Mathematical Biosciences 276 (2016) 59–66

Contents lists available at ScienceDirect

Mathematical Biosciences

journal homepage: www.elsevier.com/locate/mbs

Quota implementation of the maximum sustainable yield for age-structured fisheries

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ARTICLE INFO

Article history:
Received 9 November 2015
Revised 9 March 2016
Accepted 11 March 2016
Available online 24 March 2016

Keywords:
Bioeconomics
Mechanism design
Fisheries management
Age-structured population model
Maximum sustainable yield
Common Fisheries Policy

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.

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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 [16]. Most of the other fish stocks remain outside safe biological limits and are overfished [11,12,16,23]. 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 [14]. 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.

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http://dx.doi.org/10.1016/j.mbs.2016.03.007
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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 [10], Quaas et al. [26], Skonhoft et al. [28], Tahvonen [32–34] and Holden and Conrad [20], among others, have contributed to this literature of age-structured modeling for fisheries. Moreover, Armstrong [2] 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 [3], Björndal and Brasao [6], Stage [30] and Diekert et al. [13] for more on applications of age-structured model for different case studies. A previous study of Skonhoft et al. [28] has recently formulated an age-structured model and derived MSY fishing mortalities similar to that of Reed's [27]. In the current study, the age-structured fish population model developed by Skonhoft et al. [28] 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 [27]. 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, $X_{1,t}$ ($1 \leq$ age < 2), Old matures, $X_{2,t}$ ($2 \leq$ age).

In the model, the Beverton–Holt recruitment function, which is increasing and concave for both age classes, is employed [5]. The number of recruits to the fish population during season *t* is:

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

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:

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

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

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

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.

$$X_1 = s_0 \ R(X_1, X_2), \tag{4}$$

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

The population model developed by Skonhoft et al. [28] 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

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