Management of North-East Arctic Cod: An Age-structured, Multi-Fleet Analysis

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Abstract

The North-East Arctic cod fishery is of economic and cultural importance. The stock is subject to joint management by Norway and Russia. Today’s stock management strategy is designed to achieve the maximum sustainable yield given the current selection pattern. The current selection pattern is largely determined by the fleet-composition, i.e. the distribution of the total allowable catch in terms of shares. By use of an age-structured, multi-fleet, bioeconomic model, it is shown that the stock has biological potential that cannot be realized with today’s management. The same goes for the economic potential of the Norwegian part of the fishery. Biological gains in terms of an increase in the sustainable yield may be achieved by altering the overall selection pattern through changes in the fleet-composition. Economic gains in terms of an increase in the net present value of the Norwegian part of the fishery may be achieved by changing the fleet-composition and reducing the overall fishing pressure.

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1 Introduction

1.1 North-East Arctic Cod

North-East Arctic (NEA) cod forms the world's largest cod stock (Helgesen et al. 2018). It is of great economic and cultural importance (Eide et al. 2013; Armstrong et al. 2014; Fiskeridirektoratet 2009-2018)[1]. The stock has been subject to overfishing, but strict management and good climatic conditions have ensured that the stock is now in relatively good condition compared to earlier years (ICES 2018)[2].

Figure 1 shows the distribution and migration pattern of the NEA cod. The mature part of the population migrates between the feeding grounds in the Barents Sea and the spawning grounds of the Lofoten Islands in the Norwegian Sea (Armstrong et al. 2014). It accumulates in the spawning grounds in the period that stretches from January to April each year. Eggs and fish larvae drift from the spawning grounds to the Barents Sea along with the ocean currents. The immature part of the population grazes in the Barents Sea until it becomes sexually mature.

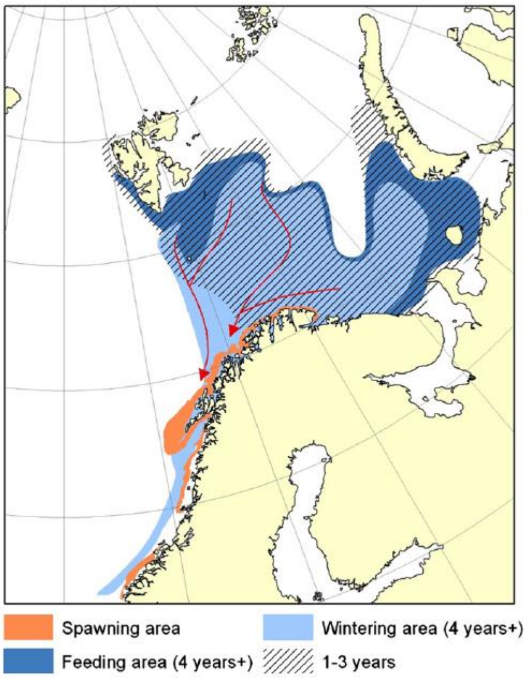

Figure 1: Map showing the distribution and migration pattern of NEA cod (Source: Armstrong et al. (2014))

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[1] In 2017, the harvest totaled at 868 thousand tons and the spawning stock biomass was estimated at about 1.8 million tons (ICES 2018). Assuming the average price for the Norwegian part of the fishery was representative for the entire NEA cod fishery, the first-hand value of the total harvest in 2017 is estimated at about 14 billion Norwegian Krones (Fiskeridirektoratet 2009-2018).

[2] In the period 1998-2008, the average yearly total harvest and average yearly total spawning stock biomass (SSB) was 522 thousand tons and 513 thousand tons, respectively (ICES, 2018). In the period 2009-2018, the average yearly total harvest and average yearly SSB was about 759 thousand tons and 1.9 million tons, respectively.

NEA cod is a top predator. Capelin, herring and different benthic organisms serve as important sources of food (Hjermann et al. 2006). It is also cannibalistic - older individuals are inclined to feed on younger individuals, especially when the availability of other sources of food is scarce (Yaragina et al. 2009). Young cod (age 0-2) feed mainly on zooplankton (Dalpadado & Bogstad 2004).

1.2 The North-East Arctic Cod Fishery

The NEA cod stock is managed jointly by Norway and Russia through a bilateral fisheries commission (NFD 2018). Every year, a total quota is set, and this is distributed between vessels that fall into three broad groups; Norwegian conventional vessels[3], Norwegian trawlers, and Russian and third countries' trawlers. The Russian and third countries' trawlers typically get 55-57.5% of the total quota, while the Norwegian part of the fishery gets the remaining share (Diekert et al 2010; JNRFC n.e.)[4]. A distribution key called "Trålstigen", which translates to "The trawl ladder", determines the distribution of the Norwegian share of the total quota as a function of its size (NOU 2016). The trawl share is rising from 27 per cent when the quota is low to 33 per cent when the quota is high.

The current stock management strategy is designed to achieve the maximum sustainable yield (MSY) given the current selection pattern (Garcia et al. 2018; Eikeset et al. 2012). The different vessel groups operate with different gears and in various geographical areas. Therefore, they target different age groups in the stock. Hence, the overall selection pattern is largely determined by today's fleet-composition, i.e. today's distribution of the TAC in terms of shares. Also important are operational restrictions concerning gear and the vessel groups' operational access to different geographical areas.

Most vessels in the Norwegian conventional fleet operate on the spawning grounds off the Lofoten Islands during the spawning-season. Hence, they naturally target the older and mature part of the stock.

[3] The Norwegian conventional fleet consists of two distinctive sub-groups; the coastal fleet and conventional ocean-going vessels. The conventional ocean-going vessels constitute a relatively small share of the Norwegian conventional fleet in terms of harvest. For simplicity, and to avoid confusion, the conventional fleet is used synonymously with the coastal fleet throughout this paper.

[4] Historically, 10-15% of the total quota has been allocated to third countries. The remaining share of the total quota has then been split equally between Norway and Russia.

Russian and third countries' trawlers operate in the Barents Sea. The same goes for Norwegian trawlers. However, the Norwegian trawlers operate further west than most of the vessels in the Russian and third countries' trawler fleet (see e.g. attachment 13a and 13b to JNRFC (2018)). Norwegian trawlers may also operate relatively close to the spawning grounds during the spawning-season. Since both trawler fleets operate in the Barents Sea, where the immature part of the population grazes, they target a younger part of the population than the Norwegian conventional fleet. Because the Norwegian trawlers operate further west and closer to the main spawning grounds than the Russian and third countries' trawler fleet, they naturally target older individuals compared to the Russian and third countries' trawler fleet.

1.3 Motivation

Bioeconomic theory indicates that alternative strategies concerning the determination of the total quota could increase the sustainable economic yield and net present value of the fishery (see e.g. Gordon 1954). When harvesting is density-dependent, as it often is for shoaling species[5] such as the NEA cod, it may be economically optimal to stabilize the stock at a higher level than the one associated with the MSY. The rationale is that an increase in the size of the stock gives rise to an increase in the harvest per unit effort which induces a reduction in the harvest costs per kg. Although such a strategy gives a lower yield than the MSY, it may generate a significant increase in the sustainable economic yield and net present value of the fishery.

Moreover, biological and bioeconomic studies on the NEA cod fishery indicate that today's selection pattern is biologically and economically inefficient (Helgesen et al. 2018; Diekert et al. 2010; Kvamme & Bogstad 2007). Biological and economic gains could be achieved by targeting older and heavier fish, i.e. by sparing younger fish for future harvest.

Changes in the selection pattern can be achieved in several ways, for example by changing the fleet-composition, altering the gear restrictions and/or changing the restrictions concerning the vessel groups' operational access to different geographical areas. In this paper, I focus on the effects of changing the fleet-composition, i.e. the distribution of the TAC in terms of shares.

[5] In biology, a group of fish swimming in the same direction in a coordinated matter are schooling, while a group of fish that stay together for social reasons are shoaling.

1.4 Links to Literature

Helgesen et al. (2018) present a stage-structured, multi-fleet, bioeconomic model inspired by the NEA cod fishery. The model structures the population in two groups, immatures and matures. It includes two fleets: the Norwegian conventional fleet and the Norwegian trawler fleet. They study both perfect and imperfect selectivity. When studying perfect selectivity, the conventional fleet targets only mature individuals, while the trawler fleet targets only immature individuals. When studying imperfect selectivity, the fleets experience bycatch, i.e. mixed catches. By using the model, they study the concepts of maximum sustainable yield (MSY) and the dynamic equivalent, which they label maximum yield (MY). In all scenarios, they find that it is optimal to prioritize harvest of the mature part of the stock. In most cases, in their study, this involves utilizing only the conventional fleet. At high levels of bycatch, however, they show that it is optimal to utilize only the trawler fleet. Furthermore, they find that distribution keys (such as "Trålstigen") may result in sub-optimal fishing schemes, generating efficiency losses. The model presented by Helgesen et al. (2018) does not include fishing costs and does not study the concepts of maximum sustainable economic yield (MEY) and maximum net present value (MNPV)[6].

Although certain changes in the fleet-composition may have the desired effect on the overall selection pattern and lead to an increase in the realization of the stocks' growth potential, it may prove to be economically inefficient to implement said changes (Skonhoft et al. 2012). A vessel group with an inefficient selection pattern may experience lower harvest costs per kilo than a vessel group with a more efficient selection pattern. The utilization of the vessel group with the efficient selection pattern, at the expense of the utilization of the vessel group with the inefficient selection pattern, will lead to an increase in the realization of the growth potential of the stock. However, since the vessel group with the inefficient selection pattern experiences lower harvest costs per kg than the vessel group with the efficient selection pattern, the overall result may be a reduction in the sustainable economic yield and net present value of the fishery. In other words, it is not always economically optimal to increase the realization of the growth potential of a fish stock.

Diekert et al. (2010) present an age-structured, multi-fleet, bioeconomic model of the NEA cod fishery. The model includes three fleets; the Norwegian conventional fleet, the Norwegian

[6] I make an important distinction between MEY and MNPV. While MEY is defined as the maximum sustainable economic yield, which involves steady-state fishing, the MNPV is defined as the maximum net present value. Although MNPV fishing may be coinciding with MEY fishing, it may also be associated with fishing schemes that do not involve steady-state fishing – it may, for example, involve pulse fishing.

trawler fleet and the Russian trawler fleet. By use of the model, they estimate that the fishery could more than double its net present value (NPV) by targeting older and heavier fish by increasing mesh-size and reducing the overall effort without changing the fleet-composition significantly. Moreover, they show that optimal harvesting policies would lead to a much more robust and abundant cod stock. When maximizing the NPV of the fishery with effort as the only control variables, they find pulse fishing to be optimal. In this scenario, they find that it is optimal to change the fleet-composition so that the Norwegian conventional fleet constitutes a smaller share of the total fleet in terms of harvest. While Diekert et al. (2010) provide interesting and valuable results related to the potential of the NEA cod fishery by applying optimal mesh-size and effort levels, little attention has been directed towards practical management questions concerning the allocation of the total quota. Furthermore, little is said about the differences between optimal and sub-optimal fishing schemes. Such differences could be of great interest for fishery managers, the industry, politicians and the public[7].

Sumaila (1997) also presents an interesting and relevant study. Using a game theoretic framework combined with an age-structured model, he investigates the economic benefits that can be realized from the NEA cod stock, and the effect of exploitation on stock sustainability under cooperation and non-cooperation between trawlers and conventional vessels. Given the data available at the time, he shows that the optimum optimorum is obtained under cooperation between the fleets. It involves side payments and no predetermined harvest shares, in which case the conventional fleet buys out the trawler fleet and becomes the producer of the optimum optimorum. However, his sensitivity analysis shows that the trawler fleet will take over as the optimum optimorum producer if the price premium assumed for mature fish is taken away.

1.5 The Trawl Ladder Debate

For the sake of enlightenment: there is currently an ongoing Norwegian public debate concerning whether "Trålstigen" should be maintained. As the Norwegian conventional fleet is known to deliver higher-quality raw material and create more jobs in coastal communities than

[7] The aim of Norwegian fisheries management is to ensure sustainability, profitability and employment in coastal societies (Havressurslova 2008). This study considers sustainability and the first-hand profits in the Norwegian part of the NEA cod fishery. However, also important is employment in coastal societies and the profitability in the rest of the industry, including processing, etc. Choosing management strategies that involves increased first-hand profits may have a negative effect on employment in coastal societies. It may also lead to a reduction in the profits in the rest of the industry (Christensen 2010). Furthermore, and since there is joint international management of the NEA cod, it may be difficult to implement optimal management strategies. These aspects make it worthwhile to investigate several management scenarios, also those which are sub-optimal.

the Norwegian trawler fleet, many argue that the conventional fleet should get more of the Norwegian share of the total allowable catch (TAC) (see e.g. Fylkesnes 2019). Others argue that “Trålstigen” should be maintained because the Norwegian trawler fleet plays an important role in the year-round supply of raw-material and the year-round employment (see e.g. Martinsen & Lysvold 2016). In addition, many seem to believe that the Norwegian trawler fleet is better than the Norwegian conventional fleet in terms of first-hand profitability (see e.g. Jensen 2019) - likely because it typically experiences higher profit margins than the Norwegian conventional fleet (Fiskeridirektoratet 2009-2018). However, the results presented by Helgesen et al. (2018) and Sumaila (1997) indicate that this need not imply that it is economically optimal to maintain “Trålstigen” or allocate more of the Norwegian share of the TAC to the Norwegian trawler fleet. It could be economically optimal to allocate more to the Norwegian conventional fleet. Although the debate is more complex than outlined here, it is explained sufficiently to understand that the distribution of the Norwegian share of the TAC is a hot topic and that the debate might be partly characterized by misconceptions.

1.6 Objectives

The main objective of this study is to provide a policy-relevant, bioeconomic analysis of different management strategies concerning the determination and allocation of the total quota for NEA cod. To do so, I have developed an age-structured, multi-fleet, bioeconomic model for the NEA cod fishery. It includes the Norwegian conventional fleet, the Norwegian trawler fleet, and Russian and third countries’ trawler fleet. While the biological part of the model and the harvest functions describe the whole fishery, the economic part is limited to describe the Norwegian part of the fishery. Hence, the paper takes on a Norwegian perspective. The model is used to provide estimates on MSY, MEY and MNPV subject to different constraints concerning the distribution of the TAC in terms of shares. In this paper, I present the model and its numerical specifications. Furthermore, I present, compare and discuss the key results generated by the model.

Although the numerical specification of the model is based on statistical analysis, the model should not be viewed as a predictive model. Due to fundamental uncertainties in marine systems, other differences between model and reality, and the rough approaches used in the estimation of several parameters, the results should be interpreted as ceteris paribus comparisons of different management scenarios.

1.7 Novelties

The paper adds to the work done by Helgesen et al. (2018) by adding detail, and by including costs and the study of MEY and MNPV. Furthermore, it adds to the work done by Diekert et al. (2010) in several ways. Firstly, I present an alternative age-structured, multi-fleet, bioeconomic model for the NEA cod fishery. Amongst other things, I endogenize the natural mortality for younger age groups and weight at age for several age groups – in accordance with the state-of-the-art in single-species biological modeling of this species (Kovalev & Bogstad 2005), Secondly, the numerical specification of the model is based on statistical analysis of recent data (which contain data points outside the range of the data Diekert et al. (2010) had access to at the time). Thirdly, I include the study of MSY. I also make an important distinction between MEY and MNPV to investigate potential differences between optimal steady-state fishing schemes and potentially optimal cyclical fishing schemes. Lastly, I shift the focus from management questions concerning the choice of mesh-size to practical management questions concerning the distribution of the total quota in terms of shares. Moreover, the paper adds to the work done by Sumaila (1997) by presenting an alternative type of model and providing an analysis based on recent data. The paper may inform the ongoing Norwegian debate concerning whether “Trålstigen” should be maintained.

1.8 Outline

Section 2 accounts for the significance of gear selectivity. Section 3 summarizes the model and its numerical specifications. Section 4 explains how the model is used to simulate different management scenarios. Section 5 presents, compares and discusses key results generated by the model. Section 6 concludes the work.

2 The Significance of Gear Selectivity

Gear selectivity refers to a fishing method’s ability to target and harvest fish by size/age from a fish stock during a fishing operation. In other words, a gears’ selectivity refers to its selection pattern. Understanding the significance of gear selectivity is essential for understanding the results generated by the model presented in this thesis. Diekert et al. (2010) explain the significance of gear selectivity by presenting a pedagogical thought experiment – one that I will re-tell with some additions, subtractions and twists in the following.

2.1 A Stylized Thought Experiment

Imagine a large tank filled with water. Then imagine that a number of fish is put in the tank. For now, assume that the fish is infertile so that there will be no natural reproduction in the tank. Each individual gains weight by age, but the number of fish declines as time passes due to natural mortality. The overall biomass of fish in the tank will grow in the beginning, assuming the individual growth is sufficiently high relative to the natural mortality. After some time, however, the overall biomass will level out and then decrease. If harvesting is done without any costs, all fish should be harvested, and the problem is reduced to when this should be done. The obvious answer, from an economic perspective, is to harvest all the fish when the value of the cohort reaches its maximum. The maximum value of the cohort will depend on the net-growth function of the cohort and on the price per kg of fish, which may be increasing with age. The optimal timing of harvest will change if we apply a discount rate, if harvesting is not costless, or if it is not possible to harvest all the fish at once or at all. When fish is harvested before it reaches its optimal age, the stock is subject to growth-overfishing.

Now imagine that a new cohort is introduced at the beginning of each period. The value of the stock will then equal the sum of the value of each cohort. If all other things are equal to the first scenario presented, and it is possible to perfectly select the fish of a specific age, the problem is identical to the single cohort-problem presented above. The gear should be designed to target the fish of the optimal age, and all fish of optimal age should be harvested every period (Beverton & Holt 1957). However, if the gear is completely non-selective, the best thing to do is to empty the tank and let the stock recover, and then repeat the process (see e.g. Hannesson 1975; Tahvonen 2009; Golubtsov & Steinshamn 2019). This is called pulse fishing. Although pulse fishing might prove to be an optimal fishing strategy in a bioeconomic model analysis, the strategy may be associated with high social and private costs (Helgesen et al. 2018).

In the real world, things are more complex. In fisheries, there exist neither perfect selectivity nor completely non-selective gears. Instead there often exist different types of vessels fishing with different types of gear in various geographical areas, targeting different age groups of the stock. And clearly, harvesting is not costless, and different types of vessels may experience both differences in costs and prices.

Returning to the example, assume that there are two types of gear that can be used to harvest fish from the tank and that there is no room for altering the design of the gear. Furthermore, assume that the value of a cohort reaches its maximum at age 8. Then assume that the first type of gear harvests fish of age 6, while the second type of gear harvests fish of age 8. When harvesting is costless and there is no time preference in terms of a discount rate, the obvious choice would be to choose the gear that harvests the fish of age 8 and spare all other fish for future periods. However, if we apply a positive discount rate, or the cost of harvesting is not costless and the cost of applying the different types of gear varies, the choice is more ambiguous. If the discount rate is sufficiently high, or the cost of using the first type of gear is sufficiently low relative to the cost of using the second type of gear, it will be optimal to use the first type of gear instead of the second one.

In the real world, harvesting also often has an impact on the reproduction potential of the stock – in many cases, a reduction in the spawning stock biomass will lead to a reduction in future recruitment to the stock, and this also has implications for the optimal fishing strategy. Recall the last scenario presented in the paragraph above. Instead of assuming the fish is infertile, assume now that it becomes fertile when it reaches the age of 7, and that the number of sexually mature individuals determines the recruitment in the next period. Then assume that harvesting is not costless and that the cost of applying the first gear is much lower than applying the second gear. When studying the scenario from a single-cohort perspective, it could be optimal to use only the first type of gear due to lower cost and harvest all the fish at age 6. However, if this is done for all cohorts, there will be no reproduction since no individuals grow old enough to become sexually mature and contribute to future recruitment. This is called recruitment-overfishing. Taking this into account, it could be optimal to use both types of gear or only the second one. Furthermore, the optimal strategy could involve continuous fishing activity or pulse fishing.

Although the real world is much more complex than outlined here, the above thought experiment provides valuable insight that is essential for optimal management of fish stocks, and understanding the model and results presented in this paper.

3 The Model

The model presented here consists of a biological dimension, an economic dimension and harvest functions. The biological part describes biologic details such as processes of growth, maturation, mortality and recruitment. The economic part describes economic details such as costs and prices. The fleet-structure in the model is three-folded: *Fleet 1* denotes the Norwegian trawler fleet, *Fleet 2* denotes the Norwegian conventional fleet and *Fleet 3* denotes the Russian and third countries' trawler fleet. The harvest functions for these fleets form the link between the biological and economic dimensions. While the biological part and harvest functions describe the whole fishery, the economic part is limited to describe the Norwegian part of the fishery – in other words, no economic details are described for *fleet 3*. The numerical specification of the model is based on statistical analysis. The model is set up in MS Excel. Stata and MS Excel have been used as statistical tools for the numerical specifications.

3.1 The Biological Sub-Model

3.1.1 Age Structure

The NEA cod may reach an age of 24 years and a weight of 40 kg (Diekert et al. 2010; Aglen et al. 2004). However, few fish survive to the age of 12 years due to natural mortality and high fishing pressure (ICES 2018). The age-structure in the model has therefore been defined from age class 3 to age class 13+. This means that recruitment to the stock happens when the fish becomes 3 years old. Age class 13+ includes all individuals that are 13 years and older. In retrospect, one or two more age classes should have been included. When too few age classes are included, the model can underestimate the growth potential of the stock (Diekert et al. 2010; Hannesson 1993).

3.1.2 Number of Individuals

In accordance with traditional Beverton-Holt modeling (see e.g. Beverton & Holt 1957), the number of individuals in age group a+1 in period t+1 ($N_{a+1,\,t+1}$) is modeled as a function of the number of individuals in age group a in period t ($N_{a,t}$), the natural mortality for age group a in period t ($M_{a,t}$) and the total fishing mortality for age group a in period t ($F_{a,\,t}$):

(1) $$\boldsymbol{N_{a+1,t+1} = N_{a,t} * \ e^{-(M_{a,t}+F_{a,t})},\ (4 \leq a \leq 12)}$$

(2) $$\boldsymbol{N_{13,t+1} = N_{13,t} * e^{-(M_{13}+F_{13,t})} + N_{12,t} * e^{-(M_{12}+F_{12,t})}}$$

The number of individuals in age group 3 in period t is determined by the recruitment in period t (R_t). The recruitment will be accounted for later.

3.1.3 *Natural Mortality*

As mentioned, the NEA cod is cannibalistic – older individuals are inclined to feed on younger individuals, especially when the availability of other sources of food is scarce. The natural mortality due to cannibalism may be significant for younger age groups and should thus be modeled (Kovalev & Bogstad 2005; Yaragina et al. 2009).

It seems reasonable that an increase in the number of sexually mature individuals will lead to an increase in cannibalistic behavior due to an increase in the pressure on the ecosystem and an increase in the competition for food, i.e. a reduction in the availability of food per individual. The natural mortality for age group a in period t ($M_{a,t}$) for the age groups 3, 4 and 5 have therefore been modeled as functions of the number of sexually mature individuals.

The sum of sexually mature individuals in each age group a in period t (K_t) is modeled as a function of the sexual maturity parameters for the different age groups (k_a), which are assumed to be constant for all age groups (see table 1)[8], and the number of individuals in each age group in period t ($N_{a,t}$):

(3) $$\boldsymbol{K_t = \sum_{a=3}^{13+} N_{a,t} * k_a}$$

Table 1: Numerical specification of the sexual maturity parameters

Parameter	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13+
k_a	0	0.003	0.050	0.274	0.578	0.810	0.937	0.985	0.995	0.997	1

The natural mortality for the age groups 3 and 4 are modeled as concave functions of the number of sexually mature individuals in period t-1 (K_{t-1})[9]:

(4) $$\boldsymbol{M_{a,t} = e^{\alpha_a^M} * K_{t-1}^{\beta_a^M},\ (3 \leq a \leq 4)}$$

[8] The numerical specification of the sexual maturity parameters is based on data from ICES (2018). Average values for the period 2000-2018 have been calculated and applied to the model.

[9] From an isolated perspective, it would be natural to model the natural mortality for the age groups 3, 4 and 5 in period t as functions of the number of sexually mature individuals in period t (K_t) or the spawning stock biomass in period t (SSB_t). However, such an approach would have produced a circular reference in the model. K_{t-1} has been used instead of K_t to avoid circular referencing and approximate the natural way of modeling the relationship. Although inaccurate, the approach can be justified to a large extent. In most simulation scenarios, there will be a strong correlation between K_{t-1} and K_t. When studying steady state situations, $K_{t-1} = K_t$ as long as the steady state situation was entered in period t-1 or earlier, and the approach will therefore not produce any bias in such cases. However, it is important to pay attention to the bias the approach produces when studying cyclical fishing patterns where K_{t-1} may be significantly higher/lower than K_t.

where α_a^M and β_a^M are coefficients estimated by log-log regressions on ICES data with the number of sexually mature individuals measured in thousands (see table 2)[10].

The natural mortality for age group 5 in period t ($M_{5,t}$) is modeled as a linear function of the number of sexually mature individuals in period t-1 (K_{t-1}) as this gave a better fit than the functional form used for age class 3 and 4:

$$\textbf{(5)} \qquad \boldsymbol{M_{5,t} = \alpha_5^M + \beta_5^M K_{t-1}}$$

where α_5^M and β_5^M are coefficients estimated by linear regression on ICES data with the number of sexually mature individuals measured in thousands (see table 2).

Table 2: Numerical specification of parameters in the natural mortality functions for age class 3, 4 and 5 (equation 4 and 5), and corresponding p-values and coefficients of determination

Age group	$\boldsymbol{\alpha_a^M}$	$\boldsymbol{\alpha_a^M}$: p > |t|	$\boldsymbol{\beta_a^M}$	$\boldsymbol{\beta_a^M}$: p > |t|	R^2
3	-4.136	0.000	0.239	0.001	0.304
4	-3.141	0.000	0.140	0.000	0.383
5	0.212	0.000	2.33e-08	0.283	0.036

The natural mortality ($M_{a,t}$) for the age groups 6-13+ are assumed to be constant and conventionally set to 0.2, in accordance with ICES data (ICES 2018).

3.1.4 *Fishing Mortality*

As mentioned, the fleet structure in the model is three folded. *Fleet 1* is Norwegian trawlers. *Fleet 2* is Norwegian conventional vessels. *Fleet 3* is Russian and third countries' trawlers. The total fishing mortality for age group a in period t ($F_{a,t}$) depends on the effort applied by each fleet i = 1, 2, 3 in period t ($E_{1,t}, E_{2,t}, E_{3,t}$) and the fleets' catchability coefficients for age group a ($q_{1,a}, q_{2,a}, q_{3,a}$). The effort units are defined as operating days and serve as control variables in the model. The catchability coefficients measure the gear selectivity of the different fleets, and the numerical specification of these will be accounted for in sub-section 3.2. The total fishing mortality for age group a in period t is modeled as follows:

$$\textbf{(6)} \qquad \boldsymbol{F_{a,t} = q_{1,a,t}E_{1,,t} + q_{2,a,t}E_{2,t} + q_{3,a,t}E_{3,t}.}$$

[10] The estimators α_a^W and β_a^W for age class 3 and 4 are estimated by log-log regressions in STATA with data from ICES (2018). Data for the period 1984-2017 has been used. The estimators α_5^M and β_5^M are estimated by linear regression in STATA with the same data.

3.1.5 Total Stock Biomass

The biomass in each age group a in period t ($b_{a,t}$) is modeled as a function of the number of individuals in age group a in period t ($N_{a,t}$) and the average weight for individuals in age group a in period t ($W_{a,t}$):

$$\textbf{(7)} \qquad \boldsymbol{b_{a,t} = N_{a,t} * W_{a,t}}$$

It seems reasonable that an increase in the number of sexually mature individuals will lead to a reduction in the average weight for most age groups due to an increase in the pressure on the ecosystem and an increase in the competition for food, i.e. reduced availability of food per individual. Analyzing ICES data, it seems that this is the case for age groups 5-11. The average weight for individuals in age group a in period t ($W_{a,t}$) has therefore been made endogenous for age groups 5-11, and are modeled as functions of the number of sexually mature individuals in period t (K_t) (Equation 8). Kovalev and Bogstad (2005) apply a similar approach when modeling weight at age.

$$\textbf{(8)} \qquad \boldsymbol{W_{a,t} = e^{\alpha_a^W} * K_t^{\beta_a^W},\ (5 \leq a \leq 11)}$$

where α_a^W and β_a^W are coefficients estimated by log-log regressions on ICES data with weight measured in kilograms (kg) and the number of sexually mature individuals measured in thousands (see table 3)[11].

Table 3: Numerical specification of parameters in the weight at age functions (equation 8), and corresponding p-values and coefficients of determination

Age group	$\boldsymbol{\alpha_a^W}$	$\boldsymbol{\alpha_a^W}$**: p > |t|**	$\boldsymbol{\beta_a^W}$	$\boldsymbol{\beta_a^W}$**: p > |t|**	**R^2**
5	1.439	0.009	-0.101	0.025	0.144
6	1.946	0.000	-0.010	0.003	0.241
7	2.424	0.000	-0.104	0.000	0.340
8	2.562	0.000	-0.085	0.002	0.260
9	2.617	0.000	-0.062	0.033	0.130
10	2.832	0.000	-0.055	0.117	0.073
11	3.078	0.000	-0.060	0.089	0.085

[11] The estimators α_a^W and β_a^W for age class 5-11 are estimated by log-log regressions in STATA with data from ICES (2018). Data for the period 1983-2017 has been used.

The average weights for the age groups 3, 4. 12 and 13+ are assumed to be constant and set to 0.274 kg, 0.66 kg, 12.67 kg and 14.27 kg, respectively. The values are average values calculated with data for the period 1983-2017 from ICES (2018).

The total biomass of the stock in period t (B_t) is the sum of the biomass in each age group a in period t ($b_{a,t}$):

$$\textbf{(9)} \qquad \boldsymbol{B_t = \sum_{a=3}^{13+} b_{a,t}}$$

3.1.6 Total Spawning Stock Biomass and Recruitment

The total spawning stock biomass in period t (SSB_t) is the sum of the number of sexually mature individuals in each age group a in period t ($N_{a,t}$*k_a) multiplied by the average weight of individuals in each age group a in period t ($W_{a,t}$):

$$\textbf{(10)} \qquad \boldsymbol{SSB_t = \sum_{a=3}^{13+} N_{a,t} * k_a * W_{a,t}}$$

In real life, recruitment appears to be somewhat stochastic. However, if there are no fish, there will be no eggs, and with no eggs, there will be no recruitment. Furthermore, it seems reasonable that there is some sort of positive diminishing relationship between the size of the spawning stock biomass and future recruitment since the NEA cod is cannibalistic. For simplicity, and to encompass this, the recruitment to the stock is modeled by a Beverton-Holt recruitment function. Since recruitment happens when the fish reaches the age of 3, the recruitment in period t (R_t) is modeled as a function of the size of the spawning stock biomass in period t-3 (SSB_{t-3}):

$$\textbf{(11)} \qquad \boldsymbol{R_t = \frac{\alpha_{SSB} * SSB_{t-3}}{\beta_{SSB} + SSB_{t-3}}}$$

where α_{SSB} and β_{SSB} are coefficients estimated using a least squares method on ICES data with recruitment measured in thousands and SSB measured in tons[12]. α_{SSB} is estimated to 725 526 and β_{SSB} is estimated to 128 392. The corresponding R^2 is calculated to 0.44.

3.2 Harvest Functions

The harvest measured in number of individuals for each fleet and from each age group in period t ($y_{i,a,t}$) is determined by the fleets' harvest functions. Fleet i's harvest from age group a depends

[12] The parameters α_{SSB} and β_{SSB} are estimated using a least squares method in MS Excel with data from ICES (2018). Data for the period 1980-2018 has been used.

on the effort applied by all fleets in period t ($E_{1,t}$, $E_{2,t}$, $E_{3,t}$), the fleets' catchability coefficients for age group a ($q_{1,a}$, $q_{2,a}$, $q_{3,a}$), the natural mortality for age group a in period t ($M_{a,t}$) and the number of individuals in age group a in period t ($N_{a,t}$). A Baranov type of harvest function has been used (see e.g. Baranov 1918)[13]. The harvest function for fleet 1 for age class a is formulated in equation 12. Symmetrical harvest functions are formulated for fleet 2 and fleet 3.

$$\textbf{(12)} \qquad \boldsymbol{y_{1,a,t} = \left(\frac{q_{1,a,t}E_{1,,t}}{q_{1,a,t}E_{1,t}+q_{2,a,t}E_{2,t}+q_{3,a,t}E_{3,t}+M_{a,t}}\right) N_{a,t}\left(1 - e^{-(q_{1,a,t}E_{1,t}+q_{2,a,t}E_{2,t}+q_{3,a,t}E_{3,t}+M_{a,t})}\right)}$$

The catchability coefficients ($q_{i,a}$) are estimated using a least squares method on data from ICES, IMR and the Norwegian Directorate of Fisheries with effort measured in operating days, and harvest and the number of individuals measured in thousands (see table 4 and figure 2)[14].

Table 4: Numerical specification of the catchability coefficients in the harvest functions ($q_{1,a}$, $q_{2,a}$, $q_{3,a}$) *and corresponding coefficients of determination for each fleet* (R_1^2, R_2^2, R_3^2) *and the entire fishery* (R_{total}^2)

Parameter	**Age 3**	**Age 4**	**Age 5**	**Age 6**	**Age 7**	**Age 8**	**Age 9**	**Age 10**	**Age 11**	**Age 12**	**Age 13+**
$q_{1,a}$	6.56E-08	4.81E-07	7.58E-07	1.01E-06	1.55E-06	2.07E-06	2.81E-06	3.4E-06	3.34E-06	3.28E-06	1.23E-06
$q_{2,a}$	4.22E-09	2.41E-08	4.56E-08	8.42E-08	1.62E-07	3.64E-07	6.21E-07	8.32E-07	1.23E-06	8.93E-07	5.6E-07
$q_{3,a}$	4.92E-08	3.45E-07	8.71E-07	1.34E-06	1.66E-06	2.09E-06	1.42E-06	6.87E-07	4.45E-07	5.23E-07	1.04E-07
R_1^2	-0.12	0.60	-0.52	0.90	0.87	0.80	0.55	0.89	0.50	0.41	-0.60
R_2^2	-0.21	0.29	0.89	0.94	0.95	0.94	0.79	0.96	0.98	0.91	0.78
R_3^2	0.76	0.98	0.76	0.83	0.60	0.76	0.78	0.56	0.75	-2.55	-3.88
R_{total}^2	0.57	0.96	0.74	0.83	0.66	0.78	0.75	0.85	0.73	0.55	0.51

[13] The Baranov Catch equation is often used in quantitative fisheries science. However, and although it may serve as a good approximation of more realistic catch equations, it may lead to a wrong understanding of seasonal fisheries dynamics (Liu & Heino 2013). See Diekert et al. (2010) for a more realistic modeling approach for this fishery.

[14] The catchability coefficients are estimated using a least squares method in MS Excel with data from ICES (2018), data received from IMR (which can be found in the appendix), and data from ICES (2018). I have used data for the period 2011-2015. Data on effort for the Norwegian coastal fleet has been used to represent the effort for the Norwegian conventional fleet. Data on effort for the Norwegian ocean-going fleet has been used to represent the effort for the Norwegian trawler fleet. This approximation involves some inaccuracy because the Norwegian ocean-going fleet includes conventional ocean-going vessels, which is part of the Norwegian conventional fleet in the model. The effort for other countries are estimated based on the assumption that the effort applied by other countries is proportional to effort applied by Norwegian trawl relative to harvest so that $E_{3,t} = E_{1,t} * \left(\frac{y^B_{3,t}}{y^B_{1,t}}\right)$, where $y^B_{1,t}$ is Norwegian trawlers' harvest measured in biomass in period t and $y^B_{3,t}$ is other countries' trawlers' harvest measured in biomass in period t. The Norwegian trawler fleet's catchability coefficient for age group 11 is calibrated.

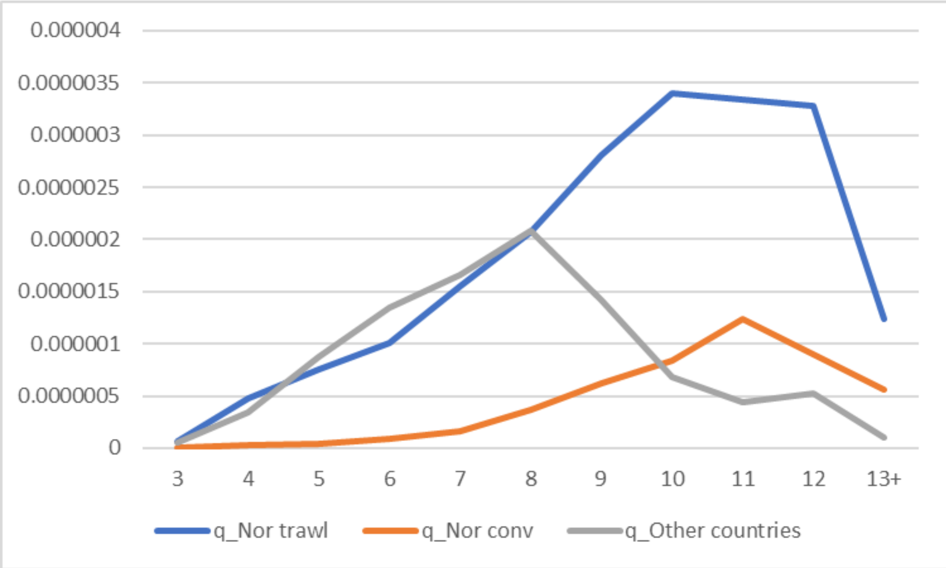

Figure 2: The fleets' gear selectivity. Numerical specification of catchability coefficients on y-axis. Age group at x-axis. q_Nor trawl = Norwegian trawler fleet, q_Nor conv =Norwegian conventional fleet and q_Other countries = Russian and third countries' trawlers.

Fleet i's total harvest measured in biomass in period t ($y^B_{i,t}$) is modeled as the sum of fleet i's harvest measured in number of individuals from each age group a in period t ($y_{i,a,t}$) multiplied by the average weight of individuals in each age group a in period t ($W_{a,t}$):

$$\textbf{(13)} \quad y^B_{i,t} = \sum_{a=3}^{13+} y_{i,a,t} * W_{a,t}$$

The total harvest measured in biomass for all fleets in period t (Y^B_t) is the sum of the total catch measured in biomass for each fleet in period t ($y^B_{i,t}$):

$$\textbf{(14)} \quad Y^B_t = \sum_{i=1}^{3} y^B_{i,t}$$

3.3 The Economic Sub-Model

3.3.1 Revenue

There are two revenue functions in the model, one for the Norwegian conventional fleet and one for the Norwegian trawler fleet. The revenue for fleet i in period t ($I_{i,t}$) depends on how much fleet i harvest in period t ($y^B_{i,t}$) and the average price faced by the fleets in period t (P_t):

$$\textbf{(15)} \quad I_{i,t} = y^B_{i,t} * P_t$$

In many age-structured models, the prices are indexed by age because larger fish tend to have a higher price/kg than smaller fish. Zimmermann et al. (2011) show that positively size-dependent pricing shifts optimal harvesting strategies towards lower harvest rates and higher mean body size of caught fish. However, the reality of the prices and price dynamics in the NEA cod fishery is way more complex than this, and although the Norwegian trawler fleet harvest more small fish relative to large fish when compared to the Norwegian conventional fleet, the Norwegian trawler fleet has experienced higher average prices/kg than the Norwegian conventional fleet multiple years (Fiskeridirektoratet 2009-2018). This can likely be explained by differences in the intra-yearly seasonal fishing pattern and differences in the fish products that are delivered and sold by the vessel groups. To achieve a more realistic picture of the price dynamics and avoid giving the Norwegian conventional fleet a potentially undeserved advantage, it is assumed that both fleets face the same average price in period t (P_t). The average price in period t (P_t) is modeled as a function of the historical average price (P_{avg}), the total harvest (Y^B_t) relative to the historical average total harvest (Y^B_{avg}) and a price elasticity (p):

$$\textbf{(16)} \qquad \boldsymbol{P_t = P_{avg} * \left(\frac{Y^B_t}{Y^B_{avg}}\right)^p}$$

The historical average price per kg (P_{avg}) is calculated with data from the Norwegian Directorate of Fisheries and Norges Bank. The historical average total harvest (Y^B_{avg}) is calculated with ICES data. The price elasticity (p) is roughly estimated by log-log regression on the same data that was used to calculate P_{avg} and Y^B_{avg}. The parameter values are presented in table 5[15].

Table 5: Numerical specification of the parameters in the price function

Parameter	Parameter value
P_{avg}	11.8 NOK/kg
Y^B_{avg}	780 921 tons
p	-0.308

[15] The numerical specification of P_{avg} and Y^B_{avg} are based on data from Fiskeridirektoratet (2009-2018), the Norwegian central bank (to adjust for inflation) and ICES (2018). Average values from the period 2009-2016 have been calculated and applied to the model.

3.3.2 Costs

There are two cost functions in the model, one for Norwegian conventional vessels and one for Norwegian trawlers. The total costs for each fleet in period t ($TC_{i,t}$) depends on the number of vessels in operation in fleet i in period t $\left(\frac{E_{i,t}}{E_{i,avg}}\right)$, the average unit cost related to operating a vessel in fleet i (C^D_i), the total effort applied by fleet i in period t ($E_{i,t}$), the average unit cost related to applying effort for fleet i (C^E_i), the revenue for fleet i in period t ($I_{i,t}$) and the share of revenue that goes to paying the crew and fees (C^L_i):

$$\textbf{(17)} \quad \boldsymbol{TC_{i,t} = \frac{E_{i,t}}{E_{i,avg}} * C_i^D + E_{i,t} * C_i^E + I_{i,t} * C_i^L.}$$

The average effort applied by fleet i per year ($E_{i,avg}$) is calculated with data from the Norwegian Directorate of fisheries. The cost parameters are estimated with data from the Norwegian Directorate of fisheries and data from the Norwegian central bank. The parameter values are presented in table 6[16].

Table 6: Numerical specification of the parameters in the cost functions

Parameter	Parameter value
C_1^D	4 696 213 NOK
C_2^D	528 189 NOK
C_1^E	12 473 NOK
C_2^E	1118 NOK
C_1^L	0.354
C_2^L	0.46
$E_{1, avg}$	305
$E_{2, avg}$	155

3.3.3 Profit

The profit for fleet i in period t ($\pi_{i,t}$) equals the revenue for fleet i in period t ($I_{i,t}$) minus the total costs for fleet i in period t ($TC_{i,t}$):

[16] The numerical specification of the cost parameters is based on data from Fiskeridirektoratet (2009-2018) and the Norwegian central bank (to adjust for inflation). Data for the period 2009-2016 has been used. Costs related to depreciation and normal taxes have been excluded. The costs have then been adjusted for inflation and categorized according to the cost structure in the model. All costs have been measured in 2016 NOK. To estimate C^D_i and C^E_i, average values for the period has been calculated by categorization and multiplied by a factor equal to the average share of revenue that was generated by the harvest of cod in the period 2009-2016. C^L_i has been estimated by calculating the average of the yearly share of total revenue that was used to pay crew and fees in fleet i.

$$\boldsymbol{\pi_{i,t} = I_{i,t} - TC_{i,t}} \tag{18}$$

The total profit for the Norwegian part of the fishery in period t (π_t) is formulated as:

$$\boldsymbol{\pi_t = \pi_{1,t} + \pi_{2,t}} \tag{19}$$

3.3.4 Net Present Value

The NPV of the Norwegian part of the fishery is defined as the sum of discounted profits for the Norwegian part of the fishery and depends on the discount factor (δ), the total profit for the Norwegian part of the fishery in period t (π_t) and the time horizon of the model (T).

$$\boldsymbol{NPV = \sum_{t=0}^{T} \delta^t \pi_t} \tag{20}$$

The discount rate is set to 5%, which implies a discount factor (δ) of 0.9523. And the model is solved for T=65 years. The choice of a long time horizon is motivated by my focus on steady-state scenarios.

3.3 Initialization of the Model

The model is initialized with somewhat arbitrary, but reasonable values for $N_{a,\ t=0}$, $M_{a,\ t=0}$, $SSB_{t=0-2}$ and $SSB_{t=0-1}$. These values are needed to start the model.

4 Simulations

The prospective biological and economic gain/loss from applying different management strategies will be illustrated by scenarios in which a hypothetical sole owner chooses effort levels to maximize either total harvest in period t=65 (Equation 14) or the net present value of the Norwegian part of the fishery for the model period (Equation 20), subject to different constraints.

The constraints implied by the fish stock dynamics (equations 1, 2, 4, 5, 6, 8 and 11, and the model initialization values) apply to all scenarios. Other constraints are scenario-specific and concern whether effort can vary between years and the distribution of the total harvest in terms of shares. When studying the concepts of MSY and MEY, which involve steady-state fishing, effort is not allowed to vary between years, i.e. $E_{i,t} = E_{i,t+1}$ for all fleets i=1, 2, 3 and all periods t=0, 1, …, 65. Since the model is deterministic, applying the same effort each year allows rapid convergence to steady-state. When studying the concept of MNPV, which may involve strategies such as pulse fishing, effort may vary between years. Table 7 provides an overview of simulated scenarios. The MS Excel Solver add-in and its GRG nonlinear solver has been used to solve the optimization problems. All simulations have been conducted several times with different initialization values. In steady-state simulations, the a final run is simulated with the model initialized at previously reported steady-state levels. This is done to ensure optimum results.

Table 7: An overview of simulated scenarios/solved optimization problems

Management scenario	**Objective**	**Effort allowed to vary between years? (Yes/No)**	**International distribution of TAC**	**Distribution of Norwegian share of TAC**
Today's management	MSY	No	Today's international distribution	Today's Norwegian distribution
MSY_NQMB	MSY	No	Today's international distribution	Determined endogenously
MSY_NQNT	MSY	No	Today's international distribution	Entire share to Fleet 1 (Nor conv)
MSY_MB	MSY	No	Determined endogenously	Determined endogenously
MSY_NT	MSY	No	Entire share to the Norwegian part of the fishery	Entire share to Fleet 1 (Nor trawl)
MSY_OCT	MSY	No	Entire share to Fleet 3 (Foreign trawl)	-
MEY_CQP	MEY	No	Today's international distribution	Today's Norwegian distribution
MEY_NQMB	MEY	No	Today's international distribution	Determined endogenously
MEY_NQNC	MEY	No	Today's international distribution	Entire share to Fleet 2 (Nor conv)
MEY_MB	MEY	No	Determined endogenously	Determined endogenously
MEY_NT	MEY	No	Entire share to the Norwegian part of the fishery	Entire share to Fleet 1 (Nor trawl)
MNPV_NQMB	Maximize NPV	Yes	Today's international distribution	Determined endogenously
MNPV_MB	Maximize NPV	Yes	Determined endogenously	Determined endogenously
MNPV_NT	Maximize NPV	Yes	Entire share to the Norwegian part of the fishery	Entire share to Fleet 1 (Nor trawl)

5 Results and Discussion

The main results from the simulation scenarios presented in table 6 are shown in table 7. In the following, I will account for the results and discuss their implications. In addition, I will provide a sensitivity analysis.

Table 8: Main results from simulated scenarios/solved optimization problems

Management scenario	Participating fleet(s) (share of total harvest)	Yearly harvest (thousand tons)	SSB (thousand tons)	Yearly profits (million NOK)*	NPV (billion NOK)*
Today's management	1 (15%), 2 (30%), 3 (55%)	659	1 652	262	5
MSY_NQMB	2 (45%), 3 (55%)	675	1 697	281	6
MSY_NQNT	1 (45%), 3 (55%)	624	1 605	199	4
MSY_MB	2 (100%)	793	2 587	2 125	43
MSY_NT	1 (100%)	692	2 172	1 685	34
MSY_OCT	3 (100%)	564	1 264	-	-
MEY_CQP	1 (15%), 2 (30%), 3 (55%)	551	3 846	1 259	25
MEY_NQMB	1 (45%) and 3 (55%)	502	4 145	1 266	25
MEY_NQNC	2 (45%) and 3 (55%)	575	3 720	1 257	25
MEY_MB	2 (100%)	701	4 397	3 351	67
MEY_NT	1 (100%)	583	4 445	3 211	65
MNPV_ NQMB	1 (12%), 2 (33%), 3 (55%)**	538**	4037**	1272**	26
MNPV_MB	2 (100%)	699	4 408	3 351	67
MNPV_NT	1 (100%)	581	4 455	3 211	65

* No economic details have been modeled for fleet 3. The economic results must be interpreted accordingly.
** Cyclical fishing pattern. Average values over the cycles are reported.

5.1 Maximum Sustainable Yield

5.1.1 Today's Management Scenario

Today's management scenario is simulated by maximizing the sustainable biological yield subject to today's international and national allocation of the TAC in terms of shares. The yearly harvest is estimated at 658 thousand tons in steady-state. This estimate is in the range of MSY-estimates provided by Kovalev and Bogstad (2005). The associated SSB is estimated at 1.65 million tons. The associated economic yield is estimated at 262 million NOK. Fleet 1 and Fleet 2's profit margins are both estimated at about 7.1%. However, the profit margin of Fleet 1 is slightly higher than the profit margin of Fleet 2. The associated NPV is calculated to 5.27 billion NOK.

5.1.2 MSY with Optimal Allocation of the Norwegian Share of the TAC

MSY_NQMB denotes the scenario in which today's management strategy concerning the determination and international allocation of the total quota is maintained, while the allocation of the Norwegian share of the total quota is determined endogenously. It is simulated by maximizing the sustainable yield with respect to effort subject to today's international allocation of the total quota in terms of shares. The results show that it is optimal, both from a biological and economic perspective, and under the given conditions, to allocate the entire Norwegian share of the total quota to Fleet 2. The yearly harvest is estimated at 675 thousand tons with an associated SSB at 1.7 million tons – an increase of about 2.6% and 3%, respectively, from today's management scenario – a significant increase considering only 15% of the TAC is reallocated. The associated sustainable economic yield is estimated at 281 million NOK – an increase of about 7.3% from today's management scenario. Fleet 2's profit margin is estimated at 7.5% - slightly higher than the overall profit margin in today's management scenario. The NPV is calculated to 5.66 billion NOK.

Considering the fleets' selection pattern and the findings in earlier research (see figure 2, section 1.3 and section 2 for a reminder), the biological results are unsurprising. Fleet 2 targets more old cod relative to young cod than Fleet 1. In line with earlier research, I find that an increase in the utilization of Fleet 2 at the expense of the utilization of Fleet 1 leads to an increase in the realization of the growth potential of the stock – more young cod grows into becoming old cod before it is harvested, and this results in a higher sustainable yield and SSB.

It is interesting that, although Fleet 1's profit margin is higher than Fleet 2's profit margin in today's management scenario, it is optimal, not only from a biological perspective, but also from an economic perspective, and under the given conditions, to allocate the entire Norwegian share of the total quota to Fleet 2. It is, however, logical. It can be partly explained by the increase in the realization of the growth potential of the stock. In addition, there is another mechanism that also plays an important role. When fewer young cod is caught, more cod grows into becoming old cod, and this gives a higher harvest per unit effort (see equation 11) which in turn gives lower harvest costs per kg. This positive effect outweighs the negative effect that the increase in harvest has on the average price (see equation 15) and results in a higher profit for the Norwegian part of the fishery.

MSY_NQNT denotes the scenario in which today's management strategy concerning the determination and international allocation of the total quota is maintained, while the entire Norwegian share of the total quota is allocated to Fleet 1. It is simulated by maximizing the sustainable biological yield with respect to effort subject to today's international allocation of the total quota and a constraint that hinders the use of Fleet 2. This simulation is done to highlight the negative effect that the utilization of Fleet 1 at the expense of the utilization of Fleet 2, has on the realization of the stock's growth potential. The yearly harvest is estimated at 624 thousand tons with an associated SSB at 1.6 million tons – a decrease of about 7.6% and 5.9%, respectively, from the *MSY_NQMB* scenario. The associated economic yield is estimated at 199 million NOK, a decrease of about 29.2% from the *MSY_NQMB* scenario. Fleet 1's profit margin is estimated at 5.6% - 1.9% less than Fleet 2 in the *MSY_NQMB* scenario. The NPV is calculated to 4 billion NOK.

5.1.3 MSY with Optimal Allocation of the TAC

MSY_MB denotes the scenario in which today's management strategy concerning the determination of the total quota is maintained, while the international and national allocation of the total quota is determined endogenously. It is simulated by maximizing the sustainable biological yield with respect to effort subject to no constraints concerning the allocation of the total quota. In line with the results from section 5.1.2, the results show that it is optimal, both from a biological and economic perspective and under the given conditions, to allocate the entire total quota to Fleet 2. The yearly harvest is estimated at 793 thousand tons with an associated SSB at 2.59 million tons – an increase of about 20.5% and 57%, respectively, from today's management scenario. The associated economic yield is estimated at 2.12 billion NOK. This result is not directly comparable with results from simulations where Fleet 3 gets 55% of the total quota since no economic details have been described for this fleet. However, by assuming that the Norwegian part of the fishery get 45% of the yearly profits, while Russia and third countries get 55% of yearly profits, the result can be made comparable with results from simulations where Fleet 3 gets 55% of the total quota. By applying this assumption, the associated economic yield is estimated at 954 million NOK – an increase of 692 million NOK from today's management scenario. Fleet 2's profit margin is estimated at 22.8% - significantly higher than the profit margins in today's management scenario. The associated NPV is calculated to 19.23 billion NOK. The drivers behind the results are the same as those explained in section 5.1.2.

MSY_NT and MSY_OCT denote the scenarios in which today's management strategy concerning the determination of the total quota is maintained, while the entire total quota is allocated to Fleet 1 and Fleet 3, respectively. These simulations are done to highlight the differences between the fleets' selection patterns/ability to realize the stock's growth potential. The results highlight the fact that Fleet 3 has a highly inefficient selection pattern when compared to Fleet 1 and Fleet 2. To be able to defend the utilization of Fleet 3 from an economic sole owner perspective, the harvesting costs per kg experienced by Fleet 3 must be significantly lower than the harvesting costs per kg experienced by Fleet 1 and Fleet 2.

5.2 Maximum Economic Yield

5.2.1 MEY with Today's Allocation of the TAC

MEY_CQP denotes the scenario in which today's management strategy concerning the international and national allocation of the total quota is maintained, while the strategy concerning the determination of the total quota is changed to maximize the sustainable economic yield. It is simulated by maximizing the sustainable economic yield with respect to effort subject to today's international and national allocation of the total quota in terms of shares. The sustainable yield is estimated at 551 thousand tons with an associated SSB at 3.84 million tons – a decrease of 16.3% and an increase of 132%, respectively, from today's management scenario. The sustainable economic yield is estimated at 1.26 billion NOK – an increase of about 1 billion NOK from today's management scenario. Fleet 1's profit margin is estimated at 42.7%, while fleet 2's profit margin is estimated at 40.7% - much higher than the profit margins in today's management scenario. The associated NPV is calculated to 25.3 billion NOK. The main drivers behind the results are the positive effect that an increase in the number of individuals in the different age groups has on harvest per unit effort and the positive effect that a reduction in the overall harvest has on the average price. These positive effects outweigh the negative effect of lower yearly harvest.

5.2.2 MEY with Optimal Allocation of the Norwegian Share of the TAC

MEY_NQMB denotes the scenario in which today's management strategy concerning the international allocation of the total quota is maintained, while the strategy concerning the determination of the total quota is to maximize the sustainable economic yield, and the allocation of the Norwegian share of the total quota is determined endogenously. It is simulated by maximizing the sustainable economic yield with respect to effort subject to today's international allocation of the total quota in terms of shares. The results show that it is optimal, from an economic perspective and under the given conditions, to allocate the entire Norwegian share of the total quota to Fleet 1. The yearly harvest is estimated at 502 thousand tons with an associated SSB at 4.1 million tons – a reduction of 8.9% and an increase of 6.7%, respectively, from the MEY_CQP scenario. The sustainable economic yield is estimated at 1.27 billion NOK

– almost the same as in the MEY_CQP scenario. In other words, there is little to gain in economic terms by changing the allocation of the Norwegian share of the total quota in terms of shares. Fleet 1's profit margin is estimated at 44% - about 1.3% higher than Fleet 1's profit in the MEY_CQP scenario. The NPV is calculated to 25.47 billion NOK.

MEY_NQNC denotes the scenario in which today's management strategy concerning the international allocation of the total quota is maintained, while the strategy concerning the determination is changed, and the entire Norwegian share of the total quota is allocated to Fleet 2. It is simulated by maximizing the sustainable economic yield with respect to effort subject to today's international allocation of the total quota and a constraint that hinders the use of Fleet 1. The yearly harvest is estimated at 575 thousand tons with an associated SSB at 3.7 million tons. When compared to the MEY_NQMB scenario, this corresponds to an increase of 14.2% in yearly harvest and a decrease of 9.8% in the SSB. The sustainable economic yield is estimated at 1.26 billion NOK – the same as in the MEY_CQP scenario, and slightly lower than in the MEY_NQMB scenario. The last result shows that the allocation of the Norwegian share of the total quota is not so important, seen from an economic perspective, when the goal is to maximize the sustainable economic yield under the given conditions. Fleet 2's profit margin is estimated at 40% - slightly lower than Fleet 2's profit margin in the MEY_CQP scenario, and 4% lower than Fleet 1's profit margin in the MEY_NQMB scenario. The NPV is calculated to 25.3 billion NOK.

The biological results from the MEY_NQMB and MEY_NQNC are key to understanding why it proves to be optimal to allocate the entire Norwegian share of the total quota to Fleet 1 when the goal is to maximize the sustainable economic yield under the given conditions. The result might appear surprising to some considering the MSY_CQP, MSY_NQMB and MSY_NQNC results. However, it is logical and easily explained. The yearly harvest in the MEY_NQMB scenario is significantly lower than in the MEY_NQNC scenario, hence the average price per kg of fish is higher. Furthermore, the SSB is higher, which is a result from a lower fishing pressure that gives a higher number of individuals in several age groups in steady-state, and this gives a higher harvest per unit effort which induces lower harvest costs per kg. Addressing the last effect and comparing the MSY_NQNC scenario with the MSY_CQP and MSY_NQMB scenario, the opposite was the case. The SSB and the number of individuals in several age groups were lower in the scenario where only fleet 1 and fleet 3 were utilized (MSY_NQNC) when compared to the other two scenarios (MSY_CQP and MSY_NQMB). As a result, Fleet 1 experienced higher harvest costs per kg in the MSY_NQNC scenario when compared to the

MSY_CQP scenario. The sum of the two positive effects outweighs the negative effect of a lower yearly harvest and explain why it is optimal to allocate the entire Norwegian share of the total quota to Fleet 1 under the given conditions in the MEY_NQMB scenario – although it is by slight margins.

5.2.3 MEY with Optimal Allocation of the TAC

MEY_MB denotes the scenario in which the strategy concerning the determination of the total quota is to maximize the sustainable economic yield and the allocation of the total quota is determined endogenously. It is simulated by maximizing the sustainable economic yield with no constraints concerning the allocation of the total quota. The results show that it is optimal, from an economic perspective, to allocate the entire total quota to Fleet 2. The yearly harvest is estimated at 701 thousand tons with an associated SSB at 4.4 million tons. The sustainable economic yield is estimated at 3.35 billion NOK. As earlier, it is assumed that the Norwegian part of the fishery gets 45% of these profits since Fleet 3 doesn't participate. By applying the assumption, the sustainable economic yield is estimated at 1.5 billion NOK – an increase of 240 million from the MEY_CQP scenario. The associated NPV is calculated to 30.38 billion NOK.

MEY_NT denotes the scenario in which the strategy concerning the determination of the total quota is to maximize the sustainable economic yield and the entire total quota is allocated to Fleet 1. It is simulated by maximizing the sustainable economic yield subject to a constraint that hinders the utilization of Fleet 2. Since no economic details are described for Fleet 3, it is not necessary to apply a constraint that hinders the utilization of this fleet – it is automatically left out of the competition. The yearly harvest is estimated at 583 thousand tons with an associated SSB at 4.44 million tons. Compared to the MEY_MB scenario, this corresponds to a decrease of 28.9% in yearly harvest and a relatively small increase of less than 1% in the SSB. The economic yield is estimated at 3.21 billion NOK. Assuming the Norwegian part of the fishery gets 45% of these profits, the sustainable economic yield is estimated at 1.44 billion NOK – a decrease of 60 million when compared to MEY_MB scenario. The associated NPV is calculated to 29.05 billion NOK.

In the MEY_NQMB scenario, it proved to be optimal to allocate the entire Norwegian share of the total quota to Fleet 1. In this scenario, Fleet 3 was also participating, harvesting 55% of the yearly total harvest. In the MEY_MB scenario, Fleet 3 is not participating, and this is the reason why it is optimal to utilize only Fleet 2. When Fleet 3 does not participate, more of the stock's growth potential can be realized, and this is the main explanation to why it is optimal to utilize only Fleet 2 under the given conditions in the MEY_MB scenario.

5.3 Maximum Net Present Value

5.3.1 MNPV with Optimal Allocation of the Norwegian Share of the TAC

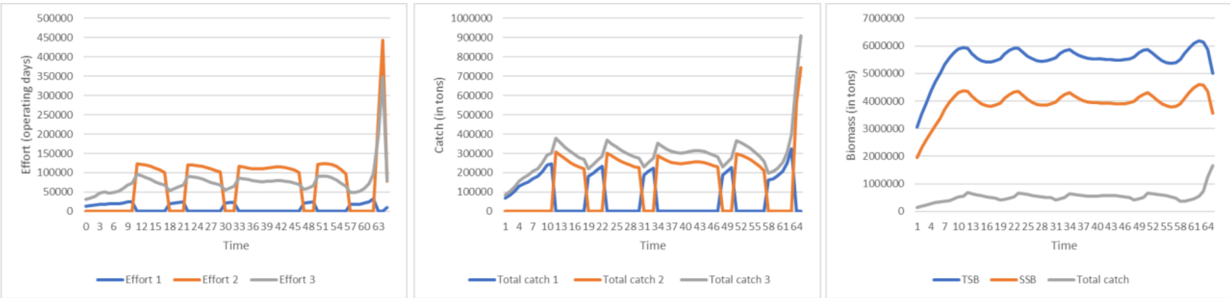

Figure 3: MNPV$_{NQMB}$ results (Left: Effort over the model period. Middle: Harvest by fleet over the model period. Right: total stock biomass (TSB), SSB and Total harvest over the model period)

MNPV_NQMB denotes the scenario in which the strategy concerning the international allocation of the total quota is maintained, while the strategy concerning the determination of the total quota is changed to maximize the net present value of the Norwegian part of the fishery. It is simulated by maximizing the net present value of the Norwegian part of the fishery with respect to effort subject to today's international allocation of the total quota in terms of shares. The results show that is optimal to apply a cyclical fishing pattern with alternation between intense harvesting and less intense harvesting with stock recovery (see figure 3). Furthermore, the results show that it is optimal to make use of Fleet 1 in periods with relatively low harvest and make use of Fleet 2 in periods with relatively high harvest. The average yearly harvest is estimated at 538 thousand tons with the SSB averaging at 4 million tons – a decrease of about 2.4% and an increase of about 4.1%, respectively, from the MEY_CQP scenario. The average yearly economic yield is estimated at 1.27 billion NOK – about the same as in the MEY_NQMB scenario. The associated NPV is calculated at 25.58 billion NOK. In other words, and compared to the MEY_NQMB scenario, there is not much to gain in economic terms by applying a cyclical fishing pattern.

5.3.2 *MNPV with Optimal Allocation of the TAC*

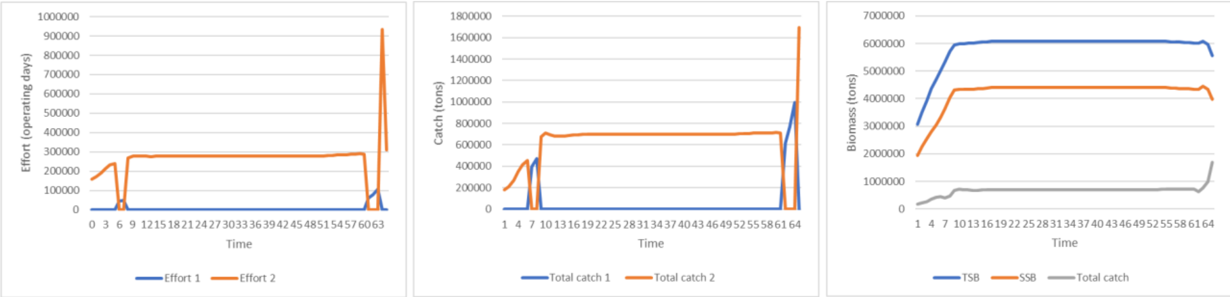

Figure 4: $MNPV_{MB}$ results (Left: Effort over the model period. Middle: Harvest by fleet over the model period. Right: total stock biomass (TSB), SSB and Total harvest over the model period)

MNPV_MB denotes the scenario in which the objective is to maximize the net present value of the Norwegian part of the fishery with the international and national allocation of the total quota determined endogenously. It is simulated by maximizing the net present value of the Norwegian part of the fishery with effort being allowed to vary between years subject to no constraints concerning the allocation of the total quota. The results are in line with the MEY_MB results (see figure 4).

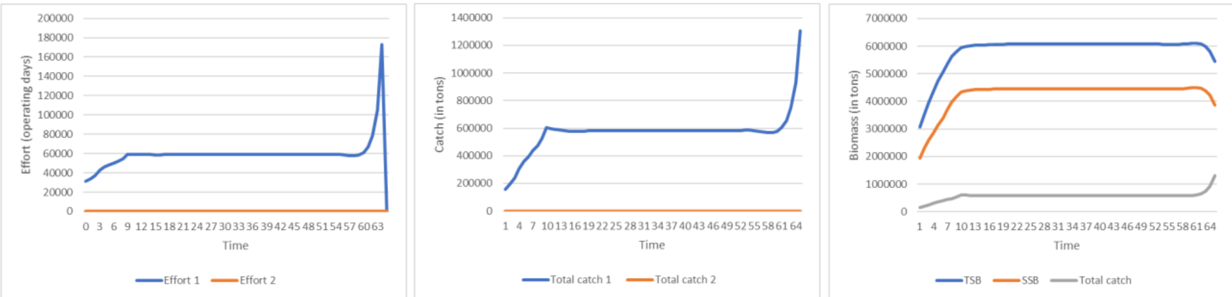

Figure 5: $MNPV_{NT}$ results (Left: Effort over the model period. Middle: Harvest by fleet over the model period. Right: total stock biomass (TSB), SSB and Total harvest over the model period)

MNPV_NT denotes the scenario in which the objective is to maximize the net present value of the Norwegian part of the fishery with the entire total quota allocated to Fleet 1. It is simulated by maximizing the net present value of the Norwegian part of the fishery with effort being allowed to vary between years subject to a constraint that hinders the use of Fleet 2. The results are in line with the MEY_NT results (see figure 5).

The MNPV_NQMB, MNPV_MB and MNPV_NT results, together with the MEY_NQMB, MEY_MB and MEY_NT results, highlights the fact that Fleet 3 has a highly inefficient selection pattern. And in line with Diekert et al. (2010), it is shown that the utilization of this fleet generates a cyclical fishing pattern when the stock management strategy is to maximize the NPV.

5.3 Discussion

All in all, the results indicate that the NEA cod stock has biological and economic potential that cannot be realized with today's management policies and overall selection pattern. Biological gains in terms of an increase in the sustainable yield can be achieved by altering the selection pattern through changes in the fleet-composition. In addition, assuming the international distribution of the yearly profits reflects today's distribution of the TAC, the results indicate that significant economic gains in terms of an increase in the net present value for the Norwegian part of the fishery can be achieved by changing the fleet-composition and reducing the overall fishing pressure.

In line with Helgesen et al. (2018), I find that the biological optimum optimorum is obtained by choosing a stock management strategy that involves maximizing the sustainable yield and allocating the entire total quota to the Norwegian conventional fleet (MSY_MB). In line with Sumaila (1997), and in contrast with Diekert et al. (2010), I find that the economic optimum optimorum is obtained by choosing a stock management strategy that involves maximizing the NPV for the Norwegian part of the fishery and allocating the entire TAC to the Norwegian conventional fleet (MEY_MB/MNPV_MB). However, the Norwegian trawler fleet is competitive and could be utilized without significant economic losses when the stock management strategy is to maximize the NPV. Since no economic details are described for the Russian and third countries' trawler fleet it is not possible to conclude that this fleet is uncompetitive. However, it is certain that the utilization of this fleet with its current selection pattern has a negative impact on the Norwegian part of the fishery. And from an economic sole owner perspective, the utilization of this fleet may only be defended if the harvest costs per kg are significantly lower for this fleet than for the other fleets.

The MEY and MNPV results are associated with SSB levels in the range of 3.7 to 4.4 million tons. As the spawning stock biomass has varied between 102 thousand tons and 2.66 million tons since 1980, and the peak of 2.66 million tons can be partly explained by two particularly strong year classes of cod, one could argue that convergence to such high and stable SSB levels appears unrealistic. Assuming estimated relationships for natural mortality, weight at age, recruitment, gear selectivity etc. are valid for higher stock levels may not be appropriate. And the results should be viewed in that context as one is extrapolating outside the range of stock sizes explored for the period when data are available. Diekert et al. (2010) who end up with optimal cod stock levels in the range of 4.5 to 6 million tons, argue that the cod stock has been estimated to have reached 5 million tons in 1936 when the fishing pressure in the Lofoten area was significant, and that high cod stock levels could be achieved. However, a spawning stock biomass of e.g. 4.4 million tons corresponds to a cod stock of about 6 million tons (in the MEY_MB and MNPV_MB scenarios), which is higher than the estimated peak level in 1936. Furthermore, the cod stock declined following several years of intensive fishing in the 1930s (Hylen 2002). In other words, it is highly uncertain that high and stable cod stock levels well above 5 million tons may be achieved with significant fishing pressure.

In addition to the mentioned uncertainties above, it is important to remember that the model presented here is a single-species model. It is possible that high cod stock levels may have undesired direct and indirect effects on other commercial stocks such as capelin, herring, shrimp and haddock. In addition, the fleets targeting the NEA cod target other species as well. It is possible that changes in the selection pattern and fishing pressure on the NEA cod could result in unwanted changes in the selection pattern and fishing pressure on other stocks, for which fish caught is usually smaller than the NEA cod. Such effects should be accounted for as well.

Since the NEA cod stock is a shared stock and subject to joint management by Norway and Russia, the biological and economic optimum optimorum scenarios may be viewed as highly unrealistic scenarios. The scenario in which the stock management strategy and international distribution of the TAC remain unchanged, while the distribution of the Norwegian share of the TAC is determined endogenously, might be the most interesting and realistic alternative scenario simulated. As mentioned, there is currently an ongoing Norwegian debate concerning whether "Trålstigen" should be maintained. Therefore, it seems realistic that changes in the distribution of the Norwegian share of the TAC could happen. Intuitively, people may think that it would be economically beneficial to allocate more of the Norwegian share of the TAC to the Norwegian trawler fleet since it typically has higher profit margins than the Norwegian conventional fleet (Fiskeridirektoratet 2009-2018). However, the results from the MSY_NQMB scenario indicate that it is optimal to allocate the entire Norwegian share of the TAC to the Norwegian conventional fleet even though the Norwegian trawler fleet has a higher profit margin than the Norwegian conventional fleet in today's management scenario. Although the economic benefits from allocating the entire Norwegian share of the TAC to Norwegian conventional vessels may be considered insignificant due to uncertainties in the model, the result could be of great interest for managers, the industry, politicians and the public.

5.4 Sensitivity Analysis

Since the projections of alternative management scenarios rest on empirically estimated parameters, and many of the estimates are uncertain due to fundamental uncertainties in marine systems, above differences between model and reality and the rough approaches used in the estimation of several parameters, the sensitivity of the MEY_MB/MNPV_MB and MSY_NQMB outcomes has been tested.

When raising the costs of the Norwegian conventional fleet by 5%, the Norwegian trawler fleet takes over as the producer of the economic optimum optimorum (MEY_MB/MNPV_MB). Furthermore, the Norwegian trawler fleet proves to be the economically optimal producer in the scenario in which the goal is to maximize the sustainable yield subject to today's international distribution of the TAC (MSY_NQMB). When raising the catchability coefficients of the Norwegian trawler fleet by 10%, both the Norwegian conventional fleet and trawler fleet are utilized in the optimum optimorum scenario (MEY_MB/MNPV_MB). And as in the scenario where the costs of the Norwegian conventional fleet were raised by 5%, the Norwegian trawler fleet proves to be the economically optimal producer in the scenario in which the goal is to maximize the sustainable yield subject to today's international distribution of the TAC (MSY_NQMB). Raising the average historical price (the basis for the price determination in the model) makes the Norwegian trawler fleet better off relative to the Norwegian conventional fleet. Considering the uncertainties in the model, these results reaffirm that the Norwegian trawler fleet is competitive with the Norwegian conventional fleet.

6 Conclusions and Suggestions for Further Work

The main objective of this study was to provide a policy-relevant, bioeconomic analysis of different management strategies concerning the determination and allocation of the total quota for NEA cod. By use of a bioeconomic model, it is shown that the NEA cod fishery has biological potential that cannot be realized with today's management policies and overall selection pattern. The same goes for the economic potential of the Norwegian part of the fishery.

Biological gains in terms of an increase in the sustainable yield may be achieved by changing the fleet-composition while maintaining today's stock management strategy. Economic gains may be achieved by changing the fleet-composition and reducing the overall fishing pressure. The Norwegian conventional fleet has the most efficient selection pattern which gives it a bioeconomic advantage. However, the Norwegian trawler fleet compensates for a more inefficient selection pattern with a cost-advantage. Economically speaking, the overall results indicate that it is not significant which of these fleets are utilized – it is the Russian and third countries' trawler fleet that has the most inefficient selection pattern, and the use of this fleet has a negative economic impact on the Norwegian part of the fishery. From an economic sole owner perspective, the use of the Russian and third countries' trawler fleet, with its overall selection pattern, may only be defended if its harvest costs per kg are significantly lower than that of the other fleets.

For further work, it could be interesting to include economic details for the Russian and third countries' trawler fleet. Furthermore, more realistic harvest functions could be applied to the model – harvest functions that consider the seasonal fishing pattern in the NEA cod fishery and possible stock elasticities. Including predator-prey relations and other relevant fish stocks could result in a more useful model.

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Appendix

Data from IMR

Table A1: Catch number in thousands by age and fleet for 2015

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	10	20	4	34
2	210	270	159	639
3	930	840	2545	4315
4	4130	3090	24163	31383
5	2750	2150	36281	41181
6	5110	3240	42859	51209
7	3440	3670	26635	33745
8	2660	3440	16430	22530
9	1460	7240	14909	23609
10	4810	12290	7453	24553
11	7010	7140	1921	16071
12	830	1220	460	2510
13		420	48	468
14	20	110	4	134
15+	30	210	14	254

Table A2: Catch number in thousands by age and fleet for 2014

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	10		7	17
2	300	30	294	624
3	1090	560	3584	5234
4	3220	1360	14646	19226
5	5400	2090	30917	38407
6	2500	2600	31533	36633
7	4120	2490	23291	29901
8	7980	12150	35979	56109
9	5430	17080	25030	47540
10	4920	10800	7018	22738
11	440	2120	1157	3717
12	90	740	339	1169
13	190	80	43	313
14		210	0	210
15+	20	130	7	157

Table A3: Catch number in thousands by age and fleet for 2013

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1		0	1	1
2		10	228	238
3	490	170	2243	2903
4	3370	770	9519	13659
5	4130	1920	16702	22752
6	3560	1850	15610	21020
7	8990	6470	38771	54231
8	10240	16580	47631	74451
9	11400	17700	18024	47124
10	900	4460	3783	9143
11	240	1690	1033	2963
12	20	380	294	694
13	40	310	99	449
14		60	29	89
15+	90	50	5	145

Table A4: Catch number in thousands by age and fleet for 2012

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1			44	44
2			167	167
3	410	230	2055	2695
4	1800	670	7992	10462
5	3330	940	12376	16646
6	6300	3790	30282	40372
7	10610	10620	48784	70014
8	7990	13650	26675	48315
9	1540	5800	4986	12326
10	320	3250	1644	5214
11		1210	716	1926
12	10	750	364	1124
13	30	200	87	317
14	10	40	20	70
15+		20	4	24

Table A5: Catch number in thousands by age and fleet for 2011

Age	Nor trawl	Nor other	Other countries (trawl)	Total
1	14	14	10	38
2	216	45	172	433
3	201	234	983	1418
4	2601	1334	4100	8035
5	5571	3600	23304	32475
6	11248	8539	51158	70945
7	13110	12653	48127	73890
8	2228	7401	11507	21136
9	1722	6314	3683	11719
10	1088	2684	1292	5064
11	876	1531	832	3239
12	10	370	220	600
13	120	249	65	434
14				12
15+				