes for the NW Mediterranean demersal fishery by the otter bottom trawler fleet in GSA06 with n=3 equal firms, $s_i = \frac{1}{n} = \frac{1}{3}$ for $i = 1,2,3$. Each firm is controlling identical vessels and maximise its profit given the sum of effort for all other firms. In all these cases we assume that individual vessels have a catchability coefficient $q_i = 2.56\ 10^{-5}$ and that total squared catch-effort costs for the total fleet is $c = 0.028/q_2^2 = 42.8\ mill$ €. Then each of the 3 fleet parts has cost parameter $c_i = 3\ c$. Stock size in equilibrium is $\bar{x}$=12,148 tonnes.

MEY Regulation of firms	Square catch-effort costs	Mean catch-ability	Shares after trade	Catch-effort after trade	Effort after trade	Total harvest Tonnes	Share price mill €	Total profit mill €	Profit minus share mill €
3 equal	$3\ c$	q_i	0.3333	0.3246	12,673	3,943	71.5	30,6	6.76
All firms	c	q_i	1	0.9738	38,021	11,830	71.5	91.8	20,3

Heterogenous vessels/firms.

Using the values in Table 1 we want to construct an arbitrary heterogenous fleet that we will subsequently investigate with respect to how the proposed scheme. Estimated results, found by

[13]For simplicity we make a small adjustment in Table 1 by claiming that there are $n = 579$ vessels (instead of 578 which is original number of vessels). Then each firm are assumed to control $n = 579/3 = 193$ vessels.

[14] The interpretation of s_i as a share of total effort might not be necessary. In Table 2, scenario 5, for the fishing industry to choose to attain the MSY target, a value $\sum_{i=1}^{n} s_i = s > 1$ might be requested. In this case, s_i's cannot be interpreted as shares because their sum becomes larger than one, in this case $\sum_{i=1}^{n} s_i = s = \frac{48804}{38021} = 1.284$.

maximizing $L_i(z_i) - C_i(e_i) - T(z_i, s_i) - \mu s_i$ with first order conditions given respectively by (26) and (29) solved simultaneously for every firm, are given in Table 4. The whole fleet consists of three types of vessels ("small, medium and large trawlers") and we assume there are respectively three firms that each separately controls the same number ($n = 579/3 = 193$ vessels)[15] of identical vessels of one type. Using (the medium) firm 2 as a reference, where specifically (from Table 1) $q_2 = 2.56\ 10^{-5}$ and $c_2 = 3 * 0.028/q_2^2 = 128\ mill$ [16], we choose $q_1 = 0.7\ q_2$ (small) and $q_3 = 1.3\ q_2$ (large). For simplicity we choose arbitrarily $c_1 = 0.8\ c_2$ (small), $c_3 = 1.4\ c_2$ (large), and $q_1 = 0.7\ q_2$ (small), $q_3 = 1.3\ q_2$ (large), i.e., $c_3 > c_2 > c_1$ and $q_3 > q_2 > q_1$. Also, here we can note that effective effort $= q_i\ e_i$ multiplied with the stock size $\bar{x}$ in equilibrium is equal to total harvest in tonnes.

Table 4: Outcomes for the NW Mediterranean demersal fishery by the otter bottom trawler fleet in GSA06 when each of 3 types of firms (each controlling identical vessels) maximise its profit given the sum of effort for all other firms. In alle these cases we assume that fleet 2 have a catchability coefficient $q_2 = 2.56\ 10^{-5}$ and that total square catch-effort costs for fleet 2 is $c_2 = 3 * c = 3 * 0.028/q_2^2 = 128\ mill$ €. Stock size in equilibrium is $\bar{x}$=12,256 tonnes.

MEY Regulation of firms	Square catch-effort costs	Mean catch-ability	Shares after trade	Catch-effort after trade	Effort after trade	Total harvest Tonnes	Share price mill €	Total profit mill €	Profit minus share mill €
fleet 1	$0.8\ c_2$	$0.7\ q_2$	0.2172	0.2086	11,634	2,557	69.53	19.7	4.56
fleet 2	$3 * c$	q_2	0.3547	0.3406	13,297	4,174	69.53	32.1	7.44
fleet 3	$1.4\ c_2$	$1.3\ q_2$	0.4281	0.4111	12,347	5,039	69.53	38.7	8.98
All 3 tot			1	0.9603	37,277	11,77	69.53	90.5	20.1

Fleet 2 (in Table 4) and one of the homogeneous fleets (first row in Table 3) have the exact same characteristics in terms of catchability and squared catch-effort cost parameters. However, trades in this heterogeneous case will lead to an equilibrium where the share holding s_2, effort e_2, profit π_2, and profit minus share expenses, increases with a few percentage points from the homogeneous case (Table 3).

5. DISCUSSION

Generally, effort rights-based management might be more effective at managing fishing mortality where uncertainty in biomass and TAC estimates is more fundamentally important than uncertainty in the estimates of the catchability coefficient (FAO, 2012). Moreover, in a

[15] See footnote 10.
[16] To be more comparable to the single firm case with cost parameter c, i.e. to expect the same outcome, c_2 is set equal to the cost parameter multiplied by 3 which is the number of firms.

multi-species fishery like in the Mediterranean, where there is very little selectivity in harvesting, and where it is very difficult to monitor harvests, effort control might be the preferred management option. It may also be the case in other fisheries around the world of which many may be poorly assessed or being in danger of overfishing (Walsh *et al.*, 2018).

A fundamental problem with effort based management is that it gives incentives to substitute unregulated inputs for regulated ones and to maximise harvest given effort. As a consequence of the latter, continual adjustment in effort controls might be required so as to counter "effort creep" (Squires *et al.*, 2017). To scale the effort variable with the catchability parameter, so that the planner employs the catch-effort variable as control, may help to reduce the need for that kind of adjustment.

In this paper we have suggested a simple effort management scheme for fisheries that turns out to be efficient when we employ the logistic Gordon-Shaefer model. With that model management measures can be expressed as a linear subsidy (22) and a quadratic tax (23). In more advanced fishery models, the principles of this scheme, i.e., implementing a combination of a subsidy (awarded benefit for delivering catches) and a progressive tax (to compensate for fishing mortality) into a function that is strictly concave, may still be operational. However, a too complicated fishery model exposed to fishers may be unfortunate. Just like the advantage of representing complex fishery management by distributing a Total Allowable Effort (TAE) or setting Total Allowable Catches (TACs) for each species, it might be more favourable to employ our scheme. It happens to be optimal in some cases and provides an easily computable (and understandable) linear subsidy (22) and quadratic tax function (23) expressions like the ones we have proposed. As we show, a variation of the system with corresponding flexible catch quotas (31) may also be possible, and likewise, probably also a multispecies version with interaction between species.

The practical advantage of our proposal, compared to the traditional effort control measure which limits the maximum allowable number of days at sea, is that its flexibility may make it easier for fishing vessels to comply with regulations for instance in cases where weather conditions at the end of the fishing season make it profitable to go for more daytrips, or if bad weather conditions result in fewer daytrips. Moreover, even if the planner has limited information, more efficient firms might choose a higher number of fishing days than the less efficient participants.

This research may be extended in different ways. An obvious extension would be to formulate a dynamic model which may also allow for quota transfers between periods, as is common in many fisheries. Another possibility is to include more than one fishery, initially in a static model, where quota transfers between fisheries might be possible. Starting with the static model presented in this article, a stochastic version of the growth function might also be considered. These extensions would enhance the potential use of this modelling approach for practical fisheries management.

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In this paper, we propose a fishery control scheme which happens to be first best efficient in the context of a Gordon-Schaefer model where asymmetric information about effort/harvesting costs is present. It is widely acknowledged that in the absence of regulations, competition between vessels leads to a competitive game wherein the outcome is inefficient. We introduce a management scheme that regulates the fishing industry through a convex tax on effort. The shares of this tax can be traded in a market, thus solving problems related to asymmetric information. This can be achieved since heterogeneous fishing firms are individually stimulated to solve the same optimality problem as a social planner would. We apply this model to the Northwest Mediterranean demersal fishery as a case study.

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