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Conflict and cooperation in an age structured fishery

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ABSTRACT

The literature on 'fish wars', where agents engage in non-cooperative exploitation of single fish stocks or interacting fish stocks is well established, but age and stage structured models do not seem to have been handled within this literature. In this paper we study a game where two agents, or fishing fleets, compete for the same fish stock, which is divided into two harvestable age classes. The situation modelled here may be representative for many fisheries, such as the Norwegian North Atlantic cod fishery where the coastal fleet targets old mature fish while the trawler fleet targets young mature fish. We analyze the game under different assumptions about the underlying information available to each fleet and the actions of the agents. The outcomes of the games are compared to the optimal cooperative solution. The paper provides several results, which differ in many respects from what are found in biomass models. The analysis is supported by numerical examples.

1. Introduction

Marine fisheries are frequently a source of international conflicts and often characterized by suboptimal resource management. Fish stocks spread across vast distances, and are often present both in the high seas and within the exclusive economic zones of one or more countries at the same time. Many fish species are also highly migratory, travelling along coastlines and up and down rivers, spending much of their lifetime outside of the breeding grounds, and are hence subject to harvest from different agents at different points in time. A particular aspect of this situation is that different age categories of the same stock frequently reside within the economic zones of different countries. In this case, different fleets do not strictly speaking aim for the same fish, but they nevertheless affect each other's harvest and profit through the biological interaction of the stock. A similar situation may also occur between fleets that are distinguished not by nationality, but by different gear, thus aiming for different age categories of the same stock. This situation, which is not adequately handled within the existing literature on biomass models and sequential fishing, is not uncommon. Examples include the Norwegian North Atlantic cod that feeds in the Barents region, thus subject to harvest by trawlers, but where the old mature fish migrates along the Norwegian cost to spawn, there being exploited by small scale coastal fishing vessels. This fishery has been extensively studied, see e.g. Sumaila (1997) and Armstrong (1999). Other examples in the same vein include the Southern bluefin tuna that spends its immature phase along the coast of Australia, but then migrates to the high seas in the Indian Ocean. Similar descriptions apply to the Canada halibut and the North Sea herring, and in general to anadromous species, such as salmon that spawns in rivers but lives most of its life in the open sea. These are some of the world's most valuable fisheries.

The literature on 'fish wars', where agents engage in non-cooperative games of exploiting a fish stock, has grown large since the seminal contributions of Munro (1979) and Levhari and Mirman (1980). A survey is provided by Kaitala and Lindroo (2007). For our purpose, the literature on 'sequential' fishing, where agents alternate in exploiting a common stock that migrates between economic zones, is of particular relevance. Hannesson (1995) studies the possibility for self-enforcing agreements in such a sequential fishery, and McKelvey (1997) expands the framework to consider the possibility of side payments. Laukkanen (2001) shows that the effectiveness of trigger strategies to maintain a cooperative equilibrium is undermined when stock recruitment is subject to stochastic shocks. However, these studies all employ biomass models, implicitly assuming that the fish caught in one area is identical to the fish caught in another. Age structured models, on the other hand, are still scarce in the economic literature, as noted by Skonhoft et al. (2012). The seminal book on bioeconomic modelling by Clark (1990) treats the Beverton-Holt model to some extent (Beverton and Holt 1957), but puts main emphasis on biomass models. Important contributions by Reed (1980), Charles and Reed (1985) and Getz and Haight (1989) have subsequently enhanced the economic understanding of the exploitation of age structured fish stocks. In a more recent contribution, Tahvonen (2009) presents a thorough study of the optimal harvesting of age structured stocks, under the assumption of non-selective gear. See also Tahvonen (2010) for a general survey, and

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Quaas et al. (2013). Very few studies address age structured stocks in a game theoretic setting. One example is Lindroos (2004) who examines the benefit of cooperation in the Norwegian spring-spawning herring fishery. Two other notable examples that both study the North Atlantic Norwegian cod fishery mainly through numerical analysis include Sumaila (1997) and Diekert et al. (2010). Sumaila analyses the difference in profitability between a trawler fleet and a coastal fleet, and demonstrates several results that concur with the findings in the present paper. Specifically, the observation that the least profitable fleet in a cooperative harvesting scenario, which typically may be the trawler fleet that targets the smaller fish, may have a strategic advantage in a non-cooperative situation due to the biological interaction of the stock. Thus, the least profitable fleet may be able to drive the other fleet entirely out of business, with large consequences for overall profit. The age structure of the fishery thus gives rise to a non-cooperative game that is even more harmful than the standard one found in biomass models. Diekert et al. (2010) assume symmetric players, i.e. two trawler fleets, that compete both through mesh size and fishing effort. They show that a non-cooperative solution implies 'fishing down the size categories', and that the outcome of a non-cooperative open loop equilibrium is both far from the cooperative optimum and close to the status quo situation in terms of profit and stock size.

In the present study we do not attempt to accurately describe a particular fishery, but to analyze a stylized situation where different age categories of a fish stock reside within two different economic zones, or management areas. The exploitation of the stock is modelled as a game between two fleets that aim for different cohorts, but nevertheless affect each other's profitability through the biological interaction of the stock. We derive analytical results characterizing the equilibrium solutions under different management regimes. First, overall optimality is addressed, which under certain conditions also can be interpreted as a cooperative equilibrium with side payments. Second, we discuss the situation where both fleets are unable to organize internally and hence exhibit myopic behavior, and derive conditions for one of the fleets to be excluded from the fishery in this case. Third, the situation where one fleet is uncoordinated and the other behaves as a single entity is studied. It is shown that, depending on parameter values, both coexistence and exclusion is possible in all different scenarios. The results are subsequently illustrated with a numerical example.

The paper is organized as follows. In the next Section 2, the population model with two harvestable age classes is formulated. In Section 3 we analyze the optimal harvest regime under cooperation Section 4 presents the non-cooperative solution where we first focus on myopic exploitation. Additionally, we also study a Stackelberg solution where one the agent is myopic while the other one has a long-term management view. In Section 5 some numerical illustrations are provided. Section 6 concludes the paper.

2. Population model and harvest

For analytical tractability, we use a population model consisting of only three cohorts; recruits (juvenils) $X_{0,t}$($year < 1$), young mature fish $X_{1,t}$($1 \leq year < 2$) and old mature fish $X_{2,t}$($2 \leq year$). Young and old mature fish are both harvestable, but the juveniles are not subject to fishing mortality. While recruitment is endogenous and density dependent, natural mortality is assumed fixed and density independent for all three age classes. The population is measured just before spawning, and in the single period of one year, three events take place in the following order; first, recruitment and spawning, then fishing and finally natural mortality.

The number of juveniles is governed by the recruitment function

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

where $R(0, 0) = 0$ and $\partial R/\partial X_{i,t} = R_i' > 0$, together with $R_i'' < 0$($i = 1, 2$). The number of young mature fish follows next as

$$X_{1,t+1} = s_0 X_{0,t}, \tag{2}$$

where $s_0$is the fixed natural survival rate. Finally, the number of old mature fish is described by

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

where $0 \leq f_{1,t} < 1$and $0 \leq f_{2,t} < 1$are the fishing mortalities, or harvest rates, of the young and old mature stage, respectively, while $0 < s_1 < 1$ and $0 < s_2 < 1$ are the natural survival rates. When combining Eqs. (1) and (2) we have

$$X_{1,t+1} = s_0 R(X_{1,t}, X_{2,t}). \tag{4}$$

Eqs. (3) and (4) represent a reduced form model in two age-classes, where both equations are first order difference equations.

The population equilibrium for *fixed* fishing mortalities $f_{i,t} = f_i$is defined by $X_{i,t+1} = X_{i,t} = X_i (i = 1, 2)$ such that Eq. (3) holds as

(3′) $X_2 = s_1(1 - f_1)X_1 + s_2(1 - f_2)X_2$,

and Eq. (4) as

$$X_1 = s_0 R(X_1, X_2). \tag{4′}$$

(3′) is identified as the *spawning constraint* while (4′) is the *recruitment constraint*. An interior equilibrium holds for $0 \leq f_1 < 1$only; that is, not all the young mature fish can be harvested. An interior equilibrium is shown in Fig. 1, where the recruitment function is specified as the Beverton-Holt function (see numerical Section 5). Based on this function, the recruitment constraint describes the number of mature fish as a positive, increasing, and convex function of the number of young mature fish. Taking the differential of Eq. (4′) yields $dX_2/dX_1 = (1 - s_0R_1')/s_0R_2' > 0$. An increasing recruitment function therefore requires $s_0R_1' < 1$which holds for all positive values of $X_2$with our Beverton-Holt function. Higher fishing mortalities shift down the spawning constraint (3′) and hence lead to smaller stocks, while higher natural survival rates work in the opposite direction. The ratio of old to young mature fish is given by the slope of the spawning constraint, $X_2/X_1 = s_1(1 - f_1)/(1 - s_2(1 - f_2))$. Therefore, none of the parameters pertaining to the recruitment function influence the equilibrium fish ratio, while it is evident that lower fishing mortalities of both age classes increase the proportion of old mature fish.

Two fishing fleets exploit the fish stock, and each fleet targets a particular age class of the fish. As explained in the introduction, this harvesting scenario fits reality in many instances, either because of differences in gear selection, and/or because the two age classes reside in different fishing zones. In most instances, the catches are composed of specimens from different cohorts and there is hence 'bycatch' irrespective of the fact that the fleets might be able to influence their catch composition. For example, the mesh size may be increased, or other gears may be adopted to leave the younger and smaller fish less exploited (see, e.g., Beverton and Holt 1957 and Clark 1990, and the more recent Singh and Weninger 2009). However, here we neglect bycatch and assume perfect targeting, where fleet one targets the young mature fish (stock one) while fleet two targets the old mature fish (stock two). We choose a specific production function in our analysis, the so-called Baranov function (see, e.g., Quinn 2003) defined as

$$H_{i,t} = X_{i,t}(1 - e^{-q_i E_{i,t}}); \;\; (i = 1, 2), \tag{5}$$

where $H_{i,t}$ is the harvest of fleet i at time t(in # of fish), $E_{i,t}$ is the fishing effort, interpreted as, e.g., the number of standardized fishing vessels, and q_i is the productivity, or 'catchability', parameter (1/effort). The Spence function exhibits decreasing marginal effort productivity. Notice also that with this harvesting function, the fishing mortalities can never reach one for a finite amount of effort, and extinction of the population is hence not possible within our modelling framework.

With the fishing mortality rate defined as $f_{i,t} = H_{i,t}/X_{i,t}(i = 1, 2)$, the mature age class growth Eq. (3) becomes

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