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Abstract: One of the main goals stated in the proposals for the Common Fisheries Policy (CFP) reform was achieving maximum sustainable yield (MSY) for all European fisheries. In this paper, we propose a fishing rights allocation mechanism or management system, which specifies catch limits for individual fishing fleets 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: Bioeconomics; Mechanism design; Fisheries management; Age-structured population model; 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 has become prominent as one of the main topics within the scope of CFP reform proposals (EC 2009). 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. These management systems define fishing rights or total allowable catch (TAC) for certain fish stocks usually defined in tonnes, and allocate these rights to fishermen as individual fishing rights or quotas. A quota for a fish stock specifies the maximum allowable catch or harvest limit in terms of total weight for a fleet. To address our main 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. A quota shares allocation mechanism defines individual quota shares. A quota share is a proportion of TAC and specifies the owner's share of a given fish stock.

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 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 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 have a higher market price. This selection for two different mature age groups can be perfect or imperfect depending on different fishing gear types or technologies used by fleets. It is also assumed, for simplicity, that juveniles are not subject to harvesting. 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.

There is a vast literature on age-structured fish population models. In recent years, Clark (2010), Quaas et al. (2013), Skonhoft et al. (2012), Tahvonen (2009a,b;2010) and Holden and Conrad (2015), 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), Björndal 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 Skonhoft et al. (2012) has 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 Skonhoft 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 using quotas is not the main purpose of their paper.

The aim of this study is to investigate the allocation problem of fishing quota shares to implement the MSY solution concept by a mechanism or management system. MSY harvesting conditions specify fishing mortalities for each age class by maximizing overall yield. Finding optimal harvest policy is a centralized problem from a viewpoint of a social planner and related to sustainable use of the biological resource. We propose a management system (or quota allocation mechanism) to achieve the MSY harvesting policy. The fishery management system, by setting TAC and specifying individual quotas, produces total biomass yield that is identical to MSY. We also investigate the implications of different fishing technologies on the design of management systems. Within this framework, we propose a new quota shares allocation mechanism and determine possible quota shares allocations to solve the 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, as 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.

The rest of the paper is organized as follows. Section 2 introduces the model and provides 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 Age-Structured Population Model

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. 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 assumed 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 during any season t is defined as follows: Juveniles, $X_{0,t}$ (age < 1), Young matures, $X_{1,t}$ (1 ≤ age < 2), Old matures, $X_{2,t}$ (2 ≤ 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 during season t is:

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

The number of recruits depends on the abundance of old mature and young mature fish and parameters of a, b and β. 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 during 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:

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

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

In this study, it is assumed 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. (4) is the recruitment constraint and (5) is the spawning constraint.

$$X_1 = s_0 R(X_1, X_2), \quad (4)$$

$$X_2 = s_1 (1 - f_1) X_1 + s_2 (1 - f_2) X_2. \quad (5)$$

The population model developed by Skonhoft et al. (2012) is described so far. In what follows, maximum sustainable yield harvesting conditions and the implementation problem using quotas are defined under given age-structured population dynamics.

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 (Reed 1980; Skonhoft et al. 2012). This section is presented for completeness of the paper. 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:

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

The biological constraints for the total harvest maximization problem are (4) and (5). 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 (6) subject to (4) and (5).

Using the Karush-Kuhn-Tucker theorem, Skonhoft et al. (2012) showed, assuming $w_2/s_2 > w_1/s_1$, that 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 $f_1 = 0$.

4 Quota Implementation of MSY

The implementation problem is to find a policy instrument (or management system) such that outcomes of the instrument is identical to MSY harvesting conditions. We refer the reader to Jackson (2001) for more details about the general implementation problem in different economic settings. The main 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. To find the possible allocations of quota shares we need to define the important details related to fishing fleets. The problem to find MSY harvesting policy is a centralized optimization problem and the information related to fishing vessels is not required for this problem. To use a management system or to be able to assign individual quotas to fishing vessels, we need to make assumptions related to number of fishing vessels, fishing technologies, fishing days and catch compositions of fishing vessels for mathematical formulation of the fishery and fishing behavior. These assumptions can alter the assignment process of individual quota shares and outcomes of our quota shares allocation mechanism. This actually validates the main policy implication of this article, technological structure of fisheries and biological structure of fish populations should be considered in defining individual fishing rights.

4.1 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 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; Squires and Vestergaard 2013). 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. We also assume that each fleet has one type of fishing gear and it is impossible to change the gear during 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 i is denoted as j_i. This degree of selection for fishable age classes can depend on gear types used by fleets (Madsen 2007). 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 $j_i x 100$ percent of H_i, and exploitation rate of young mature fish is equal to $(1 - j_i) x 100$ 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 harvests 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 ($j_i > 0.5$ 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. 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.

These assumptions are also biologically reasonable. For example, the population for the North Sea cod is dominated by the age (or year) classes one and two. Estimated average values for cod population year-class abundance are 273 million for age class one (wet weight 32 grams), 84.3 million for age class two (wet weight 466 grams), 24.8 million for age class three (wet weight 1856 grams), 8.86 million for age class four (wet weight 3980 grams), 3.56 million for age class five (wet weight 5990 grams), 1.44 million for age class six (wet weight 8212 grams), 0.60 million for age class seven (wet weight 9420 grams), 0.27 million for age class eight (wet weight 10622 grams), 0.12 million for age class two (wet weight 11543 grams), 0.079 million for age class two (wet weight 12235 grams) (Hansson et al. 1996). Given that North Sea cod usually reach maturity at the age of 3-5 years, we can label age classes 3 to 5 as young mature fish and age classes 6 to 10 as old mature fish. Then, the total biomass of young mature fish is $w_1 X_1 = 102616$ tonnes, and the total biomass of old mature fish is $w_2 X_2 = 22696.95$ tonnes.

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. In Case 1, fleet 1 has perfect fishing selectivity ($j_1 = 1$), and fleet 2 has imperfect fishing selectivity ($0.5 < j_2 < 1$). There are two fleets having imperfect fishing selectivity in Case 2 ($0.5 < j_1 < 1$ and $0.5 < j_2 < 1$). 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, Case 4 refers to a fishery with two identical fleets having perfect fishing selectivity ($j_1 = j_2 = 1$). We consider only the most interesting cases, Case 1 and Case 2, in this paper. We refer the reader to (Kanik and Kucuksenel 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 Skonhoft 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 specially designed mesh and hence fish larger than a specific size can be harvested in trawls (Millar and Fryer 1999).

4.2 Fishing Fleets: Fishing Days

We assume that fishing can occur on several days during a given season t. On the first fishing day, two fleets *simultaneously* exert fishing effort and harvest the same total weight of fish on the first fishing day due to identical capacity of fishing vessels. 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. If there is a fleet whose quota is not reached or fulfilled, then fishing continues on the second fishing day. Otherwise, fleets stop fishing and fishery is closed for the season t. If there are two fleets on the second day, then the second day is identical to the first day. If there is one fleet on the second day, the fleet continues fishing and fulfills its quota according to its updated utilization of the fishing technology 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 on the second day and hence the utilization of the fishing technology changes on the second day unless fishing technology is perfect on the first fishing day. If all old mature fish are harvested on the first day, then utilization of fishing technology is updated to zero for a fleet with imperfect fishing technology on the first fishing day. Thus, the 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 on the previous day. This is to say that fishing days can end even though TAC is not reached in Case 1. The reason is that it is not possible for a fleet with perfect selectivity to fulfill its remaining quota on a given day if all old mature fish are harvested on the previous fishing day. This is due to the assumption that the fleet has one type of fishing gear (mesh size is large enough for perfect fishing selectivity) and it is impossible to change the gear during a given season. See the last paragraph in Section 5 for an illustration of this case.

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 on each fishing day, and hence fishing stops after a finite number of fishing days. If there is only one fleet on the second fishing day and all old mature is harvested on 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 on each fishing days rules out this possibility.

4.3 Fishing Fleets: Catch Compositions

We first look at the the simplest case of our model in which all quota is assigned to a fleet (a corner solution). 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 $\alpha_2 = 0$. Assuming 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. 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 on the first fishing day, the total bycatch of young mature age class is equal to $[(1 - j_1)/j_1]\, w_2\, X_2$. Since fleet 1's quota is exhausted on 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 on the first day by exerting fishing effort $E_1 = 1/q_1^2$. Individual quota is not exhausted and fishing continues on the second day. Moreover, all old mature fish are harvested on the first day.

On the second day, the fleet exerts fishing effort to fulfill its quota with only young mature fish and catches $100 - 1.25 w_2 X_2$ 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 harvesting young mature fish on the second day under the assumption that fishermen are nonsatiated. 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 whenever possible harvesting fish till the fleet fulfills its assigned quota independent of the cost structure of fishing. It may be impossible for a fleet with perfect fishing technology to fulfill its quota and fishing days can end even though TAC is not reached in Case 1. Fleets are quota-filling whenever possible and fishing activity does not stop unless TAC is reached or it is impossible to fulfill TAC due to perfect fishing technology. This implies that 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 possible solutions where quota shares are such that $\alpha_1 > 0$ and $\alpha_2 > 0$ (an interior solution). In Case 1, if fleet 1 harvests n tonnes of old mature fish on 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 on the second day since all old mature fish would be harvested on the first day. Therefore, fleet 2 harvests $\alpha_2 TAC - n$ additional tonnes of young mature fish on 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 on the second day and harvests both age classes according to its fishing technology and assigned quota level. The total biomass of old mature stock on the second fishing day is $w_2 X_2 - n - j_2 n$ tonnes and the total biomass of young mature stock on the second day is $w_1 X_1 - (1-j_2)n$. Fleet 2 harvests all remaining old mature fish on the second day to minimize the number of fishing days. The degree of selection is $\frac{q_2^2(w_2 X_2 - n - j_2 n)}{q_2^2(w_2 X_2 - n - j_2 n) + q_2^1(w_1 X_1 - (1-j_2)n)}$ on the second day. If its quota is still not fulfilled, then the fleet fulfills its remaining quota with young mature fish on the third fishing day (the degree of selection is zero), and fishing season ends. If $n = \alpha_2 TAC < \alpha_1 TAC$, then fleet 1 fulfills its remaining quota with old mature fish on 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 on the second day.

In Case 2, for example, if fleet 1 harvests $j_1 n$ tonnes of old mature fish and $(1 - j_1)n$ tonnes of young mature fish during 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 on 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 1.

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 on 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:

$$\alpha_i\, TAC = h_i^2\, w_2\, X_2 + b_i^1\, w_1\, X_1, \; \textstyle\sum_{i=1,2} \alpha_i = 1 \tag{7}$$

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:

$$h_1^2\, w_2\, X_2 = j_1\, \alpha_1\, TAC > b_1^1\, w_1\, X_1 = (1 - j_1)\, \alpha_1\, TAC, \tag{8}$$

$$h_2^2\, w_2\, X_2 = j_2\, \alpha_2\, TAC > b_2^1\, w_1\, X_1 = (1 - j_2)\, \alpha_2\, TAC. \tag{9}$$

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 of fishing days can also be more than one to fulfill the assigned quota allotment.

4.4 Results

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

$$TAC = f_1\, w_1\, X_1 + f_2\, w_2\, X_2. \tag{10}$$

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 that are compatible with the fishing technologies 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. Note that fishing activity occurs after spawning and before natural mortality, and hence $0 \leq f_1 < 1$ and $f_2 = 1$ can be a possible solution.

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

Possible allocations of quota shares to implement MSY harvesting conditions at different biomass conditions for Case 1 are characterized in the following propositions. The mechanism specifies TAC and quota shares allocations for a given biomass condition and total fishing mortality rate for each mature stock at MSY.

Proposition 1.1: If MSY fishing mortalities are such that $f_1 = 0$ and $0 < f_2 \leq 1$, then $TAC = f_2\, w_2\, X_2$, and MSY can be achieved only for a quota share $\alpha_1 = 1$ and $\alpha_2 = 0$.

Proof: Using (10), $TAC = f_2\, w_2\, X_2$. 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 $\alpha_2 = 0$. MSY is implemented on the first fishing day and Fleet 2 should be kept outside the allocation process of fishing rights to implement MSY harvesting conditions. □

Proposition 1.2: If MSY fishing mortalities are $0 < f_1 < 1$ and $f_2 = 1$ such that (i) $\frac{w_2 X_2 (1-j_2)}{(1+j_2)} \leq f_1\, w_1\, X_1 < [(1-j_2)/j_2]\, w_2\, X_2$, or (ii) $f_1\, w_1\, X_1 < \frac{w_2 X_2 (1-j_2)}{(1+j_2)}$, then $TAC\; = f_1\, w_1\, X_1 + w_2\, X_2$, and MSY can be achieved for any quota shares such that for (i) $\alpha_1 \in [\underline{\alpha}_1, \overline{\alpha}_1]$ and $\alpha_2 = 1 - \alpha_1$; for (ii) $\alpha_1 = \underline{\alpha}_1$ and $\alpha_2 = 1 - \alpha_1$, where $\underline{\alpha}_1 = (w_2 X_2 - j_2 TAC)/[TAC(1-j_2)]$ and $\overline{\alpha}_1 = \frac{w_2 X_2}{(1+j_2)TAC}$.

Proof: Given that (i) holds, $w_2\, X_2 < TAC = f_1\, w_1\, X_1 + w_2\, X_2 < w_2\, X_2 + [(1-j_2)/j_2]\, w_2\, X_2$. 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 on 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 $\alpha_1 \in [\underline{\alpha}_1, \overline{\alpha}_1]$ 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 on 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 on the first fishing day, and fleet 2 tries to fulfill its remaining quota with old mature fish and young mature fish on the second fishing day since $\alpha_2 TAC \geq n$. Total biomass harvest on the first fishing day is equal to $2n$. The total biomass of old mature fish on the second day is $w_2 X_2 - (1+j_2)n$ and the total biomass of young mature fish is

$w_1X_1 - (1-j_2)n$. The degree of selection for fleet 2 is equal to $\frac{q_2^2(w_2X_2-(1+j_2)n)}{q_2^2(w_2X_2-(1+j_2)n)+q_2^1(w_1X_1-(1-j_2)n)}$ on the second fishing day since relative abundance of young mature fish changes. Fleet 2 harvests all of remaining old mature fish on 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 on the third fishing day. Moreover, $2\,w_2X_2/(1+j_2) \le TAC$ since $\alpha_2 TAC \ge n$. Therefore, different quota shares allocations produce the same TAC, which is equal to $f_1w_1X_1 + w_2X_2$, if $f_1 \ge \frac{w_2X_2(1-j_2)}{w_1X_1(1+j_2)} = f^*$.

At $\overline{\alpha}_1$, fleet 2 should fulfill its quota by harvesting only young mature fish on the second fishing day after all old mature fish are harvested on the first fishing day. This implies that $h_2^2\,w_2\,X_2$ should be at the minimum possible level such that $h_2^2\,w_2X_2 = w_2X_2 - n = j_2n$ and $n = \overline{\alpha}_1\,TAC = w_2X_2/(1+j_2)$. Therefore, $\overline{\alpha}_1 = \frac{w_2X_2}{(1+j_2)TAC}$. At $\underline{\alpha}_1$, fleet 2 should harvest the maximum possible weight of old mature fish on the first fishing day besides its total young mature fish harvest is $f_1w_1X_1$ after three fishing days at most. This is only possible if $\left(1-\underline{\alpha}_1\right) TAC\,(1-j_2) = f_1w_1X_1$. Thus, $\underline{\alpha}_1 = (w_2X_2 - j_2TAC)/[TAC(1-j_2)]$.

Now, suppose that $h_2^2w_2X_2 = w_2X_2 - n < j_2n$. This is only possible if fleet 2 fulfills its quota on the first fishing day and fleet 1 fulfills its remaining quota with old mature fish on the second fishing day. That is, biomass condition (ii) holds and $w_2X_2 < TAC < 2w_2X_2/(1+j_2)$. Moreover, due to fleet 1's fishing technology, $b_2^1w_1X_1 = f_1w_1X_1 = [(1-j_2)/j_2]\,(w_2X_2 - n) = (1-\alpha_1)\,TAC$. This implies that $\alpha_1 = \underline{\alpha}_1 = (w_2X_2 - j_2TAC)/[(1-j_2)TAC]$. □

Proposition 1.3: If MSY fishing mortalities are $0 < f_1 < 1$ and $f_2 = 1$ such that $f_1\,w_1\,X_1 \ge [(1-j_2)/j_2]\,w_2\,X_2$, then $TAC = f_1\,w_1\,X_1 + w_2\,X_2$, and MSY can be achieved for quota shares such that $\alpha_1 \in [0, \overline{\alpha}_1]$ and $\alpha_2 = 1 - \alpha_1$, where $\overline{\alpha}_1 = w_2\,X_2/\,(1+j_2)\,TAC$.

Proof: Under these conditions, $w_2\,X_2 + [(1-j_2)\,/\,j_2]\,w_2\,X_2 \le TAC = f_1\,w_1\,X_1 + f_2\,w_2\,X_2$. 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 on the second fishing day with young mature fish after all old mature fish are harvested on 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 α_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 α_1 level, $\overline{\alpha}_1$. Now, possible interior solutions such that $\alpha_1 \epsilon [0, \overline{\alpha}_1]$ and $\alpha_2 = 1 - \alpha_1 > 0$ 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 on 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 on 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 on 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 $\overline{\alpha}_1$, we have $h_1^2 w_2\, X_2 = n = \overline{\alpha}_1 TAC$, $h_2^2 w_2\, X_2 = n j_2$ 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. □

***Case 2**: Fleets have imperfect fishing selectivity* ($j_1 < 1 \; and \; j_2 < 1$).

Proposition 2.1: If MSY fishing mortalities are $0 < f_1 < 1$ and $f_2 = 1$ such that $f_1\, w_1\, X_1 < \min\{\, [(1 - j_1)/j_1] w_2\, X_2, [(1 - j_2)/j_2] w_2\, X_2\}$, then $TAC = f_1\, w_1\, X_1 +\, w_2\, X_2$, and MSY cannot be achieved for any quota shares.

Proof: 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 $f_1\, w_1\, X_1$ on the first fishing day. On the second fishing day, fleets harvest old mature fish and hence young mature fish due to imperfect selectivity to fulfill their quotas. Then, total harvest of young mature fish is more than the total harvest of young mature fish at MSY. As a result, it is not possible to implement MSY harvesting conditions using quotas. □

Proposition 2.2: If MSY fishing mortalities are $0 < f_1 < 1$ and $f_2 = 1$ such that $[(1-j_1)/j_1]w_2\,X_2 \leq f_1\,w_1\,X_1 < [(1-j_2)/j_2]w_2\,X_2$, then $TAC = f_1\,w_1\,X_1 + w_2\,X_2$, and MSY can be achieved for any quota shares such that $\alpha_1 \in [\underline{\alpha}_1, 1]$ and $\alpha_2 = 1-\alpha_1$ where $\underline{\alpha}_1 = \frac{[\mathrm{w}_2\,\mathrm{X}_2 - \mathrm{j}_2\mathrm{TAC}]}{(j_1-\mathrm{j}_2)\mathrm{TAC}}$.

Proof: Under these conditions, $w_2\,X_2 + [(1-j_1)\,/\,j_1]\;w_2\,X_2\; \leq TAC = f_1\,w_1\,X_1 + \;w_2\,X_2\; < w_2\,X_2 + [(1-j_2)/j_2]\;w_2\,X_2$. 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 on 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 ε is equal to the weight of young mature fish harvested by fleet 1 on the second fishing day to fulfill its remaining quotas after the old mature fish population is fully harvested on 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 on the first fishing day before the old mature fish age class is fully harvested. Hence, MSY cannot be implemented using $\alpha_2 = 1$ and $\alpha_1 = 0$. As a result, there is a lower bound for α_1. For each $\alpha_1 \in [\underline{\alpha}_1, 1]$, we can find constants θ and ψ 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 catching young mature fish on the second fishing day after the old mature fish age class is fully harvested on the first fishing day. Thus, $\theta(\alpha_1) \geq 0$ and $\psi(1-\alpha_1) \geq 0$. If $= \psi = 0$, then $\alpha_1' = \frac{(w_2X_2 - j_2TAC)j_1}{(j_1-j_2)w_2\,X_2}$. For a given α_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, $\underline{\alpha}_1 = \frac{[\mathrm{w}_2\,\mathrm{X}_2 - \mathrm{j}_2\mathrm{TAC}]}{(j_1-\mathrm{j}_2)\mathrm{TAC}}$ to implement MSY harvesting conditions. □

Proposition 2.3: If MSY fishing mortalities are $0 < f_1 < 1$ and $f_2 = 1$ such that $f_1\,w_1\,X_1 \geq \max\{[(1-j_1)/j_1]w_2\,X_2, [(1-j_2)/j_2]w_2\,X_2\}$, then $TAC = f_1\,w_1\,X_1 + w_2\,X_2$, and MSY can be achieved for any possible quota shares $\alpha_1 \in [0,1]$ and $\alpha_2 = 1-\alpha_1$.

Proof: Total harvest of old mature fish is always equal to $w_2\, X_2$ in all possible quota shares 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 on 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 $f_1\, w_1\, X_1$ for all possible quota shares. Therefore, MSY can be implemented for all $\alpha_1 \in [0,1]$ and $\alpha_2 = 1 - \alpha_1$. □

5 Numerical Illustration

A numerical example is given to clarify our solution to the implementation problem of MSY harvesting conditions. The arbitrary parameter values in Table 1, not directly related to any particular fisheries, are used for this illustration. The values of the endogenous variables f_1, f_2, X_1, and X_2 are calculated using the optimal harvest policy 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 $\beta = 1.2$.

Table 1 Fishery with a single age-structures fish stock

Parameter	Description	Values
$\boldsymbol{w_1}$	Weight for the young mature fish	3.0 (kg/per fish)
$\boldsymbol{w_2}$	Weight for the old mature fish	5.0 (kg/per fish)
$\boldsymbol{q_1^2}$	Catchability coefficient (fleet 1)	0.04
$\boldsymbol{q_1^1}$	Bycatch coefficient (fleet 1)	0
$\boldsymbol{q_2^2}$	Catchability coefficient (fleet 2)	0.05
$\boldsymbol{q_2^1}$	Bycatch coefficient (fleet 2)	0.01
$\boldsymbol{f_1}$	Fishing mortality rate for young mature fish (at MSY)	0.1
$\boldsymbol{f_2}$	Fishing mortality rate for old mature fish (at MSY)	1
$\boldsymbol{X_1}$	Total population of young mature fish (at MSY)	100,000
$\boldsymbol{X_2}$	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 (10), the TAC is calculated using MSY fishing mortalities derived from the overall yield optimization problem:

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

As being one of the key variables of the paper, fishing technologies on 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:

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

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 $2\mathrm{w}_2\, \mathrm{X}_2/(1 + \mathrm{j}_2) \leq TAC < w_2\, X_2 + [(1 - j_2)/j_2]\, w_2\, X_2$. 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 (Proposition 1.2):

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

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

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 $\alpha_1 + \alpha_2 = 1$.

As an example, equal quota shares, $\alpha_1 = \alpha_2 = 0.5$, cannot be a solution for this environment. 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 on the the first fishing day. All old mature fish are harvested on the first fishing day. Fleet 2's degree of selection is zero on the second fishing day. Fleet 2 fulfills its quota by harvesting 2.5 additional tonnes of young mature fish on the second fishing day. Fleet 1 cannot fulfill its quota since there are not any old mature fish on the second day. Fishing season ends 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 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' (Frost and Andersen 2006). 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 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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