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Analysis

Maximum Yield Fishing and Optimal Fleet Composition. A Stage Structured Model Analysis With an Example From the Norwegian North-East Arctic Cod Fishery

Irmelin Slettemoen Helgesen[a], Anders Skonhoft[a,*], Arne Eide[b]

[a] Economic Department, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] Norwegian College of Fishery Science, University of Tromsø, Tromsø, Norway

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ABSTRACT

A stage structured fishery model with three stages; recruits, immature fish and mature fish is formulated and utilized to analyse maximum sustainable yield (MSY) and optimal harvesting composition in a fishery with two heterogeneous fleets. The stage structured model developed bundles the age classes found in age structured models into stage classes based on their level of maturity, but also the pattern according to which they are harvested. Two fleets, high sea and coastal vessels, harvest respectively the immature and mature stages. The maximum sustainable yield (MSY) is studied in light of both perfect and imperfect fishing selectivity. In addition, we analyse the biomass loss of a sharing rule where the high sea trawler fleet is granted a certain share of the harvested biomass. The paper provides a theoretical extension to the literature on age structured models, and presents several new analytical results related to stage structured models which are supported by a numerical illustration inspired by the North-East Arctic cod fishery.

1. Introduction

The use of *age* structured fishery models is common when studying optimal harvest compositions; that is, which of the population's year classes and how much is it beneficial to harvest. Some recent publications on this include Tahvonen (2008), Skonhoft et al. (2012), Quaas et al. (2013), Diekert et al. (2010a, 2010b), Diekert (2013) and Skonhoft and Gong (2014). In line with the result of the well-known Reed (1980) paper, when the objective is maximum sustainable yield (MSY), the general finding is to prioritise the harvest of larger mature fish. As harvest costs generally differ between the vessel groups targeting different year classes, the outcome is more ambiguous when such costs are included. For instance, if the unit harvest cost is relatively high when targeting mature fish and relatively lower while targeting the young fish, the above result may be reversed (Skonhoft et al., 2012). The inclusion of dynamics, or the issue of selectivity, further complicates the outcome, see Hannesson (1975) and Tahvonen (2009). In line with Hannesson's results Tahvonen finds pulse fishing to be the optimal strategy. Pulse fishing may however involve high social and private costs that are not accounted for (e.g., idle harvest capacity, work instability of fishers, etc.). Diekert et al. (2010a, 2010b) and Diekert (2013) also use an age structured model to find that it is optimal to spare the young, though their inclusion of gear selectivity as a control enable a steady harvest.

In reality, however, fishermen, or fishing vessels, rarely operate with perfect gear selectivity, and thus they do not have the option to only harvest fish that are, e.g. eight years old. Instead, it may make more sense to characterise the population by *stages* where each stage class typically consist of several age classes. This is what is done in the present paper, which is motivated by the North-East Arctic (NEA) cod (*Gadus morhua*) fishery, the world's largest cod fishery with a harvest of 864,000 tonnes in 2015 (Anon., 2016). The vessels exploiting the NEA cod fishery can be categorised as two fleets; the coastal fleet with conventional fishing gear and the high sea trawler fleet. Due to different gear, as well as restrictions on harvesting area, the coastal fleet mainly harvest the mature and spawning fish, typically comprising fish of six years and older, while the trawler fleet mainly harvest younger, immature fish, typically comprising age classes three to six. The main goal of our paper is to analyse the optimal harvesting composition of mature and immature fish under different conditions, and relate these findings to our construction of a stage model.

In the bioeconomic literature there are to our best knowledge few, if any, models aiming to analyse optimal harvesting composition in stage structured models. Caswell (2001, Ch. 4) and Getz and Haight (1989)

* Corresponding author.
E-mail address: anders.skonhoft@svt.ntnu.no (A. Skonhoft).

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study stage structured models, and derive the main differences in comparison to age structured models. However, both these books are mainly concerned with biological issues. Our model is analysed with different assumptions about fishing selectivity, and fleet sharing rules. The latter refers to politically determined rules concerning how the harvest is shared between various vessel groups. Currently the Norwegian share of the NEA cod is allocated between the trawlers and the coastal fleet according to the so-called trawl ladder; a sharing rule that, depending on the size of the TAC, determines the allocation of the TAC between the two fleets.

A number of studies have analysed the population dynamics and fleet economics of the NEA cod fishery. Several of these studies discuss interactions and trade-offs between different user groups (as for example trawlers and coastal boats, different nations, gillnetters and trawlers, etc.). Sumaila (1997) use a game theoretic framework in combination with an age structured population model, to study cooperation and non-cooperation between the trawlers and the coastal fleet. The same system is analysed by Zimmermann et al. (2011) who find that, with size-dependent pricing, it is optimal to target larger (older) individuals combined with a lower harvesting rate. Using a type of prey-predator model for cannibalism Eide and Wikan (2010) examine a fishery targeting the mature stock with bycatch of immatures. With gear selectivity as a control, they find that although it would be optimal to reduce total fishing mortality, the share of immatures harvested should be increased. Using a two-stage biomass model Armstrong (1999) analyses the optimal harvest composition between the coastal and trawler fleet. She does not find any biological or economic justification for the structure of the trawl ladder.

This paper only studies Maximum Sustainable Yield (MSY) fishing, or the dynamic equivalent, which we label Maximum Yield (MY) fishing. It is well known that MY fishing in equilibrium, or steady state, coincides with MSY fishing for zero discount rate. While this is, as indicated, a simplification compared to the maximum economic yield (MEY) problem where costs are included, and a narrow goal that does not account for social welfare or ecosystem services, our choice is also motivated by the fact that fishery managers frequently regard MSY as the relevant management goals. MSY is for instance, the goal set by the EU Common Fishery Policy (CFP) and the United Nations Convention on the Law of the Sea, which is ratified by Norway (http://europa.eu/rapid/press-release_MEMO-13-1125_en.htm, http://www.un.org/depts/los/convention_agreements/convention_overview_fish_stocks.htm). See also the discussion in Wilen (2000). Within the given framework, we aim to find and characterise the optimal harvest composition, and to examine the driving forces behind the exploitation scheme, both with and without bycatch. The social cost in terms of biomass loss of applying a sharing rule for the two fleets is also examined. The paper provides several results concerning the harvest of populations subject to imperfect selectivity and sharing rules which in most cases will coincide what we find in age structured models.

Section 2 gives first a brief overview of the Norwegian North-East Arctic cod fishery and in Section 3 the stage structured biological model is formulated. Our notion of fishing selectivity is described in Section 4. Throughout the paper we implicitly assume a Baranov catch function for both fleets (see, e.g., Quinn, 2003), indicating that the fishing mortalities always are below one. In Section 5, we first analyse the fishery assuming perfect harvesting selectivity, followed by Section 6 where the case of imperfect selectivity is studied. In Section 7 a numerical illustration is provided, while we in Section 8 introduce the sharing rule where the trawler fleet is guaranteed a minimum fraction of the harvested biomass. The outcome here is also supported by a numerical illustration. Section 9 finally summarises our findings.

2. The Norwegian North-East Arctic Cod Fishery

The North-East Arctic (NEA) cod is the world's largest cod stock, with an estimated stock size of 4.2 million tonnes in 2015 (Anon., 2016). It follows that the stock is considered to be reasonably well managed, an achievement due to the two sharing nations Russia and Norway's joint management effort (Eide et al., 2013; Armstrong et al., 2014). In 2015 the TAC was 894,000 tonnes, and Norway receives about 45% of this, in fact the Norwegian fleet harvested and sold cod for over 500 million NOK in 2015. This harvest of NEA cod accounts for about one-half of the total Norwegian harvest in demersal fisheries, and in 2015 the average Norwegian demersal fishing vessel had an operating profit of about 1190 thousand NOK (http://www.fiskeridir.no/Yrkesfiske/Statistikk-yrkesfiske/Loennsomhet). That said, the fishery's lack of realised resource rent suggests an inefficient harvesting pattern, both due to quotas above the scientific advice and a shift towards the harvest of younger age classes (Steinshamn, 2005; Arnason et al., 2004; Ottersen, 2008; Gullestad et al., 2015).

The NEA cod stock is characterised by significant inter- and intra-annual fluctuations in the spatial and temporal distribution of stock biomass, biological growth and recruitment. During its life cycle the population annually migrates between Norwegian, Russian and international waters. Moreover, while the mature stock migrates towards the Norwegian coast for spawning Russian waters observe a higher frequency of immature cod (Armstrong et al., 2014). The harvesting follows a strict seasonal pattern, where the main season takes place during the first quarter of the year (Eide et al., 2013). While the Russian share is harvested entirely with ocean-going vessels, i.e. trawlers, the Norwegian fleet consist of both trawlers and conventional fishing gear, i.e. the coastal fleet. Fig. 1 illustrates how recent catches (2005–2013) are

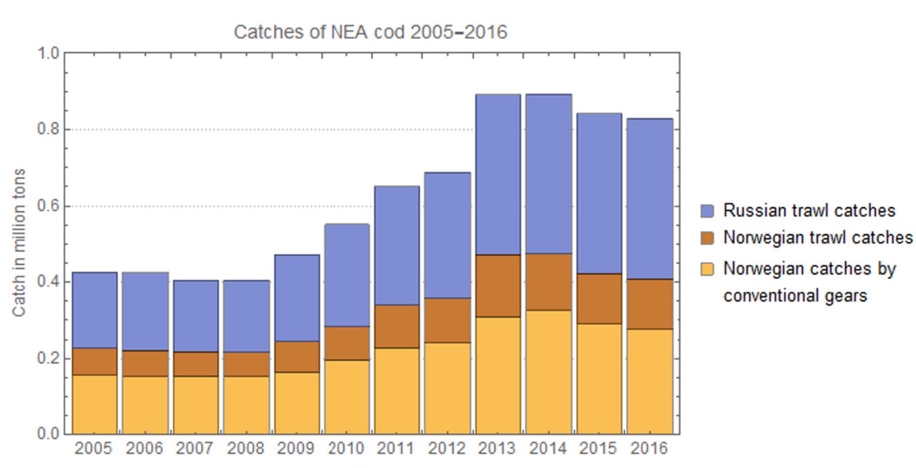

Fig. 1. Russian and Norwegian catches of NEA cod 2005–2013 (Source: Norwegian fisheries directorate and Anon., 2017).