

# Implementation of the maximum sustainable yield under an age-structured model

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**Abstract:** One of the main goals stated in the proposals for the Common Fisheries Policy (CFP) reform is achieving maximum sustainable yield (MSY) for all European fisheries by 2015. In this paper, we propose a decentralized fishing rights allocation mechanism or management system to implement MSY harvesting conditions in an age-structured bioeconomic model. An age-structured model in a single species fishery with two fleets having perfect or imperfect fishing selectivity is studied. If fishing technology or gear selectivity depends on the relative age composition of the mature fish stock, fixed harvest proportions, derived from catchability and bycatch coefficients, is not valid anymore. As a result, not only the age-structure and fishing technology but also the estimated level of MSY is steering the allocation of quota shares. The results also show that allocation of quota shares based on historical catches or auctioning may not provide viable solutions to achieve MSY.

**Keywords:** Mechanism design; Fisheries management; Age-structured model; Fishing technology; Fishing gear selectivity; Maximum sustainable yield; Common Fisheries Policy

## **1 Introduction**

In European fisheries, maximum sustainable yield (MSY) has not been achieved for all economically valuable fish stocks. According to Facts and Figures on the Common Fisheries Policy, only 11 fish stocks in the Atlantic shoreline and 21 fish stocks in the Mediterranean are fished at MSY (EU 2014). Most of the other fish stocks remain outside safe biological limits and are overfished (Daw and Gray 2005; Khalilian et al. 2010; Da Rocha et al. 2012; EU 2014). This implies that the provision of sustainable fish stock levels, which is one of the most important environmental objectives of the Common Fisheries Policy (CFP), has not yet been achieved in European fisheries. There is a consensus in the European Union (EU) on the medium term benefits of implementing MSY on environmental, social and economic sustainability. Therefore, achievement of MSY for all fish stocks by 2015 has become prominent as one of the main topics within the scope of CFP reform proposals.<sup>1</sup> However, it is not easy to put the concept of MSY into practice. Thus, the goal of MSY has not been accomplished for more than 30 years in European waters.

These discussions boil down to a question of how MSY can be sustainably implemented for a given fish stock. Management systems play a key role in the implementation process of MSY harvesting conditions. Fisheries in the EU are managed through various systems. The most prominent options among those are rights-based management (RBM) systems. To address the question, this paper examines the implementation problem of MSY harvesting conditions under the individual (non-transferable) quota system, which is one of the most well-known types of RBM systems. The implementation problem is solved by proposing a well-designed quota shares allocation mechanism that guarantees sustainability of fish stocks and achieves MSY harvesting conditions.

The functionality of an individual quota system depends on three main steps of the regulation. The initial step is the determination process of the total allowable catch (TAC) level. The second

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<sup>1</sup> See the Green Paper for more details on the reform of the EU's CFP (EC 2009).

step is the implementation of a well-designed quota shares allocation mechanism. The final step is the design of effective control system to control the output landed by fleets. This study combines the first and second steps stated above by considering the design problem of a decentralized fishing rights allocation mechanism to implement MSY.

It is known that precise data about the biological structure of a given fish population is required to manage the stock in accordance with MSY objectives. Given that MSY is calculated for a given fish stock, this paper presents an RBM system implementing MSY fishing mortality rates (or exploitation rates) in a simple age-structured fish population model with three interacting age classes (juveniles, young mature fish and old mature fish) of a single fish stock, and without loss of generality two fishing fleets having perfect or imperfect fishing selectivity. In the model, fleets are able to select for young mature fish and old mature fish where old mature fish has a higher market price. It is also assumed that juveniles are not subject to harvesting for simplicity. This selection for two different mature age groups can be perfect or imperfect depending on different fishing gear types or technologies used by fleets.

The aim of this study is to investigate the allocation problem of fishing quota shares to implement the MSY solution concept by a decentralized mechanism or management system. MSY harvesting conditions specify fishing mortalities for each age classes by maximizing overall yield. Finding these optimal fishing mortalities is a centralized problem from a viewpoint of a social planner and related to sustainable use of the biological resource. We propose a decentralized management system (or quota allocation mechanism) whose outcomes are identical to MSY harvesting conditions and investigate the implications of different fishing technologies on the design of the decentralized management system. Within this framework, we propose a new quota shares allocation mechanism and determine possible quota shares allocations to solve implementation problem under different fishing technologies or gear selectivities. The analysis indicates that a well-designed RBM system is required to implement MSY harvesting conditions. It

is also shown that not only the age-structure and fishing technology but also the estimated level of MSY is steering the allocation of fishing rights.

The allocation of quota shares, percentages of the overall TAC, is usually based on historical catches (grandfathering rule). Moreover, auctions are also used to determine the allocation of fishing rights. The findings of this paper imply that allocating quotas based on historical catches or auctioning may not provide viable solutions to achieve MSY harvesting conditions since these allocation mechanisms do not take into account the age distribution of the fish population and fishing technologies of fleets.

There is a vast literature on age-structured fish population models. In recent years, Clark (2010), Quaas et al. (2013), Skonhøft et al. (2012), and Tahvonen (2009a,b;2010), among others, have contributed to this literature of age-structured modeling for fisheries. Moreover, Armstrong (1999) investigated the harvest shares of trawlers and coastal vessels at particular TAC levels using the actual allocation rule for the Norwegian cod fishery. See also Armstrong and Sumaila (2001), Bjørndal and Brasao (2006), Stage (2006) and Diekert et al. (2010) for more on applications of age-structured model for different case studies. A previous study of Skonhøft et al. (2012) have recently formulated an age-structured model and derived MSY fishing mortalities similar to that of Reed's (1980). In the current study, the age-structured fish population model developed by Skonhøft et al. (2012) is employed and fishing mortality rates at MSY are calculated using a simple Lagrangian method proposed by them. However, the implementation problem of this solution concept is not the main purpose of their paper.

The rest of the paper is organized as follows. Section 2 introduces the model and provide basic definitions. In Section 3, the optimization problem to find MSY fishing mortalities is formulated. Section 4 studies the implementation problem of MSY harvesting conditions. Section 5 provides a numerical illustration of the main results. Section 6 discusses policy implications of the analysis and contains concluding remarks.

## 2 Bioeconomic Model

### 2.1 Fish Population

The population model is based on three cohorts of a fish population. The juveniles are the members of the youngest class in the population. They are neither harvestable nor members of the spawning stock, while old mature and young mature cohorts are both harvestable and members of the spawning stock.<sup>2</sup> In addition, old mature fish have higher fertility rate than young mature fish, as supposed by Reed (1980). Moreover, weight per fish is higher for the older fish ( $w_0 < w_1 < w_2$ ). It is considered that the juvenile has no market value and price per weight for old mature fish is higher than the price per weight for young mature fish ( $p_0 = 0, p_1 < p_2$ ). The population at any season  $t$  is defined as follows: Juveniles,  $X_{0,t}$  (age  $< 1$ ), Young matures,  $X_{1,t}$  ( $1 \leq \text{age} < 2$ ), Old matures,  $X_{2,t}$  ( $2 \leq \text{age}$ ).

In the model, the Beverton-Holt recruitment function, which is increasing and concave for both age classes, is employed (Beverton and Holt 1957). The number of recruits to the fish population at season  $t$  is:

$$X_{0,t} = R(X_{1,t}, X_{2,t}) = \frac{a(X_{1,t} + \beta X_{2,t})}{[b + (X_{1,t} + \beta X_{2,t})]}. \quad (1)$$

The number of recruits depends on the abundance of old mature and young mature fish and parameters of  $a, b$  and  $\beta$ . The parameters of  $a$  and  $b$  are the scaling and shape parameters, respectively. Besides,  $\beta > 1$  is the fertility parameter indicating the higher natural fertility of old mature fish than that of young mature fish. The number of young mature fish at season  $t+1$  is defined by the following equation:

$$X_{1,t+1} = s_0 X_{0,t} = s_0 R(X_{1,t}, X_{2,t}). \quad (2)$$

The number of old mature fish at  $t+1$  is given as:

$$X_{2,t+1} = s_1 (1 - f_{1,t}) X_{1,t} + s_2 (1 - f_{2,t}) X_{2,t}. \quad (3)$$

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<sup>2</sup> It is assumed that only mature fish are subject to harvesting for simplicity. There are significant harvests of immature fish in many fisheries. The model can also be extended to fisheries where fishing selection for age is not possible.

In the above notation,  $s_0$  is the fixed natural survival rate of juveniles. Moreover,  $f_{1,t}, s_1$  and  $f_{2,t}, s_2$  are aggregate fishing mortality rates (or exploitation rates) and fixed natural survival rates of young mature and old mature fish, respectively.

In this study, it is considered that fishing activity occurs after spawning and before natural mortality. We propose a quota shares allocation mechanism at the population equilibrium ( $X_{i,t+1} = X_{i,t} = X_i$ ). It is also assumed without loss of generality that the total biomass of the old mature fish is less than the total biomass of the young mature fish ( $w_2 X_2 < w_1 X_1$ ) at steady-state outcomes. This assumption refers to a stylized real life situation, but all results can easily be extended to other possible cases ( $w_2 X_2 \geq w_1 X_1$ ).

The following equations are the biological constraints of the maximization problem to find MSY harvesting conditions. Eq. (2') is the recruitment constraint and Eq. (3') is the spawning constraint.

$$X_1 = s_0 R(X_1, X_2), \quad (2')$$

$$X_2 = s_1 (1 - f_1) X_1 + s_2 (1 - f_2) X_2. \quad (3')$$

The population model developed by Skonhoft et al. (2012) is described so far. In what follows, fishing technologies, fishing days and catch compositions are defined under given age-structured population dynamics.

## 2.2 Fishing Fleets: Technologies

In this mechanism design setting, there are without loss of generality two fishing fleets characterized by their fishing technologies or gear types. These exogenously given technologies are such that only mature fish can be harvested (juveniles cannot be harvested), and selecting for old mature fish or young mature fish may be perfect or imperfect. This type of selection is observed in some fisheries (Quaas et al. 2013; Madsen 2007; Broadhurst and Millar 2011). See also Squires and Vestergaard (2013) for a review of technological progress in fisheries. The current analysis focuses on the situation in which both fleets target or try to select the old mature class since the market price

of old mature fish is higher than the market price of young mature fish.<sup>3</sup> We also assume that each fleet has one type of fishing gear and it is impossible to change the gear in a given season.

Catchability and bycatch coefficient for fleet  $i$  are denoted by  $q_i^2$  and  $q_i^1$ , respectively. For fleet  $i$ ,  $q_i^2$  is the proportion of old mature fish catch per unit of effort from total biomass of old mature fish, and  $q_i^1$  is the proportion of young mature fish catch per unit of effort from total biomass of young mature fish. The actual fishing effort of fleet  $i$  is denoted by  $E_i$ . Under given coefficients, total harvest of fleet  $i$  is defined as  $H_i = \sum_{c=1}^{c=2} q_i^c w_c X_c E_i$ .

The fishing technology or the degree of selection for fleet 1 and fleet 2 are denoted as  $j_1$  and  $j_2$ , respectively.<sup>4</sup> Technology level of  $j_i$  simply derived from the catchability and bycatch coefficients of fleet  $i$ , and relative age composition of mature age classes. Let  $j_i = \frac{q_i^2 w_2 X_2}{q_i^2 w_2 X_2 + q_i^1 w_1 X_1}$  be the fishing technology of fleet  $i$ . At a given  $j_i$  level, exploitation rate of old mature fish is equal to  $j_i \times 100$  percent of  $H_i$ , and exploitation rate of young mature fish is equal to  $(1 - j_i) \times 100$  percent of  $H_i$ . This implies that actual age composition of the total harvest is linked to the age composition in the mature age fish stock. It is easy to see that fleet  $i$  harvest primarily young mature fish if relative abundance of young mature fish ( $\frac{X_1}{X_2}$ ) is very high. We assume that the lower bound for fishing technologies without loss of generality is 0.5 because it is considered that both fleets have fishing technologies compatible with harvesting the targeted (old mature) fish. Therefore,  $j_1$  and  $j_2$  are always greater than 0.5. The implication of this assumption is that the relative abundance of young mature fish is not very high ( $\frac{X_1}{X_2} < \frac{q_i^2 w_2}{q_i^1 w_1}$ ). Moreover, fleets harvest more old mature fish than young mature fish in terms of weight until the old mature fish stock is completely harvested. That is,  $q_i^2 > q_i^1$  since we assumed that  $w_2 X_2 < w_1 X_1$  for the fish stock. Given the structure of the fishery ( $j_i >$

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<sup>3</sup> The model can be easily extended to cases where one fleet targets old mature fish cohort and the other fleet targets young mature fish cohort.

<sup>4</sup> The degree of selection for fishable age classes can depend on gear types used by fleets. See Madsen (2007) for more on selectivity estimations for different fishing gear types.

0.5 and  $w_2 X_2 < w_1 X_1$ ), the first age class that gets fully harvested in the mature stock is always the old mature age class.<sup>5</sup>

If  $j_i = 1$  ( $q_i^1 = 0$ ), then fleet  $i$  has a perfect fishing selectivity and hence can select for only old mature fish. If  $j_i < 1$  ( $q_i^1 > 0$ ), the selection is imperfect and hence fleet harvests both old mature fish and young mature fish. There are four possible cases given the structure of fishing technologies considered in this paper. Case 1 refers to a fishery with two identical fleets having perfect fishing selectivity ( $j_1 = j_2 = 1$ ). In Case 2, fleet 1 has perfect fishing selectivity ( $j_1 = 1$ ), and fleet 2 has imperfect fishing selectivity ( $0.5 < j_2 < 1$ ). In Case 3, fleet 2 has perfect fishing selectivity ( $j_2 = 1$ ), and fleet 1 has imperfect fishing selectivity ( $0.5 < j_1 < 1$ ). Finally, there are two fleets having imperfect fishing selectivity in Case 4 ( $0.5 < j_1 < 1$  and  $0.5 < j_2 < 1$ ). We consider only Case 2 and Case 4 in this paper. We refer the reader to (Kucuksenel and Kanik 2015) for a complete treatment.

This type of fishing technology or degree of selection is also observed in real life fisheries. Fleets choose fishing grounds according to expected age composition in that fishing ground since different cohorts can be found in different regions in the British Columbia, Canada, groundfish trawl fishery (Branch and Hilborn 2008). Fish can be segregated perfectly or imperfectly by size and age for some species, and fleets choose particular fishing areas to target one specific size or age (Walters and Martell 2004; Bacheler et al. 2010). See also Skonhøft and Gong (2014) for perfect selectivity assumption for the old cohort in age-structured modelling of the Atlantic salmon fishery. Moreover, Madsen (2007) estimates selectivity of fishing gears used in the Baltic Sea cod fishery and shows that the degree of precision for selecting specific age groups can be increased by using passive gear types. Perfect selectivity for the old mature fish cohort ( $j_i = 1$  or  $q_i^1 = 0$ ), is always possible in our environment if the mesh size is large enough. Moreover, small fish can escape from

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<sup>5</sup> This set of assumptions is sufficient to ensure that the old mature cohort is the only cohort that can be fully harvested at any management systems implementing MSY harvesting conditions. If we change this set of assumptions, there can be cases where young mature age class is fully harvested. This type of harvesting cannot maximize the overall yield, and hence it is impossible to implement MSY for such cases. See Subsection 2.2 for more about this.

specially designed mesh and hence fish larger than a specific size can be harvested in trawls (Millar and Fryer 1999).

### 2.3 Fishing Fleets: Fishing Days

We assume that fishing can occur at several days until all fishing quotas are exhausted (or TAC is reached) at a given season  $t$ . At the first fishing day, two fleets *simultaneously* exert fishing effort and harvest the same total weight of fish at the first fishing day due to identical capacity of fishing vessels.<sup>6</sup> If there is a fleet whose quota is not reached or fulfilled, then fishing continues at the second fishing day. Otherwise, fleets stop fishing and fishery is closed for the season  $t$ . If there are two fleets at the second day, then the second day is identical to the first day. If there is a fleet at the second day, the fleet continues fishing and fulfills its quota according to its updated utilization of the fishing technology or the degree of selection due to change in the age composition of the fish stock given that fishing technology is imperfect. The relative abundance of mature age stocks changes at the second day and hence the utilization of the fishing technology changes at the second day unless fishing technology is perfect. If all old mature fish are harvested at the first day, then utilization of fishing technology is updated to zero. Thus, a fleet can fulfill its remaining quotas only with young mature fish.

Fishing days continue in a similar fashion. Fishing days end if TAC is reached (all fleets fulfill their quotas) or there is a fleet with perfect fishing selectivity whose quota is not exhausted and all old mature fish are harvested at the previous day. This is to say that for some cases fishing days can end even though TAC is not reached. The reason is that it is not possible for a fleet with perfect selectivity to fulfill his remaining quota in a given day if all old mature fish are harvested at the previous fishing day.<sup>7</sup> This is due to the assumption that the fleet has one type of fishing gear

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<sup>6</sup> Note that  $j_i = \frac{q_i^2 w_2 X_2}{q_i^2 w_2 X_2 + q_i^1 w_1 X_1}$  at the beginning of each fishing day. Thus, the utilization of the technology level is constant due to simultaneous effort in a given fishing day, but it can change depending on the relative abundance of young mature stock at the beginning of the next fishing day.

<sup>7</sup> See the last paragraph in Section 5 for an illustration of this case.

(mesh size is large enough for perfect fishing selectivity) and it is impossible to change the gear in a given season.

We also assume that fleets are trying to minimize number of fishing days to fulfill their quotas. This implies that fleets exert the highest possible level of fishing effort at each fishing day, and hence fishing stops at a finite number of fishing days. Note that if there is only one fleet at the second fishing day and all old mature is harvested at the first fishing day, it may take infinitely many fishing days for the fleet to fulfill its quota if the fleet exerts infinitesimal fishing effort level in each of the remaining fishing days. The assumption of maximum possible effort at each fishing days rules out this possibility.

#### 2.4 Fishing Fleets: Catch Compositions

We first look at the the simplest case of our model in which all quota is assigned to a fleet. The quota share or percentages of the overall TAC assigned to fleet  $i$  is denoted by  $\alpha_i \in [0,1]$ . Suppose without loss of generality that  $\alpha_1 = 1$  and  $\alpha_2 = 0$ . Given that  $j_1 = 0.8$ ,  $w_2 X_2 \geq 80$  and the quota allocation of fleet 1 is  $\alpha_1 TAC = TAC = 100 \leq w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2$  tonnes, fleet 1 catches  $j_1 TAC = 80$  tonnes of old mature fish while capturing  $(1 - j_1)TAC = 20$  tonnes of young mature fish.<sup>8</sup> Since fleet 1's quota is exhausted at the first fishing day, fishing stops at the end of the first fishing day. If  $j_1 = 0.8$ , and  $w_2 X_2 < j_1 TAC = 80$ , then fleet 1 captures  $w_2 X_2$  tonnes of old mature fish and  $[(1 - j_1)/j_1] w_2 X_2 = 0.25 w_2 X_2$  tonnes of young mature fish at the first day by exerting fishing effort  $E_1 = 1/q_1^2$ . Note that its quota is not exhausted and fishing continues to the second day. Moreover, all old mature fish is harvested at the first day.

At the second day, the fleet exerts fishing effort to fulfill its quota with only young mature fish and catches  $100 - 1.25w_2 X_2$  tonnes of additional young mature fish. Thus, the fleet's total harvest is  $w_2 X_2$  tonnes of old mature fish and  $100 - w_2 X_2 > [(1 - j_1)/j_1] w_2 X_2$  tonnes of young mature fish. Note that  $(1 - j_1)TAC < TAC - w_2 X_2$  since fleet 1 fulfills its remaining quota by

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<sup>8</sup> In this case, fleet 1 cannot harvest all old mature age class due to fishing technology constraint unless  $TAC = w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2$ . If all old mature age class is harvested at the first fishing day, the total bycatch of young mature age class is equal to  $[(1 - j_1)/j_1] w_2 X_2$ .

harvesting young mature fish at the second day under the assumption that fishermen are non-satiated.<sup>9</sup> As a result, the ratio of old mature fish harvest to the young mature fish harvest derived from fishing technologies ( $1$  to  $(1 - j_i)/j_i$ ) is valid until the old mature fish class is fully harvested.

We now look at the cases where  $\alpha_1 > 0$  and  $\alpha_2 > 0$ . In Case 2, if fleet 1 harvests  $n$  tonnes of old mature fish at the first day, then fleet 2 harvests  $j_2 n$  tonnes of old mature fish and  $(1 - j_2)n$  tonnes of young mature fish given that  $n + j_2 n \leq w_2 X_2$  and  $n$  is less than the quota assigned to both fleet 1 and fleet 2,  $n \leq \min\{\alpha_1 TAC, \alpha_2 TAC\}$ . If  $n = \alpha_1 TAC < \alpha_2 TAC$  and  $w_2 X_2 = n + j_2 n$ , then fleet 2 fulfills its remaining quota with young mature fish at the second day since all old mature fish would be harvested at the first day. Therefore, fleet 2 harvests  $\alpha_2 TAC - n$  additional tonnes of young mature fish at the second day and its total harvest of young mature fish is equal to  $\alpha_2 TAC - j_2 n$  tonnes.

On the other hand, if  $n = \alpha_1 TAC < \alpha_2 TAC$  and  $w_2 X_2 - n > j_2 n$ , then fleet 2 exerts effort at the second day and harvest both age classes according to its fishing technology and assigned quota level. Note that the total biomass of old mature stock at the second fishing day is  $w_2 X_2 - n - j_2 n$  tonnes and the total biomass of old mature stock at the second day is  $w_1 X_1 - (1 - j_2)n$ . Fleet 2 harvest all remaining old mature fish at the second day to minimize the number of fishing days.

Note that the degree of selection is  $\frac{q_2^2(w_2 X_2 - n - j_2 n)}{q_2^2(w_2 X_2 - n - j_2 n) + q_1^2(w_1 X_1 - (1 - j_2)n)}$  at the second day. If its quota allocation is still not fulfilled, then the fleet fulfills its remaining quota with young mature fish at the third fishing day (the degree of selection is zero), and fishing stops. If  $n = \alpha_2 TAC < \alpha_1 TAC$ , then fleet 1 fulfills its remaining quota with old mature fish at the second day (the degree of selection is now equals to one due to change in the age composition of the fish stock), and hence harvests  $\alpha_1 TAC - n = w_2 X_2 - (1 + j_2)n$  additional tonnes of old mature fish at the second day.

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<sup>9</sup> The cost of fishing is not modelled explicitly for the general purpose of this paper. This behavioral assumption guarantees that a fleet continues exerting effort and harvesting fish till the fleet fulfills its assigned quota independent of the cost structure of fishing. That is, fleets are quota-filling whenever possible and fishing activity does not stop unless TAC is reached.

In Case 4, for example, if fleet 1 harvests  $j_1 n$  tonnes of old mature fish and  $(1 - j_1)n$  tonnes of young mature fish at a given season, then fleet 2 harvests  $j_2 n$  tonnes of old mature fish and  $(1 - j_2)n$  tonnes of young mature fish given that  $n \leq \min\{\alpha_1 TAC, \alpha_2 TAC\}$ . If without loss of generality  $n = \alpha_1 TAC < \alpha_2 TAC$ , then fleet 2 fulfills its quota at the remaining fishing days according to its fishing technology constraint, the assigned quota level and the age composition of surviving fish stocks as in Case 2.

To summarize, the initial process of estimating the catch compositions of fleets is to determine the cut-off levels for TAC under given fishing technologies. For example, consider a fishery including two fleets having imperfect fishing selectivity ( $0.5 < j_1 < 1$ ,  $0.5 < j_2 < 1$ ). Under given fishing technologies, the cut-off levels for TAC are  $w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2$  and  $w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$ . The cut-off  $w_2 X_2 + [(1 - j_i)/j_i] w_2 X_2$  is the overall TAC at which all old mature age class can be harvested at the first fishing day by fleet  $i$  if all quotas are assigned to fleet  $i$ . If  $TAC < \min\{w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2, w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2\}$ , then fishing stops at the end of the first fishing day and catch composition of fleet  $i$  can be defined as follows:

$$\alpha_i TAC = h_i^2 w_2 X_2 + b_i^1 w_1 X_1, \sum_{i=1,2} \alpha_i = 1 \quad (4)$$

where  $h_i^2$  is the exploitation rate of old mature age class by fleet  $i$ , and  $b_i^1$  is the exploitation rate of young mature age class by fleet  $i$ . Then, the total biomass harvest of fleet  $i$  is equal to  $\alpha_i TAC$  consisting of  $h_i^2 w_2 X_2$  tonnes of old mature fish, and  $b_i^1 w_1 X_1$  tonnes of young mature fish. Catch compositions of fleets for the specified TAC can also be expressed in the following way:

$$\begin{aligned} h_1^2 w_2 X_2 &= j_1 \alpha_1 TAC > b_1^1 w_1 X_1 = (1 - j_1) \alpha_1 TAC, \\ h_2^2 w_2 X_2 &= j_2 \alpha_2 TAC > b_2^1 w_1 X_1 = (1 - j_2) \alpha_2 TAC. \end{aligned}$$

In this specific environment in which fishing stops at the end of the first fishing day, the total weight of old mature fish harvest is higher than the total weight of young mature fish harvest for both fleets. On the other hand, the TAC may also be between the two cut-off levels or higher than the maximum of the cut-off levels depending on MSY harvesting conditions. The number fishing days can also be more than one to fulfill the assigned quota allotment.

### 3 Maximum Sustainable Yield

In this section, MSY harvesting conditions are investigated. The problem of finding MSY harvesting strategies,  $f_1$  (total fishing mortality rate of the young mature fish cohort) and  $f_2$  (total fishing mortality rate of the old mature fish cohort), for this environment has been studied in the literature. This section is presented for completeness of the paper. The approach of Skonhøft et al. (2012) is directly applied to show the total fishing mortality rates (or exploitation rates) at MSY. The total biomass harvested at the population equilibrium must be equal to the sum of the total biomass harvest of old mature fish and the total biomass harvest of young mature fish. That is, the total biomass harvest function is:

$$Y = f_1 w_1 X_1 + f_2 w_2 X_2. \quad (5)$$

The biological constraints for the total harvest maximization problem are:

$$X_1 = s_0 R(X_1, X_2), \quad (2')$$

and

$$X_2 = s_1 (1 - f_1) X_1 + s_2 (1 - f_2) X_2. \quad (3')$$

The general problem to find MSY harvesting conditions is to find the maximum total biomass harvest given these biological constraints. That is, the problem is to maximize (5) subject to (2') and (3').

The Lagrangian function for this maximization problem is written as  $L = f_1 w_1 X_1 + f_2 w_2 X_2 - \varphi [X_1 - s_0 R(X_1, X_2)] - \mu [X_2 - s_1 (1 - f_1) X_1 + s_2 (1 - f_2) X_2]$ . Note that  $\varphi > 0$  is a Lagrange multiplier for the recruitment constraint, (2') and  $\mu > 0$  is a Lagrange multiplier for the spawning constraint, (3'). It is easy to see from the first order necessary conditions that  $\partial L / \partial f_1$  and  $\partial L / \partial f_2$  are independent of the recruitment function. It is also assumed that the natural survival rates of old mature and young mature fish do not differ at a significant level. Hence, the ratios of weights to natural survival rates satisfy the strict inequality of  $w_2 / s_2 > w_1 / s_1$  (Skonhøft et al. 2012). The conditions for fishing mortality (or exploitation) rates, which can be derived from the first order necessary conditions are: 1) Given that  $\mu = w_1 / s_1 < w_2 / s_2$ ,  $f_2 = 1$  and  $0 < f_1 < 1$ ; 2)

Given that  $w_1/s_1 < \mu < w_2/s_2$ ,  $f_2 = 1$  and  $f_1 = 0$ ; 3) Given that  $w_1/s_1 < \mu = w_2/s_2$ ,  $0 < f_2 < 1$  and  $f_1 = 0$ . We refer the reader to Skonhøft et al. (2012) and Reed (1980) for more on this.

#### 4 Implementation of the Maximum Sustainable Yield

The implementation problem is to find a decentralized policy instrument (or management system) such that outcomes of the instrument is identical to MSY harvesting conditions.<sup>10</sup> That is, the problem is to find quota shares allocations such that if these quota shares are assigned to fleets with different fishing gear types, the resulting total biomass harvest and harvest compositions are identical to the total biomass harvest and harvest compositions at MSY. The aggregate fishing mortality rates for two mature age classes at MSY ( $f_1$  and  $f_2$ ) are found using the maximization problem defined in the previous section. To implement MSY harvesting conditions, we first need to set the overall TAC equal to the aggregate fishing mortalities of mature stocks at MSY. We then determine the possible allocations of quota shares given the overall TAC to solve the implementation problem.

The following equation defines the overall TAC for the allocation mechanism given MSY harvesting conditions,  $f_1$  and  $f_2$ :

$$TAC = f_1 w_1 X_1 + f_2 w_2 X_2. \quad (6)$$

Given this fishery, the remaining problem is to determine the allocations of quota shares or fishing rights to implement MSY under different assumptions about fleets' fishing technologies. It should be noted that only the fishing mortality solutions, which are compatible with the fishing technologies given in that case, are analyzed. For instance, given that both fleets have imperfect fishing selectivity, then MSY harvesting conditions such as  $f_1 = 0$  and  $f_2 = 1$  or  $f_1 = 0$  and  $f_2 < 1$  are not taken into consideration. Implementation of MSY is not possible for these cases since total harvest of young mature fish can never be equal to zero with imperfect fishing technology. Hence, the allocation of quota shares for MSY harvesting conditions which can be obtained under given fishing technologies are determined and represented in the following two different cases.

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<sup>10</sup> See also Jackson (2001) for more details about the general implementation problem in different economic settings.

*Case 2: Fleet 1 has perfect fishing selectivity and fleet 2 has imperfect fishing selectivity ( $j_1 = 1$  and  $0.5 < j_2 < 1$ ).*

Case 2.1: MSY fishing mortalities are  $f_1 = 0$  and  $0 < f_2 < 1$ . Then,  $TAC = f_2 w_2 X_2$ . Under these conditions, MSY can only be implemented by assigning all quota shares to fleet 1 since fishing mortality of young mature fish can only be equal to zero for this allocation,  $\alpha_1 = 1$  and  $\alpha_2 = 0$ . Note that MSY is implemented in the first fishing day.

Case 2.2.a: MSY fishing mortalities are  $f_1 = 0$  and  $f_2 = 1$ . Then  $TAC = w_2 X_2$ . The argument for this case is identical to Case 2.1. MSY is implemented if all quotas are assigned to fleet 1,  $\alpha_1 = 1$  and  $\alpha_2 = 0$ .

Note that for some fish populations the fishing fleet with imperfect fishing technology should be kept outside the allocation process of fishing rights under Case 2.1 and Case 2.2.a to implement MSY harvesting conditions.

Case 2.2.b: MSY fishing mortalities are  $0 < f_1 < 1$  and  $f_2 = 1$  such that  $f_1 w_1 X_1 < [(1 - j_2)/j_2] w_2 X_2$ . Then,  $w_2 X_2 < TAC = f_1 w_1 X_1 + w_2 X_2 < w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$ . If all quota shares are assigned to fleet 1, it is easy to see that MSY cannot be implemented since fleet 1 does not harvest young mature fish. On the other hand, if all quotas are assigned to fleet 2, then the fleet fulfills its total quota at the first fishing day before harvesting all old mature fish. Owing to the fact that both corner solutions cannot be used to solve the implementation problem, interior solutions should be checked. It is now shown that any quota shares such that  $\alpha_1 \in [\underline{\alpha}_1, \bar{\alpha}_1]$  and  $\alpha_2 = 1 - \alpha_1 > 0$  can be used to implement MSY harvesting conditions given that fishing mortality rate of young mature fish is above a certain level at MSY. Fleet 1 fulfills its quota at the first fishing day  $h_1^2 w_2 X_2 = n = \alpha_1 TAC$  and  $b_1^1 w_1 X_1 = 0$  since we assume that fleets try to minimize the number of fishing days. Then, either  $h_2^2 w_2 X_2 = w_2 X_2 - n \geq j_2 n$  or  $h_2^2 w_2 X_2 = w_2 X_2 - n < j_2 n$  is possible.

Suppose that  $h_2^2 w_2 X_2 = w_2 X_2 - n \geq j_2 n$ . Then,  $f_1 w_1 X_1 \geq (1 - j_2)(w_2 X_2 - n)/j_2$ .

This implies that fleet 1's quota exhausts first at the first fishing day, and fleet 2 tries to fulfill its

remaining quota with old mature fish and young mature fish at the second fishing day since  $\alpha_2 TAC \geq n$ . Note that total biomass harvest at the first fishing day is equal to  $2n$ . The total biomass of old mature fish at the second day is  $w_2 X_2 - (1 + j_2)n$  and the total biomass of young mature fish is  $w_1 X_1 - (1 - j_2)n$ . The degree of selection for fleet 2 is equal to  $\frac{q_2^2(w_2 X_2 - (1 + j_2)n)}{q_2^2(w_2 X_2 - (1 + j_2)n) + q_1^2(w_1 X_1 - (1 - j_2)n)}$  at the second fishing day since relative abundance of young mature fish changes. Fleet 2 harvests all of remaining old mature fish in the second fishing day. If fleet 2's quota is not exhausted at the end of the second fishing day, the fleet fulfills its quota with only young mature fish at the third fishing day. Moreover,  $2 w_2 X_2 / (1 + j_2) \leq TAC$  since  $\alpha_2 TAC \geq n$ . Therefore, different quota shares allocations produce the same TAC, which is equal to  $f_1 w_1 X_1 + w_2 X_2$ , if  $f_1 \geq \frac{w_2 X_2 (1 - j_2)}{w_1 X_1 (1 + j_2)} = f^*$ .

At  $\bar{\alpha}_1$ , fleet 2 should fulfill its quota by harvesting only young mature fish at the second fishing day after all old mature fish are harvested at the first fishing day. This implies that  $h_2^2 w_2 X_2$  should be at the minimum possible level such that  $h_2^2 w_2 X_2 = w_2 X_2 - n = j_2 n$  and  $n = \bar{\alpha}_1 TAC = w_2 X_2 / (1 + j_2)$ . Therefore,  $\bar{\alpha}_1 = \frac{w_2 X_2}{(1 + j_2) TAC}$ . At  $\underline{\alpha}_1$ , fleet 2 should harvest the maximum possible weight of old mature fish at the first fishing day besides its total young mature fish harvest is  $f_1 w_1 X_1$  in at most three fishing days. This is only possible if  $(1 - \underline{\alpha}_1) TAC (1 - j_2) = f_1 w_1 X_1$ . Thus,  $\underline{\alpha}_1 = (w_2 X_2 - j_2 TAC) / [TAC (1 - j_2)]$ .

Now, suppose that  $h_2^2 w_2 X_2 = w_2 X_2 - n < j_2 n$ . This is only possible if fleet 2 fulfills its quota at the first fishing day and fleet 1 fulfills its remaining quota with old mature fish at the second fishing day. That is,  $w_2 X_2 < TAC < 2w_2 X_2 / (1 + j_2)$ . Moreover, due to fleet 1's fishing technology,  $b_2^1 w_1 X_1 = f_1 w_1 X_1 = [(1 - j_2) / j_2] (w_2 X_2 - n) = (1 - \alpha_1) TAC$ . This implies that  $\alpha_1 = (w_2 X_2 - j_2 TAC) / [(1 - j_2) TAC]$ .

Case 2.3: MSY fishing mortalities are  $0 < f_1 < 1$  and  $f_2 = 1$  such that  $f_1 w_1 X_1 \geq [(1 - j_2) / j_2] w_2 X_2$ . Then,  $w_2 X_2 + [(1 - j_2) / j_2] w_2 X_2 \leq TAC = f_1 w_1 X_1 + f_2 w_2 X_2$ . Under these conditions, MSY can be implemented if all quota shares are assigned to fleet 2 since fleet 2 harvests all old mature fish and also  $f_1 w_1 X_1$  young mature fish by fulfilling its remaining quota at

the second fishing day with young mature fish after all old mature fish are harvested in the first fishing day. On the other hand, assigning all quotas to fleet 1 cannot be a solution since fleet 1 does not bycatch young mature fish. Hence, there is an upper bound of  $\alpha_1$ , and fleet 1 fulfills its all quotas by harvesting old mature fish for all other quota shares that are equal to or below this  $\alpha_1$  level,  $\bar{\alpha}_1$ . The analysis in the next paragraph finds this upper bound and shows that any quota shares such that  $\alpha_1 \in [0, \bar{\alpha}_1]$  and  $\alpha_2 = 1 - \alpha_1 > 0$  can be used to implement MSY harvesting conditions for this case.

Now, possible interior solutions should be checked. Since TAC is set at a level equal to or higher than  $w_2 X_2 + [(1 - j_2) / j_2] w_2 X_2$ , all old mature fish are harvested at the first fishing day regardless of the quota shares allocation. Moreover, fleet 2 fulfills its remaining quota with young mature fish for all feasible quota shares at the second fishing day since  $f_1 w_1 X_1 \geq [(1 - j_2) / j_2] w_2 X_2$ . According to the fishing technologies, it is known that at the first fishing day, if fleet 1 captures  $n$  tonnes of the old mature fish, fleet 2 captures  $j_2 n$  tonnes of the old mature fish and  $(1 - j_2) n$  tonnes of the young mature fish as long as  $n + j_2 n \leq w_2 X_2$ . At  $\bar{\alpha}_1$ , we have  $h_1^2 w_2 X_2 = n = \bar{\alpha}_1 TAC$ ,  $h_2^2 w_2 X_2 = n j_2$  and  $b_2^1 w_1 X_1 = f_1 w_1 X_1 \geq (1 - j_2) n$ . Therefore, quota shares allocations satisfying  $0 \leq \alpha_1 \leq w_2 X_2 / (1 + j_2) TAC$  can be used to solve the implementation problem of MSY harvesting conditions.

Possible allocations of quota shares to implement MSY harvesting conditions by a decentralized mechanism at different biomass conditions for Case 2 is summarized in Table 2. The mechanism specifies TAC and quota shares allocations for a given biomass condition and total fishing mortality rate for each mature stock at MSY. For example, given that biomass condition is  $\mu = w_1 / s_1 < w_2 / s_2$ , and MSY harvesting conditions are such that  $f_2 = 1$  and  $f^* \leq f_1 < 1$  (Case 2.2.b), then the management system sets  $TAC = f_1 w_1 X_1 + w_2 X_2$  and specifies a quota shares allocation such that  $\alpha_1 \in \left[ \frac{[w_2 X_2 - j_2 TAC]}{(1 - j_2) TAC}, \frac{w_2 X_2}{(1 + j_2) TAC} \right]$  and  $\alpha_2 = 1 - \alpha_1$ .

**Table 1** Quota shares allocation mechanism for Case 2

	Biomass conditions	Total fishing mortality rates at MSY	Quota shares allocations
Case 2	i. $TAC = f_2 w_2 X_2 < w_2 X_2$		
	$w_1/s_1 < \mu = w_2/s_2$	$f_1 = 0, 0 < f_2 < 1$	$\alpha_1 = 1, \alpha_2 = 0$
	ii. $w_2 X_2 \leq TAC = f_1 w_1 X_1 + w_2 X_2 < w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$		
	$w_1/s_1 < \mu < w_2/s_2$	$f_1 = 0, f_2 = 1$	$\alpha_1 = 1, \alpha_2 = 0$
	$\mu = w_1/s_1$	$f^* \leq f_1 < 1$	$\frac{[w_2 X_2 - j_2 TAC]}{(1 - j_2) TAC} \leq \alpha_1 \leq \frac{w_2 X_2}{(1 + j_2) TAC}, \alpha_2 = 1 - \alpha_1$
	$\mu < w_2/s_2$	$f_2 = 1$	
	$j_1 = 1$	$0 < f_1 < f^* < 1$	$\alpha_1 = \frac{[w_2 X_2 - j_2 TAC]}{(1 - j_2) TAC}, \alpha_2 = 1 - \alpha_1$
	$0.5 < j_2 < 1$	$f_2 = 1$	
iii. $w_2 X_2 + [(1 - j_2) / j_2] w_2 X_2 \leq TAC = f_1 w_1 X_1 + w_2 X_2$			
$\mu = w_1/s_1 < w_2/s_2$	$0 < f_1 < 1,$	$0 \leq \alpha_1 \leq w_2 X_2 / (1 + j_2) TAC$	
	$f_2 = 1$	$\alpha_2 = 1 - \alpha_1$	

*Result 1: In a fishery consisting of two fleets characterized by their fishing technologies such that fleet 1 has perfect fishing selectivity and fleet 2 has imperfect fishing selectivity, allocation of quota shares does matter to implement MSY harvesting conditions.*

**Case 4:** Fleets have imperfect fishing selectivity ( $j_1 < 1$  and  $j_2 < 1$ ).

Case 4.1: MSY fishing mortalities are  $0 < f_1 < 1$  and  $f_2 = 1$  such that  $w_2 X_2 \leq TAC = f_1 w_1 X_1 + w_2 X_2 < \min \{ w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2, w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2 \}$ . Then, MSY cannot be implemented since the old mature fish age class cannot be fully harvested due to the fact that TAC is set below the cut-off levels. The weight of old mature fish harvest is equal to  $j_1 \alpha_1 TAC + j_2 \alpha_2 TAC = h_1^2 w_2 X_2 + h_2^2 w_2 X_2 < w_2 X_2$  and young mature fish harvest is equal to  $f_1 w_1 X_1$  at the first fishing day. In the second fishing day, fleets harvest more young mature fish

but then total harvest is more than the total harvest of young mature fish at MSY. As a result, it is not possible to implement MSY harvesting conditions by a decentralized mechanism for this case.

Case 4.2: MSY fishing mortalities are  $0 < f_1 < 1$  and  $f_2 = 1$  such that  $w_2 X_2 + [(1 - j_1) / j_1] w_2 X_2 \leq TAC = f_1 w_1 X_1 + w_2 X_2 < w_2 X_2 + [(1 - j_2) / j_2] w_2 X_2$ . Under these conditions, MSY can be implemented if all quota shares are assigned to fleet 1. In such a case, fleet 1 harvests  $w_2 X_2$  tonnes of old mature fish in the first fishing day and  $f_1 w_1 X_1$  tonnes of young mature fish in two fishing days, where  $f_1 w_1 X_1 = \varepsilon + [(1 - j_1) / j_1] w_2 X_2$  and  $\varepsilon$  is equal to the weight of young mature fish harvested by fleet 1 at the second fishing day to fulfill its remaining quotas after the old mature fish population is fully harvested in the first fishing day ( $0 \leq \varepsilon < \{[(1 - j_2) / j_2] w_2 X_2 - [(1 - j_1) / j_1] w_2 X_2\}$ ). At the other corner solution,  $\alpha_2 = 1$  and  $\alpha_1 = 0$ , fleet 2 fulfills its quota in the first fishing day before the old mature fish age class is fully harvested. Hence, MSY cannot be implemented by a decentralized mechanism using  $\alpha_2 = 1$  and  $\alpha_1 = 0$ . As a result, there is a lower bound for  $\alpha_1$ . Let's check for the lower bound of quota shares that can be assigned to fleet 1,  $\underline{\alpha}_1$ .

For each  $\alpha_1 \in [\underline{\alpha}_1, 1]$ , we can find constants  $\theta$  and  $\psi$  such that  $TAC = w_2 X_2 + \alpha_1 w_2 X_2 [(1 - j_1) / j_1] + \theta(\alpha_1) + (1 - \alpha_1) w_2 X_2 [(1 - j_2) / j_2] + \psi(1 - \alpha_1)$ . Both fleets may fulfill their remaining quotas by capturing young mature fish in the second fishing day after the old mature fish age class is fully harvested in the first fishing day. Thus,  $\theta(\alpha_1) \geq 0$  and  $\psi(1 - \alpha_1) \geq 0$ . If  $\psi = 0$ , then  $\alpha'_1 = \frac{(w_2 X_2 - j_2 TAC) j_1}{(j_1 - j_2) w_2 X_2}$ . For a given  $\alpha_1$ ,  $h_1^2 w_2 X_2 = \alpha_1 w_2 X_2$ ,  $h_2^2 w_2 X_2 = (1 - \alpha_1) w_2 X_2$ ,  $b_1^1 w_1 X_1 = \alpha_1 w_2 X_2 [(1 - j_1) / j_1] + \theta(\alpha_1)$ ,  $b_2^1 w_1 X_1 = (1 - \alpha_1) w_2 X_2 [(1 - j_2) / j_2] + \psi(1 - \alpha_1)$ . This implies that  $\alpha_1 \geq \alpha'_1$  since  $\theta, \psi \geq 0$  and  $j_2 > j_1$ . Therefore,  $\underline{\alpha}_1 = \alpha'_1$  and  $j_1 \underline{\alpha}_1 TAC = \alpha'_1 w_2 X_2$ . Then,  $\underline{\alpha}_1 = \frac{[w_2 X_2 - j_2 TAC]}{(j_1 - j_2) TAC}$  to implement MSY harvesting conditions.

Case 4.3: MSY fishing mortalities are  $0 < f_1 < 1$  and  $f_2 = 1$  such that  $TAC \geq \max \{w_2 X_2 + [(1 - j_1) / j_1] w_2 X_2, w_2 X_2 + [(1 - j_2) / j_2] w_2 X_2\}$ . Total harvest of old mature fish is always equal to  $w_2 X_2$  since TAC is set higher than or equal to the maximum of two cut-off

levels. Furthermore, both fleets harvest young mature fish to fulfill their quotas after the old mature fish stock is fully harvested in the first fishing day since  $f_1 w_1 X_1 \geq [(1 - j_1)/j_1] w_2 X_2$  and  $f_1 w_1 X_1 \geq [(1 - j_2)/j_2] w_2 X_2$ . As a result, the total harvest of young mature fish is equal to  $f_1 w_1 X_1$ . Therefore, MSY can be implemented for all quota shares allocations.

Possible quota shares allocations to implement MSY harvesting conditions at different biomass conditions for Case 4 is summarized in Table 2. The mechanism or management system specifies TAC and quota shares allocations for a given biomass condition and total fishing mortality rates at MSY. For example, if biomass condition is  $\mu = w_1/s_1 < w_2/s_2$ , and MSY harvesting conditions are calculated such that  $f_2 = 1$ ,  $0 < f_1 < 1$  and  $f_1 w_1 X_1 + w_2 X_2 \in [w_2 X_2 + w_2 X_2 [(1 - j_1) / j_1], w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2)$ , Case 4.2, then the management system sets  $TAC = f_1 w_1 X_1 + w_2 X_2$  and specifies a quota shares allocation such that  $\alpha_1 \in \left[ \frac{[w_2 X_2 - j_2 TAC]}{(j_1 - j_2) TAC}, 1 \right]$  and  $\alpha_2 = 1 - \alpha_1$ .

**Table 2** Quota shares allocation mechanism for Case 4

	Biomass conditions	Total Fishing mortality rates at MSY	Quota shares allocations
Case 4	i. $w_2 X_2 < TAC = f_1 w_1 X_1 + w_2 X_2 < \min \{ w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2, w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2 \}$		
	$\mu = w_1/s_1 < w_2/s_2$	$0 < f_1 < 1, f_2 = 1$	MSY is not achieved
	ii. $w_2 X_2 + w_2 X_2 [(1 - j_1) / j_1] \leq TAC = f_1 w_1 X_1 + w_2 X_2$ $TAC = f_1 w_1 X_1 + w_2 X_2 < w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$		
	$\mu = w_1/s_1 < w_2/s_2$	$0 < f_1 < 1$ $f_2 = 1$	$\frac{[w_2 X_2 - j_2 TAC]}{(j_1 - j_2) TAC} \leq \alpha_1 \leq 1$ $\alpha_2 = 1 - \alpha_1$
	$0.5 < j_1 < 1$ $0.5 < j_2 < 1$		
	iii. $TAC = f_1 w_1 X_1 + w_2 X_2 \geq \max \{ w_2 X_2 + [(1 - j_1)/j_1] w_2 X_2, w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2 \}$		
	$\mu = w_1/s_1 < w_2/s_2$	$0 < f_1 < 1, f_2 = 1$	$\{ \alpha \mid \alpha_i \in [0,1] \wedge \alpha_1 + \alpha_2 = 1 \}$

The following result can now be stated for this case in the light of above findings.

*Result 2: In a fishery consisting of two fleets with imperfect fishing selectivity, the allocation of quota shares, which depends on the age distribution of the fish population and fishing technologies, does matter to implement MSY harvesting conditions.*

## 5 Numerical Illustration

A numerical example is given to clarify our solution to the implementation problem of MSY harvesting conditions. The following random data set below, not directly related to any particular fisheries, is used for this illustration.

**Table 3** Fishery with a single fish stock

Parameter	Description	Values
$w_1$	Weight for the young mature fish	3.0 (kg/per fish)
$w_2$	Weight for the old mature fish	5.0 (kg/per fish)
$q_1^2$	Catchability coefficient (fleet 1)	0.04
$q_1^1$	Bycatch coefficient (fleet 1)	0
$q_2^2$	Catchability coefficient (fleet 2)	0.05
$q_2^1$	Bycatch coefficient (fleet 2)	0.01
$f_1$	Fishing mortality rate for young mature fish (at MSY) <sup>11</sup>	0.1
$f_2$	Fishing mortality rate for old mature fish (at MSY)	1
$X_1$	Total population of young mature fish (at MSY)	100,000
$X_2$	Total population of old mature fish (at MSY)	45,000

The total biomass for each age class can now be calculated since the total population and average weight per fish values are given. Furthermore, by using Eq. 6, the TAC is calculated using MSY fishing mortalities derived from the overall yield optimization problem:

<sup>11</sup> The endogenous variables  $f_1, f_2, X_1$  and  $X_2$  are determined through optimization process defined in Section 3 given that  $s_0 = 0.2, s_1 = 0.5, s_2 = 0.8$  and Beverton-Holt recruitment parameters:  $a = 10^6, b = 1.2 \times 10^6$  and  $\beta = 1.2$ .

$$TAC = f_1 w_1 X_1 + f_2 w_2 X_2 = 255 \text{ tonnes.}$$

As being one of the key variables of the paper, fishing technologies at the first fishing day are calculated as follows:

$$j_1 = \frac{q_1^2 w_2 X_2}{q_1^2 w_2 X_2 + q_1^1 w_1 X_1} = 1,$$

$$j_2 = \frac{q_2^2 w_2 X_2}{q_2^2 w_2 X_2 + q_2^1 w_1 X_1} \cong 0.8.$$

Given the fact that the only fleet 2 has imperfect fishing selectivity, it can be deduced that there is only one cut-off level for the TAC that can be written as:

$$w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2 = 281.25 \text{ tonnes.}^{12}$$

TAC is higher than the total weight of old mature fish ( $w_2 X_2$ ) and less than the cut-off level of  $w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$ . Hence TAC is at a level satisfying the condition of  $2w_2 X_2/(1 + j_2) \leq TAC < w_2 X_2 + [(1 - j_2)/j_2] w_2 X_2$ . Note also that the critical fishing mortality rate for the young mature fish is  $f^* \cong 0.08 < f_1 = 0.1$ . The solution for this case was found as the following (Case 2.2.b):

$$\frac{[w_2 X_2 - j_2 TAC]}{(1 - j_2)TAC} \leq \alpha_1 \leq \frac{w_2 X_2}{(1 + j_2)TAC}$$

$$\alpha_2 = 1 - \alpha_1.$$

The possible quota shares computed using the above equations are,  $\frac{21}{51} (\cong 0.4118) \leq \alpha_1 \leq \frac{225}{459} (\cong 0.4902)$  and  $\frac{30}{51} (\cong 0.5098) \leq \alpha_2 \leq \frac{234}{459} (\cong 0.5882)$  such that  $\alpha_1 + \alpha_2 = 1$ .

Note that equal quota shares,  $\alpha_1 = \alpha_2 = 0.5$ , cannot be a solution for this case. At this quota shares allocation, the total harvest composition is  $h_1^2 = 125$  tonnes,  $b_1^1 = 0$ ,  $h_2^2 = 100$  tonnes, and  $b_2^1 = 27.5$  tonnes. Fleet 2 harvests 100 tonnes of old mature fish and 25 tonnes of young mature fish due to imperfect fishing technology ( $j_2 = 0.8$ ) and fleet 1 harvests 125 tonnes of old mature fish at the the first fishing day. All old mature fish are harvested at the first fishing day. Fleet 2's degree of

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<sup>12</sup> This is the minimum level of TAC to be able to assign all fishing rights to fleet 2 to implement MSY at the first fishing day.

selection is zero at the second fishing day. Fleet 2 fulfills its quota by harvesting 2.5 additional tonnes of young mature fish at the second fishing day. Fleet 1 cannot fulfill its quota since there is not any old mature fish at the second day. Fishing stops at the end of the second fishing day. Thus, the total biomass harvest  $H_1 + H_2 = 252.5 \neq TAC = 255$  tonnes, and equal allocation of quota shares cannot solve the implementation problem.

## 6 Conclusion

In the reform process of CFP, the EU is seeking for an economically and socially viable, well-designed management system for EU fisheries (EC 2011). In this regard, the EU promotes measures for implementing MSY. The process is under way in this direction as pointed by Cardinale et al. (2013), but the EU will not be able to achieve the MSY target for all economically valuable fish stocks by 2015 if the current trends continue (Froese and Proelß 2010). This paper analyzes the problem of designing quota shares allocation mechanisms or management systems to implement MSY harvesting conditions. It is shown that not only biological limitations due to the age structure of different fish populations but also composition of fisheries and different fishing technologies should be taken into consideration in the determination process of maximum catch limits. Furthermore, the analysis shows that the determination process of individual quota shares is highly dependent on MSY harvesting conditions. Thus, one of the important policy implications of the analysis is that fishing technologies and TAC levels should be analyzed together while distributing fishing quota shares (or assigning property rights).

In the EU, TACs are determined at the Union level and distributed to the EU countries based on the principle of 'relative stability'.<sup>13</sup> Member States use different management systems to allocate these assigned national quotas to domestic fleets. The allocation is usually determined by grandfathering, a proportional rule based on historical catches of existing fleets (Anderson et al. 2011). It is also possible to use auctions to determine the allocation of quota shares in a Member

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<sup>13</sup> See the European Commission fisheries webpage, [http://ec.europa.eu/fisheries/index\\_en.htm](http://ec.europa.eu/fisheries/index_en.htm), for more on EU fishing rules. See also Frost and Andersen (2006) for more details about the EU fisheries policy.

State. This paper shows that allocating quota shares in a Member State according to this history depended proportional distribution rule or auctioning may not provide economically and biologically viable solutions to implement MSY since these allocation rules do not depend on the age distribution of a fish population and fishing technology composition of domestic fleets. Therefore, main policy suggestion of this study is that the technological structure of the fishing industry and the biological structure of fish populations should be considered in the process of distributing national quotas to implement MSY.

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