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Optimal Age- and Gear-specific Harvesting Policies for North-East Arctic Cod*

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Running Title (41 characters)**:**

Optimal Age- and Gear-specific Harvesting

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Abstract

We examine optimal harvest policies in a multi-cohort, multi-gear bioeconomic model of North-East Arctic cod (*Gadus morhua*) which includes cannibalism and contains broader ecosystem effects. By controlling the selectivity of the different fishing equipment, we can partially target different age cohorts. We show that current gear selectivity implies that the wrong fish are targeted. Optimization shifts the exploitation pattern towards older and heavier fish. This increases the harvested biomass while reducing the number of fish removed from the ocean. The result is a much more robust and abundant cod stock with an age/size distribution closer to the stocks natural state. We optimize the Net Present Value (NPV) generated by the fishery by letting effort and selectivity be the control variables and find that NPV may be more than doubled, even when only gear selectivity or harvest effort is allowed to vary. (141 words)

Keywords: Bioeconomics, North-East Arctic cod, Age-structure, Gear selectivity, Optimal harvest policies.

1 Introduction

Atlantic cod (*Gadus morhua*) is currently being threatened by over-fishing. Overall catches that once have been rich are declining, and some fisheries had to be closed as stocks have collapsed. The fish stock of the Barents Sea, the North-East Arctic (NEA) cod, is one of the few cod stocks in a "reasonably good condition"[1]. Nevertheless, scientific analysis (see e.g. Arnason et al. [6, p.531]) has repeatedly shown that the harvesting pattern is "hugely inefficient". Not only have catches and quotas been consistently above scientific advice [1], but catch by age has also been consistently shifted towards younger age classes [27, 38]. Here we provide an estimate of the magnitude of economic gains by optimizing the exploitation pattern of the NEA cod fishery.

In general, the main part of the literature on fisheries rests on a "lumped parameter" description of the underlying biological system. Due to the analytically appealing, but overly simplifying properties of these models, it has been claimed that fishery economics has had a limited impact on actual fisheries management [55]. It is becoming increasingly clear that summarizing the fish stock by one or two variables leads to unacceptable large deviations in optimal policy prescriptions [52]. Lumped parameter models fail to take the full growth potential of the biological resource into account, and in particular, they cannot capture the effect of gear selectivity, and are therefore, as Wilen [54, p.219] puts it; "better left for pedagogical use". More complex, age-structured models are needed to take account of the effects of individual life histories and ecosystem interactions that shape the resource dynamics. The most prominent aspect is clearly the fact that the individual fish grow in length and weight, while their overall numbers declines with age due to natural and fishing mortality. Consequently, the question of optimal management becomes not only how many fish should be harvested, but also a question of which age- and weight classes should be

[1]Fiskeri og Kystdepartementet (FKD) *North East Arctic Cod – fisheries.no*, Online, accessed April 25, 2008, from `http://www.fisheries.no/marine_stocks/fish_stocks/cod/north_east_arctic_cod.htm`

harvested. Additionally, not only "growth overfishing", where too many, inefficiently small, specimen are targeted, but also "reproductive overfishing", where fish are caught before they are able to spawn, has to be avoided [30]. High fishing pressure necessarily has ecological effects, i.e. it changes the stocks demography such as abundance and age/size distribution [47], but it might also have evolutionary effects, changing genetically based life-history traits such as the stocks maturation pattern [28, 32]. Olsen et al. [37] suggest that such fishery-induced evolution contributed to the collapse of the cod stock at the coast of New Foundland.

There are several several economic applications of multi-cohort models to specific fisheries (e.g. [12, 14, 41, 44, 45, 50, 51, 52]), yet the problem of optimal gear selection has received surprisingly little attention. Most contributions deal with this issue from a more technical perspective of Fisheries Sciences [11, 26, 53, 20, 31], where the main part simulate for various given values of mesh size. The only explicitly economic optimization is from Stollery [49], who assumes perfect selectivity and provides a steady-state analysis.[2] To the best of our knowledge, this paper is the first interdisciplinary approach to the optimization of age- and gear-specific harvesting policies of a fishery over a significant time horizon. An important feature of our study is that it rests upon an ecological model which has been derived through statistical analysis of available time-series data from the Barents Sea system (published in [22]). The economic model strikes a balance between the necessary detail and tractability by establishing age- and fleet-specific harvest functions. By combining biology with economics we are able to show that the Net-Present-Value (NPV) of the fishery could be dramatically enhanced while at the same time resulting in a much more robust and abundant fish stock.

[Figure 1 here (floating)]

[2] There are however some rather abstract contributions from Mathematics, see Brokate [7], Murphy and Smith [35] and the references therein.

The North-East Arctic cod stock is jointly managed by Russia and Norway by a total allowable catch (TAC) quota as well as several technical regulations. The fishery is conducted with a variety of gears in diverse places. The fish migrate seasonally between its spawning grounds along the coasts and around Lofoten, where it is targeted by the more traditional coastal fleet, and its feeding grounds in the Barents Sea, where it is targeted by the ocean-going fleet consisting mainly (but not exclusively) of trawlers.

Given the economic and cultural importance of the fishery to Norway and North-Western Russia, it is not surprising that there exist numerous studies on fishery management in the Barents Sea. Topics range from overall studies of efficiency [6, 29, 45] to the impact of climate change [19]. The interaction between the different participating fleets is analyzed by Hannesson [15], Steinshamn [46], and Sumaila [51]. Closely related, the effect of cannibalism and inter-species competition on optimal harvesting and fleet selection is studied by Armstrong [3], Armstrong and Sumaila [5], and Sandal and Steinshamn [42]. In contrast to these studies, our study does not need to rely on restrictive assumptions with respects to the targets of the different fleets. Neither does optimality require an elimination of the trawler fleet as our fleet-specific harvest function and the underlying age-structured model allow sufficient flexibility in the exploitation pattern. The relation between cod and capelin is treated by Sumaila [50]. Finally, the strategic game between Russia and Norway has been analyzed cooperatively by Armstrong and Flaaten [4], Armstrong [2], Hannesson [17], and non-cooperatively by Diekert [9], Hannesson [18].

We present an empirically derived model that builds on a density-dependent recruitment function incorporating the effects of ambient temperature, capelin abundance, and cannibalism. It specifies the average characteristics of a given cohort and allows effort and the age-specific selectivity of different gears to be choice variables. We can therefore simulate a rich set of management scenarios. The resources NPV could be more than doubled in all cases of optimization. Even with effort kept constant at the current level, this implies a net gain of 100 billion Norwegian Krones over the next 75 years, by enlarging the mesh size to roughly 200 mm. The maladaptation of the current gear is also becoming visible through the occurrence of pulse fishing when only effort is optimized at the fixed selectivity.

In general, the optimal age to target the cod is 8 to 9-years while today predominantly 4 to 5-year old fish are caught [27]. Hence essentially the wrong fish are targeted. Optimization shifts the exploitation pattern towards older and heavier fish. This increases the harvested biomass while reducing the number of fish removed from the ocean. The result is a cod stock with an age/size distribution closer to the stocks natural state, even though this has not been an explicit objective. We therefore aim not only to present results that extend the knowledge about the dynamic impacts of different management scenarios, but also to present results that are policy relevant. The article proceeds as follows: The bioeconomic model is developed in the next two sections. The outcomes of the simulations are then presented and discussed in section 4. Section 5 concludes.

2 Biological Model

As a living resource, the NEA cod stock depends on the conditions of its biotic and abiotic environment. Temperature and salinity of the water, the inflow of warm currents and climatic factors fluctuate strongly in this sub-arctic region. The food web is relatively simple in that it consists of only a few species at the various trophic levels. Cod is a top predator, feeding along the polar front during summer-autumn and spawning on the Norwegian coast (especially around Lofoten) in March-April [36]. Cod larvae drift with Atlantic currents into the Barents Sea, which are the feeding grounds of the fish. Predatory cod follow the schools of capelin to the coasts of Northern Norway and Northwestern Russia.

Whenever there is not enough capelin available, the older cod turn to juveniles as a source of food (i.e., cannibalism). Such cannibalistic cod mainly consists of 3-6 year old immature cohorts [22]. These fish do not migrate to the spawning grounds yet and share much the same area as juvenile cod for the whole year. Largely the same circumstances determine length/weight growth and survival probability of cod after the age of 3 years[3] [21]. In addition, the fishing pattern is age dependent, since older and larger fish are more likely to be caught by the nets then their smaller and younger counterparts. The individual fish are hence summarized in cohorts.

The biological model describes the number of cod ($N_{a,t}$) of a given cohort of age a at time t, its length-at-age l_a, weight-at-age w_a, and the maturity probability mat_a. Somatic growth and maturation was assumed to depend only on age, not on food supply or temperature. Cod keeps on growing with age even if energy is also allocated to reproduction after maturation, hence, they may reach an age of 24 years old and a weight of 40 kg [1]. Due to natural mortality and the high fishing intensity in recent times, however, few fish survive an age of 12 years [27]. Nevertheless, it is important to include more age-classes in the bioeconomic model, as the results of the simulations could otherwise seriously underestimate the growth potential of the resource [16]. Age a therefore runs from 3 to 15.[4] The total biomass of the stock is the sum of the biomass of each age group ($X_{a,t} = N_{a,t}w_a$: number of fish multiplied with their average individual weight). The probability that a fish of a given year class will mature is primarily influenced by its length and the environmental conditions of its cohort. The values for length-at-age l_a, weight-at-age w_a, and the maturity probability mat_a result from regressions on ICES data, and are given as time-independent parameters (Table I).

[3] Three years is presumed to be the age of recruitment into the fishery. That is, 3 year old fish have grown sufficiently large to be susceptible for being caught.

[4] Cod reaches its maximum biomass with 12 years (see section 4.1) and few individuals would survive up to an age of 15 even in absence of fishing pressure.

[Table I here]

The function for the recruitment of fresh cod to the fishery is adapted from Hjermann et al. [22]. The model assumes that the cod's spawning stock biomass[5] (SSB) and recruits are linked by the Beverton-Holt relationship $f \cdot SSB/(1 + g \cdot SSB)$. This relationship is then modified by a coefficient for the positive effect of temperature[6] ($temp$) and the negative effect of the ratio between cannibalistic cod ($X_{can,t}$) and capelin (cap). The resulting recruitment function and the estimated parameters are:

$$\log N_{3,t} = \log\left(\frac{f \cdot SSB_{t-3}}{1+g \cdot SSB_{t-3}}\right) + c \cdot temp - d\left(\frac{X_{can,t-2}+X_{can,t-1}}{cap}\right) \quad (1)$$

$\log(f) = -1,12[\mathrm{SE}=0,74], \log(g) = -4,68[\mathrm{SE}=0,77], c = 0,70[\mathrm{SE}=0,18], d = 0,16[\mathrm{SE}=0,07]$

From then on the number of cod develops according to the difference equation:

$$N_{a+1,t+1} = N_{a,t} \cdot e^{-M} \cdot (1 - F_{a,t}). \quad (2)$$

where M is the natural mortality, conventionally set to 0,2 for all cohorts [27], and $F_{a,t}$ is the age-specific fishing mortality. With each time step a certain fraction dies from natural mortality, a certain fraction gets fished, and the rest graduates to the next age. Fishing mortality (the probability that a certain cohort is caught at a given time) has a

[5]The spawning stock biomass is defined as the sexually mature part of the stock and calculated by multiplying the age-specific biomass with the probability that the fish have matured, summed over all ages: $SSB_t = \sum_{a=3}^{15} X_{a,t} mat_a$.

[6]Temperature has, at least during the last decades, turned out to be closely correlated with the recruitment success of cod, i.e. cod abundance at age 3 [40]. More precicely, it is a good proxy for the general environmental conditions that determine the survival probability of the larvae during its first five months [39].

direct impact on its survival rate, but it also has an indirect impact on the stock dynamics via the spawning stock biomass and via the effect of cannibalism.

3 Economic Model

The three most distinguishable sub-fisheries out of the many gear and fleet types will be introduced. The Lofoten fishery (denoted *lof*) targets the mature stock in the spawning grounds (in Lofoten and elsewhere on the Norwegian coast). It consists of rather small boats (8 to 20,9 m) using gillnet and handline. Norwegian trawlers (denoted *Ntrl*) and Russian trawlers (denoted *Rtrl*) fish in the Barents Sea. Differences in boat-size and technology have implications on the cost of one unit effort exercised. Differences in gear and location have an impact on which fish are targeted and hence on the productivity of one unit effort exercised [46]. The three fleets differ in their harvest function and cost structure. For simplicity it is assumed that they face the same prices.

3.1 Objective Function

The managing authorities have to accommodate a variety of diverging or even conflicting needs when formulating a harvesting strategy [43]. They aim at making the economic value-added as large as possible while at the same time maintaining the existing employment and settlement patterns. Sustainability is demanded not only on economic but also on ethical grounds and international commitments further constrain the room for manoeuvre.

As we are seeking to provide an estimate of possible economic gains, we presume the existence of a hypothetical sole owner with complete control over resource exploitation. The objective is taken to be the maximization of the Net-Present-Value (NPV).[7] For the entire fishery this is the sum of discounted annual profits of the three fleets:

[7]Contrary perhaps to public perception, the confinement to profit maximization is no reason for concern, as what turns out to be good economically is also good for the fish stocks. (See the discussion below)

$$\text{NPV} = \sum_{t=0}^{T} \delta^t \cdot [\pi_t^{Lof} + \pi_t^{NTRL} + \pi_t^{RTRL}] \tag{3}$$

Discounting with a rate of 5% was introduced to include a rate of time preference.[8] The profits of fleet j in a given year t are determined by:

$$\pi_t^j(X_t, E_t, m_t) = \sum_{a=3}^{15} p_a \cdot H_{a,t}^j(X_t, E_t, m_t) - c^j(E_t) \tag{4}$$

$c^j(E)$ represents the cost of applying effort E for fleet j. $H_{a,t}^j(X, E, m)$ is the age-specific harvesting function which depends on the state of the resource X, on the amount of effort E, and on the gear selectivity which is influenced by the choice of mesh size m. Price p_a is age-specific as older and heavier fish receive a higher price per kg. Prices-at-age were taken to be constant. Although this is hardly an accurate description of the demand schedule, it might be not too unrealistic: 90% of the cod products are exported, and the price which the Norwegian fishermen receive is to a large extent determined by the negotiations between the organization for the fishing industry and the fishermen's sales organization [43]. These minimum prices[9] have been employed after it has been accounted for the fact that these prices are given for headed and gutted fish while the fish in the model and in the ocean are whole.

[Table II here]

[8] A discount rate of 5%, which implies a discount factor of $\delta = 0,9523$, is high but advantageous for the simulation because it makes the distant periods less important for the NPV.

[9] Norges Råfiskelag, Pressemelding (May 3, 2007) `www.rafisklaget.no/pls/portal/url/ITEM/6D4F5250DAD24D22A026C2F97847477B`

3.1.1 Harvest Function

The harvest function $H_{a,t}(\cdot)$, equation (5), tells how many fish of age a are caught at time t. Conceptually, it is simply the biomass times the age-specific fishing mortality $F_{a,t}$.

$$H_{a,t} = X_{a,t} \cdot \underbrace{r(l_a, m_t) \cdot (1 - e^{-q \cdot E_t})}_{F_{a,t}} \tag{5}$$

This fishing mortality $F_{a,t}$ displays decreasing returns to scale and contains two concepts: First, the gear specific selectivity $r(l_a, m_t)$, defined as "the probability that a fish of length $[l_a]$ is captured, given that it contacted the gear $[m_t]$" [33, p.92]. The second concept is the fleet specific catchability, summarized by the coefficient q. The level of exploitation (i.e. how many fish caught) is determined by the amount of effort.[10] The exploitation pattern (which fish are caught) is determined by the location of fishing and mainly by the gear which is being used.[11] Because the harvest function is age-specific and the selectivity of the fleets can be adjusted, we do not need to rely on the assumption that trawlers cannot catch mature fish, and consequently we do not get corner solutions with respect to the use of different fleets.

The shape of $r(l_a, m_t)$ varies between the different gear types. Trawlers catch the fish by actively pulling a net through the water with a speed higher than the targets' maximum speed. The fish is thereby overtaken and must pass through the netting to escape. The size of its mesh openings determine the gear selectivity [33]. Accordingly, few fish below a certain size and most fish above a certain size are caught, and the gear selectivity curve is of S-shaped form. It is commonly described by the length of 50% retention L_{50},[12] and

[10] Effort is defined as *tonnage-day* of standardized vessel. It is assumed to take values in $[0, \infty)$.

[11] For a given type of gear its selectivity can be influenced by the mesh size m which is presumed to take values between 60 and 300 mm. These bounds are somewhat arbitrary, but the mesh size cannot vary indefinitely in real life.

[12] Describing the length of a fish which is captured with 50% probability, given that it had contact with the gear [33].

the selection range SR, which specifies the distance between the length of 25% and 75% retention, thereby defining the steepness of the curve. However, if we want to include the mesh size m as a choice variable, we need express the gear selectivity curve in dependence of m. Halliday et al. [13] have gathered data from selection studies or different mesh sizes and established the following relationships between mesh-size m in mm, L_{50}, and SR:

$$L_{50} = 0,499m - 16,105; \quad SR = 0,112m - 4,335 \tag{6}$$

Kvamme [30] found the logistic curve to fit best to the data so that the following selectivity curve for trawl nets is established:

$$r^{trl}(l_a, m_t) = \left(1 + \exp\left(\frac{-2,2}{\{0{,}112m_t - 4{,}335\}} \cdot (l_a - \{0{,}499m_t - 16.105\})\right)\right)^{-1} \tag{7}$$

The Lofoten fleet differs in this respect. Gillnets and other passive gear entangle the fish that swim into them. While sufficiently small fish pass through the meshes, sufficiently large fish do not penetrate far enough to become wedged. Therefore the selection curve is usually assumed to be bell-shaped. Huse et al. [25] found the gamma curve with $\alpha = 48,9558$ and $\kappa = 0,0106$ to fit best to catch data. This gives a modal length of 94,7 cm (spread: 13,7 cm) for the commonly used mesh size of $m = 186$ mm:

$$r^{lof}(l_a, m) = \left(\frac{l_a}{(\alpha - 1) \cdot \kappa \cdot m}\right)^{(\alpha-1)} \cdot \exp\left(\alpha - 1 - \frac{l_a}{\kappa \cdot m}\right) \tag{8}$$

In general, a larger mesh-size m moves the selectivity curves to the right, but it also makes the selection range larger, so that the curves get flatter. They are plotted for various mesh sizes below:

[Figure 2 Trawl Selectivity and reffig:GillnetSelectivity Gillnet Selectivity here]

A model which portrays the NEA cod fishery should take the spatial distribution of the stock into account, since Russia and Norway have sovereignty only in their territory. However, they concede each other the right to fish large parts of their quota in their respective zones [48]. For simplicity, it is therefore assumed that both trawler fleets have complete access to the entire biomass. Nevertheless, a fish must not be caught twice in the model. To this end, the Lofoten fleet is set up to first harvest exclusively on the mature biomass and what is left enters the feeding grounds. The biomass in the harvest functions of the trawlers is therefore multiplied with the term $(1 - F^{lof}_{a,t})$. Furthermore, the fishing mortality of the trawler fleets is modified so that the sum of both trawler efforts in the exponent ensures that the combined mortality does not exceed 1. The last term assigns the respective share according to the fleet's effort:

$$F^{lof}_{a,t}(E, m) = r^{lof}(l_a, m^{lof}_t)\cdot (1 - e^{-q^{lof}\cdot E^{lof}}) \tag{9a}$$

$$F^{Ntrl}_{a,t}(E, m) = (1 - F^{lof}_{a,t})\cdot r^{trl}(l_a, m^{Ntrl}_t)\cdot (1 - e^{-q^{trl}\cdot(E^{Ntrl}+E^{Rtrl})})\cdot \frac{E^{Ntrl}}{E^{Ntrl} + E^{Rtrl}} \tag{9b}$$

$$F^{Rtrl}_{a,t}(E, m) = (1 - F^{lof}_{a,t})\cdot r^{trl}(l_a, m^{Rtrl}_t)\cdot (1 - e^{-q^{trl}\cdot(E^{Rtrl}+E^{Ntrl})})\cdot \frac{E^{Rtrl}}{E^{Ntrl} + E^{Rtrl}} \tag{9c}$$

Finally, the catchability coefficient q contains that part of fishing mortality which is not captured by the gear selectivity. It is influenced by the composition of the fishing fleet, the effort and skill of the fishermen, as well as the distribution and behavior of the fish. Given the information about the gear selectivity and the effort applied from the Norwegian Directorate of Fisheries [10] as well as the fish stock for the period of 1998-2002 from ICES [27]. Equation 5 is used to calibrate fleet specific catchability[13] as $q^{lof} = 3,87\cdot 10^{-8}$ and $q^{Ntrl} = q^{Rtrl} = 2,67\cdot 10^{-8}$.

[13]The same value of q is assumed for both trawling fleets, because there is no reason to presume that the skill of Russian fishermen differs in any systematic way from that of their Norwegian counterparts.

3.1.2 Cost Structure

A constant cost per unit of effort is assumed, which is consistent with a regulatory regime where allowable catch is a proportion of the biomass.

$$c^j(E) = c^j \cdot E \tag{10}$$

Using data from the profitability surveys of the Norwegian Directorate of Fisheries [10] from 1998-2002, the cost parameters were estimated to be $c^{Lof} = 315$ [SE = 12,9] for the Lofoten fishery and for the Norwegian trawl fishery $c^{NTRL} = 190$ [SE = 9,5]. There was no data on Russian cost, but benefiting from the technical identity between Russian and Norwegian trawl, the latter cost-structure – weighted by a factor to account for differences in labor cost etc. – is used for the former. In lack of an adequate foundation for estimating such a factor, 0,9 was arbitrarily chosen. This makes the Russian cost: $c^{RTRL} = 171$. Note that even if the costs of effort are linear, the marginal costs of catching fish are increasing due to the diminishing rate of return in the harvest function. Stated differently, it costs the same whether the first or the hundredth unit of effort is used, but a lot more effort is needed to catch the first or the last fish in the ocean.

3.2 Simulation

The main questions of optimal management are at which age and weight should the cod be targeted? How much effort should be applied by which fleet? Which mesh size should be used? In order to isolate these effects, we simulate four different scenarios: Firstly, today's exploitation level and pattern is projected by employing the current value of effort (the average values from 1998 to 2002) and mesh sizes as constants over the entire time horizon. This scenario is called *Status Quo* and serves as a benchmark against which optimal harvesting is compared. Secondly, a hypothetical sole owner chooses effort E_t, given today's mesh size regulations, so as to maximize the NPV of the fishery (*Sole Owner-E*). In the third scenario, today's effort is taken as fixed and the optimal mesh size m_t is chosen (*Sole Owner-m*). Finally, both effort and mesh size are controls (*Sole Owner-Em*). The sole owner's problem will be:

$$\max_{u_t} \sum_{t=0}^{T} \delta^t \cdot [\pi^{lof}(X_t, u_t) + \pi^{Ntrl}(X_t, u_t) + \pi^{Rtrl}(X_t, u_t)] \tag{11}$$
$$\text{subject to : } \quad \text{the biological system } X_t; \; X_0 = \text{given}; \; \text{and } u_t \in U$$

- The time horizon runs from $t = 0$ to $T = 75$. A period of 75 years has been chosen, because on the one hand capacity constraints of the numerical optimization tool had to be respected, while on the other hand, the horizon had to be long enough to offset end-of-the-world effects.

- The control region depends on the simulation scenario. For *Sole Owner-E* in the second scenario: $U = E$ and $u_t = \{E_t^{lof}, E_t^{Ntrl}, E_t^{Rtrl}\}$, for *Sole Owner-m* in the third scenario: $U = m$ and $u_t = \{m_t^{lof}, m_t^{Ntrl}, m_t^{Rtrl}\}$, and finally for *Sole Owner-Em*: $U = (E, m)$ and $u_t = \{E_t^{lof}, E_t^{Ntrl}, E_t^{Rtrl}, m_t^{lof}, m_t^{Ntrl}, m_t^{Rtrl}\}$. In all cases, U is convex since $E \in [0, \infty)$ and $m \in [60, 300]$.

- The biological system, summarized by the Leslie-matrix X_t, is specified by the recruitment function (1), the cohort development according to equation (2) and the weight, length, and maturity parameters summarized in Table 1. The complexity stems not only from the number of state variables and the non-linearity of the employed functions but also from the time lags of up to 4 years. As a short-hand notation the system is written as the function $X_{t+1} = f(X_{t-2}, X_{t-1}, X_t, u_{t-3}, u_{t-2}, u_{t-1}, u_t)$.

4 Results and Discussion

4.1 The Effect of Selectivity

Imagine that a number of fish of all the same age (conveniently the age of recruitment) are put in a pond. The aim is to let them grow and to reel in the harvest at the optimal point in time. Suppose that the individual fish gain weight with age, but at a decreasing rate. Suppose further that the number of fish declines due to natural mortality. Consequently, the biomass will grow in the beginning but level out and decrease after some time. The point where it has reached its maximum will depend on the specific growth function and the assumed natural mortality M. In the present case, where M is set to 0.2, the fish are between 11 and 12 years old (see Figure 4). The economical value of the biomass, in short the *biovalue* (see Clark [8]), is additionally influenced by the price the fish would get when they were sold on the market. If heavier fish receive a higher price as it is the case with NEA cod, the overall pattern is strengthened. Two things appear especially noteworthy: The late age at which the biovalue of a cod cohort is highest, and the steep rise of the natural biomass in the beginning.

[Figure 4 here]

Even though the fish have reached their maximum biomass and highest biovalue 9 years after recruitment (with age 12), this is in general not the optimal time to take the fish out of the pond. Many additional factors influence that decision, namely the cost of harvesting, a possible time-preference, the reproductive potential of the fish, etc. [54].

So far, only one year-class of fish has been considered. Hence the biovalue of the stock was the biovalue of that cohort. When new fish are added to the imaginary pond every year, the biovalue of the stock would be the sum of all the cohorts in the pond. In order to cope with the analysis of multicohort populations, the hypothetical concept of "knife-edge selectivity" is introduced. It characterizes a gear where all fish above a certain size/age are caught and none below. Its opposite is completely non-selective gear which targets all fish with equal probability. With knife-edge selectivity, the best is obviously to calibrate the gear such that only cod of optimal biovalue are targeted. But what should be done if the gear is completely non-selective? The best is then to empty the pond and let the stock replenish before the pond is emptied again. Because it is not possible to single out the cohort with the highest biovalue, one has to wait until the stock itself has reached an adequate biovalue. A formal proof that periodic fishing produces a greater average yield than continuous catch given non-selective gear can be found in Clark [8], pp.299. This harvesting pattern is called *pulse fishing*. It was first analyzed for Icelandic cod by Hannesson [14].

Now in real life, there is neither knife-edge selectivity nor completely non-selective gears. Unlike in the imaginary pond, the fish stock in the Barents Sea consists of many overlapping cohorts that have been subject to environmental fluctuations and fishing in varying degrees. With these real-world complexities taken into account, the model rapidly loses its tractability. Nonetheless, the reasoning from the example carries over: The better it can be controlled which fish are targeted, the more profitable it becomes to continually withdraw part of the stock. Conversely, the less adapted the gear selectivity is, the more worthwhile it becomes to invest great effort to indiscriminately harvest as much as possible and start afresh afterwards. Note that the occurrence of pulse fishing in the present simulations is not due to an assumption of completely non-selective gear, neither is it an artefact of a linear Hamiltonian yielding bang-bang controls, as the objective is concave in effort (see section 3.1). It highlights the importance of gear regulations. Its emergence is ultimately a result of not seeing the fish as a uniform mass but acknowledging that the stock is composed of many fish with individual characteristics.

4.2 Outcome of the Simulations

In order to simulate a continuation of the current harvesting pattern, the average effort values of the last five years have been applied over the entire time horizon. Using the Lofoten fleet with 2 million tonnage-days and both trawler fleets with 11 million tonnage-days, *Status Quo* exploitation yields a Net-Present-Value of 79 billion Norwegian Krones (NOK). Since the model is essentially deterministic, using the same effort lets the state settle down after 16 years (Figure 6a). Hence the composition of the stock remains identical with more than half of the fish being younger than 6 years. The total biomass is a little bit less than 2 million tons and the average harvest from the status quo pattern is about 640 thousand tons. When examining the composition of the harvest, it is not surprising that it consist mainly of inefficiently small fish. Fish of age 9 and older sum up to only 17% of total harvest (see Fig. 5).

[Figure 5 Harvest Composition here]

In contrast, optimal management fully exploits the growth potential of the fish. Fish of age 9 and older make up more than 68% of the catch for any optimization. In all cases, the NPV could be more then doubled: It is 200 billion NOK for the *Sole Owner-E* scenario, 186 billion NOK for the *Sole Owner-m* scenario, and 215 billion NOK for the *Sole Owner-Em* scenario. Common to all scenarios with optimization is also that the exploitation level in terms of numbers of fish removed is reduced whereas the harvested biomass was actually increased. This is because the exploitation pattern is shifted towards older and heavier fish. Consequently, the standing stock biomass grew in these scenarios to over 5 million tons on average. Table III below summarizes the results.

Perhaps the most surprising outcome of the economic analysis is that even when effort is held fixed at the current level, the economic gain from the resource could be doubled, simply by choosing the right mesh size. This could be important in practice, when there is some rigidity in varying the effort levels of the fleets caused by technical or political reasons. For example, fishermen might reject to decrease their effort for fear of short-term losses, and increasing the minimum mesh size might hence prove a viable management alternative. The chosen mesh size in the *Sole Owner-m* scenario is somewhat higher than in the *Sole Owner-Em* scenario in order to compensate for the inability to reduce effort.

The age-structured analysis shows therefore clearly that there is overfishing of the stock, but the problem is not so much that effort is employed excessively, but that the wrong fish are targeted. When only effort is a choice variable and m is fixed (see Fig.6c), it becomes evident that the current regulation of 135 mm for trawl is maladapted: the optimization produce fishing pulses (see the discussion above). Consequently, there are too many old and too many young fish in the nets as compared to an optimally chosen mesh size (Fig.5). Obviously the best result is obtained when both effort and selectivity is chosen freely. Optimization over a 75 year horizon then implies a net gain of 135 billion Norwegian Krones. The exploitation pattern is now characterized by continuous harvesting and a mesh size of 201 mm for trawl and 234 mm for gillnets. A mesh size of 201 mm translates to a length of 50% retention of 84,2 cm (see Table I) at which the fish are between 8 and 9 years old.

As it can be seen in table III, the gillnets contribute only to a small part of the harvest. This can clearly be attributed to its disadvantageous cost-catch ratio. It was to be expected that the Russian fleet is preferred to the Norwegian fleet given its cost advantage. This plays out strongly under the pulse fishing pattern where a large amount of effort is used. However, since the marginal cost of catching fish are increasing, all three fleets are used to some degree in the *Sole Owner-Em* optimization.

[Table III and Figure 6 here]

Although the model is robust, it should not be forgotten that its conclusions rest on an extrapolation of empirical results. Especially the gear selectivity curves were estimated for mesh sizes between 80 and 155 mm and it is not evident that these curves maintain their properties when the mesh size are enlarged to over 200 mm. Therefore a sensitivity analysis was undertaken. Multiplying the selection range by a factor of two makes the selectivity curves considerably flatter. However, the resulting change in outcome was small: in the Em simulation the mesh openings were reduced by 10 mm so as to still target the largest part of the 9 year old fish. As a consequence of the increased spread, more inefficient fish were caught in the nets and the NPV was reduced to 194 billion NOK. To offset the increased fishing mortality on younger specimen effort was roughly reduced by 1 million tonnage-days for the trawlers. Conversely, dividing the selection range by a factor of 2 – thus making the curves considerably steeper – allowed a better tailoring of the gear (the mesh size was changed by 2 mm to 203 mm) and hence a higher NPV of 224 billion NOK and a higher use of effort (again by roughly 1.000.000 units for trawl).

The other estimated parameters contained in the objective function were the cost and the catchability. Raising / lowering the cost by 10% had no significant impact on the optimal exploitation pattern and it changed the obtainable NPV by less than 2,5% (reinforcing the result from Homans and Wilen [24] that it is not so much the cost inefficiency but the foregone revenue that distinguishes regulated open access from optimal management). Finally, the catchability coefficient q was varied by 10% as well; but again, the changes in outcome were close to insignificant. Raising the catchability obviously lead to a slightly higher NPV (by less than one billion NOK) and reduced effort, while lowering q resulted in a lower NPV (again by less than one billion NOK) and somewhat tighter nets (199,8 mm instead of 201 mm) and increased effort (0,8 / 5,5 / 11,6 million *tonnage-days* as compared to 0,7 / 4,6 / 11 million *tonnage-days* for the Lofoten, Norwegian trawler, and Russian trawler fleet respectively). Also increasing the catchability of the Lofoten fleet while simultaneously reducing q of the trawlers lead only to a minor shift in the ratio of employed effort (1,1 / 5,5 / 11,2 million *tonnage-days* were used).

4.3 Discussion

At first glance it might be surprising that the Lofoten fleet is only marginally used in an optimal regime. From the outset, the fleet has the better adapted harvest function: its gear selects mainly for fish around the stock's maximum biomass, it is assumed to target only the mature fish, and in the model, it even gets to catch the fish before the trawlers can. Yet it turns out that its advantages are small compared to its cost. The better selectivity of the Lofoten fleet does not play out strongly under the optimal regime: Under pulse fishing, the gillnets do not catch the fish effectively enough. When the trawlers adapt their mesh size, they select for fish of 9 years and older. At that age, 91% of a year class have reached maturity and the Lofoten fleet loses its comparative advantage. For the same reason does the location of the fishing fleets lose its relevance in the optimizations.

Similarly, the biological model allowed to account for the maturity of the individual fish and to consider cannibalism but neither aspect emerged as a prominent feature in the economic analysis. The reason is that it is most profitable to target fish of age 8-9, which are largely mature by that age, so that reproductive overfishing was no cause for concern. Additionally, we considered the immature cod of age 3-6 to be cannibalistic, so that it did not pay to reduce their number either. However, cannibalism affected only recruitment in our model, while in Armstrong [3], Armstrong and Sumaila [5], and Sandal and Steinshamn [42] the entire immature substock was targeted by the mature substock.[14] The age- and fleet-specific structure of our model enabled a rich set of possible management scenarios. Even though we concentrated on two segments of the variety of gear and boat types that

[14]Sandal and Steinshamn [42] actually found cannibalism to be not statistically significant.

are catching cod in the Barents Sea, we could show that selecting for the right age is more important than the overall properties of the harvest function (its shape and whether it targets only mature fish or immature as well). Since the Lofoten fleet catches the fish not effectively enough, it was too expensive to be used extensively. Although its cost structure is only a rough approximation, it is in line with the literature (e.g. 3, 46, 51).

This not withstanding, the bell-shaped selectivity curve for the Lofoten fleet and hence its ability to avoid some of the largest fish could be advantageous when taking effects of fishery-induced evolution into account. Moreover, exploiting the high contribution to recruitment of the largest cod [31] in this way could be beneficial when the stock is in an optimal steady state. Here we have taken todays stock composition as a starting point. After all, the aim was not to pass a verdict on the fleets but to see how the different setup influences the harvesting decisions. To be able to study the bio-economic efficiency of the various fleets specifically, it would be necessary to use a wider and finer selection of boat and gear types, a more thoroughly estimated cost function and incorporate broader aspects of the social and natural environment.[15]

A remarkable feature of the economic analysis is the occurrence of pulse fishing. Its practicability is doubtful, to say the least. It is hard to envisage that the fishermen sit idle for eight years and then fish with very high effort in the ninth year. One could imagine that other fish species are targeted while the cod stocks are recovering [14], but the practical problem would be to dissuade cods from swimming into the nets when hunting for other groundfish such as plaithe or haddock. Yet, the most important aspect is the market: Unlike lumber, fish is a perishable good. Huge investments would be necessary to store fish for eight years. In the current model prices were assumed to be constant; any downward sloping demand curve should attenuate the pulses. Indeed did Moxnes [34] show that pulse

[15]Especially the fact that the coastal fleets can deliver cod of better quality as they can deliver 1-2 day old cod. Trawlers can usually not deliver cod faster than 3-4 days. It seems that the present system of price negotiations and distribution has the result that this difference in quality is not reflected. `http://www.forskning.no/artikler/2005/februar/1108731627.74`

fishing is much less pronounced if economic feedbacks are included. However, these aspects are of hypothetical nature if one considers the superiority of an adapted gear selectivity. Choosing mesh-size as well as effort produces not only a larger NPV but also a steady harvest. With continuous harvesting, the stock remains in a healthy condition, whereas it is left at vulnerable low levels immediately after a pulse. This is particularly relevant in the erratically fluctuating environment of the Barents Sea.

In fact, the most important drawback of the simulations is that they are deterministic while uncertainty abounds in reality. Especially environmental and climatic conditions vary, but also the economic situation changes. What is more, the level of uncertainty tends to be compounded in the future. As the development of the biomass until the planned fishing pulse becomes increasingly uncertain, the optimal rotation period may be significantly affected [8]. Stochastic analysis has been beyond the scope of this paper, but we were able to show that the bioeconomic model and its conclusions are robust. Extending it and including uncertainty will be the task of future work.

5 Conclusion

The Net-Present-Value of the NEA fishery might be more than doubled if optimal age-specific harvesting pattern were applied. In particular, 8 to 9-year old fish should be targeted instead of 4 to 5-year old as it is currently the case. Especially the selectivity of the different gears turned out to be a most important policy choice. Even if changing the effort levels were not feasible, the economic gain obtained from the resource could be significantly increased by adapting a larger mesh size. Moreover, optimization results in a biologically much healthier fish stock. Although this has not been an explicit management objective, the overall biomass would be increased, and the stock would consist of older and heavier individuals. The danger of reproductive overfishing would thus be avoided.

Additionally, older and heavier individuals are better able to buffer adverse fluctuations, which are presumably amplified by climate change [40].

Our results could prove to be highly relevant for policy makers. Moreover, they highlight the necessity of age-structured modeling in fishery economics. Benefiting from an interdisciplinary approach, we could present a detailed model of the NEA cod fishery. The Barents Sea is a rich and productive ecosystem and it is one of the main reasons why Norway is the third largest exporter (measured by value) of fish in the world [23]. However, this sub-arctic area is also quite vulnerable. In spite of a history of 25 years of joint fisheries management, the stock has clearly been overharvested during this period. Firstly, the authorities have tended to give quotas that are larger than the advice from fisheries scientists; secondly, the actual harvest have been significantly higher than the quotas due to unreported and illegal fisheries. A driving factor of the ongoing overfishing might simply be the strategic interaction between the two nations exploiting this transboundary stock [9]. Finally, offshore oil and gas production in the area is starting up (and is considered in the spawning areas of the cod), and climate change may change the abundance and geographic distribution of the cod. Future research should include these aspects into a bioeconomic analysis of the Barents Sea. More effort should also be put in determining a disaggregated cost function. Furthermore, one could fully exploit the possibilities of the biological model and ask how the underlying incentive structures change with regards to climatic fluctuations or fishery-induced evolution.

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Age	3	4	5	6	7	8	9	10	11	12	13	14	15
Length in cm	33,9	44,2	54,1	63,6	72,9	81,9	90,8	99,7	108,6	117,0	125,5	133,9	142,4
Weight in kg	0,36	0,69	1,31	2,20	3,36	4,78	6,46	8,39	10,56	12,99	15,67	18,60	21,77
Maturity Probability	0,01	0,02	0,07	0,21	0,47	0,75	0,91	0,97	0,99	0,997	0,999	1,000	1,000

Table I: Biological Parameters

Age	3	4	5	6	7	8	9	10	11	12	13	14	15
Price in NOK	10	10	13	13	15	15	17	17	17	17	17	17	17

Table II: Price at age

	Status Quo	Sole Owner-E	Sole Owner-m	Sole Owner-Em
Joint NPV	79 billion NOK	200 billion NOK	186 billion NOK	215 billion NOK
Harvest *lof*	330.225 t	0 t	83.911 t	50.342 t
Harvest *Ntrl*	301.584 t	207.515* t	484.285 t	322 475 t
Harvest *Rtrl*	301.584 t	911.608* t	484.285 t	655.065 t
Effort *lof*	2.000.000	0	2.000.000	771.059
Effort *Ntrl*	11.000.000	2.230.608*	11.000.000	4.562.118
Effort *Rtrl*	11.000.000	9.152.406*	11.000.000	10.956.255
Mesh size (*lof* / *trl*)	186/135 mm	186/135 mm	241/211 mm	234/201 mm
Total Biomass	1.974.644 t	5.300.175* t	5.608.594 t	5.791.165 t

Table III: Summary of simulation results

*Note that all resulting values for the respective choice and state variables (except the NPV) are reported as averages. The asterisk marks the occurrence of pulse-fishing which make these averages less meaningful.

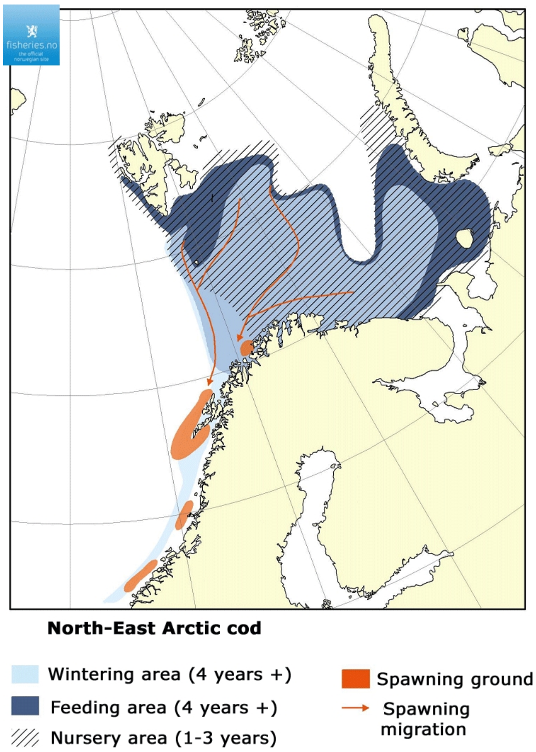


Figure 1: Distribution of NEA cod Source: FKD[†]

[†] *fisheries.no*, Online, accessed April 25, 2008, from `http://www.fisheries.no/NR/rdonlyres/73D7EB3E-0E3F-446A-B88D-2C5625D27241/44587/NAtorsk_kart800px.gif`

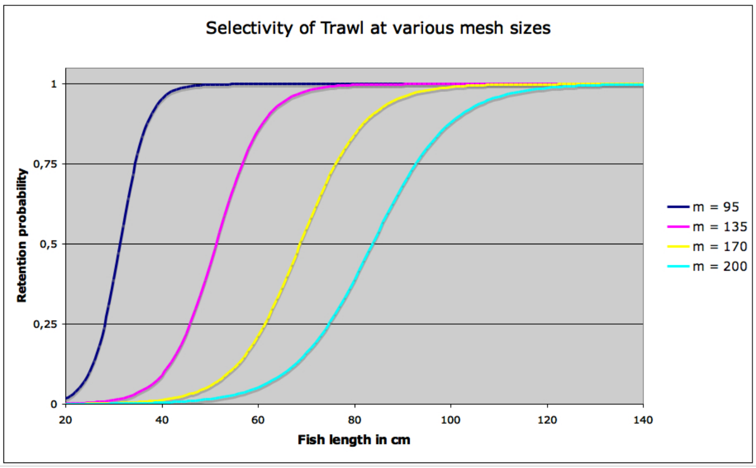


Figure 2: Trawl Selectivity

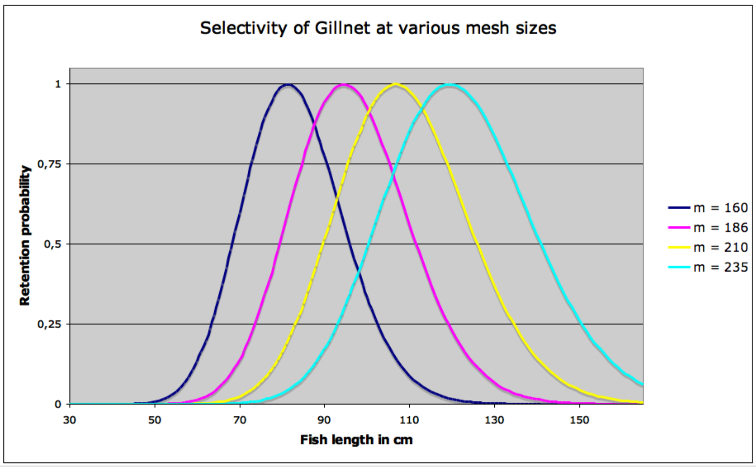


Figure 3: Gillnet Selectivity

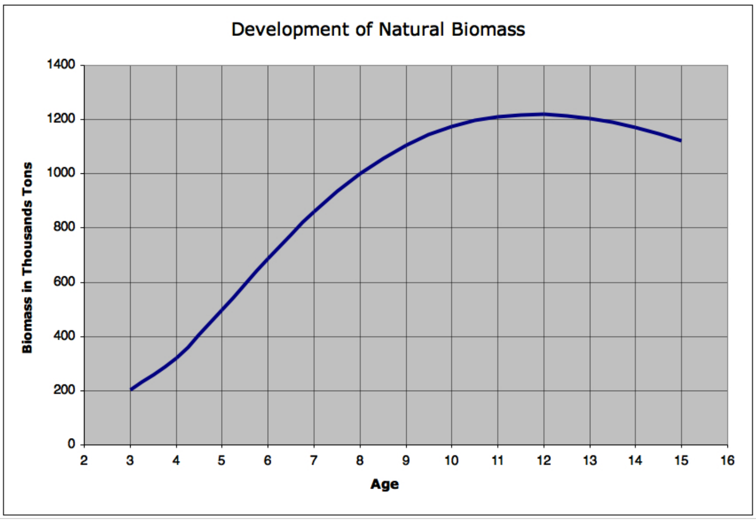


Figure 4: Development of natural biomass

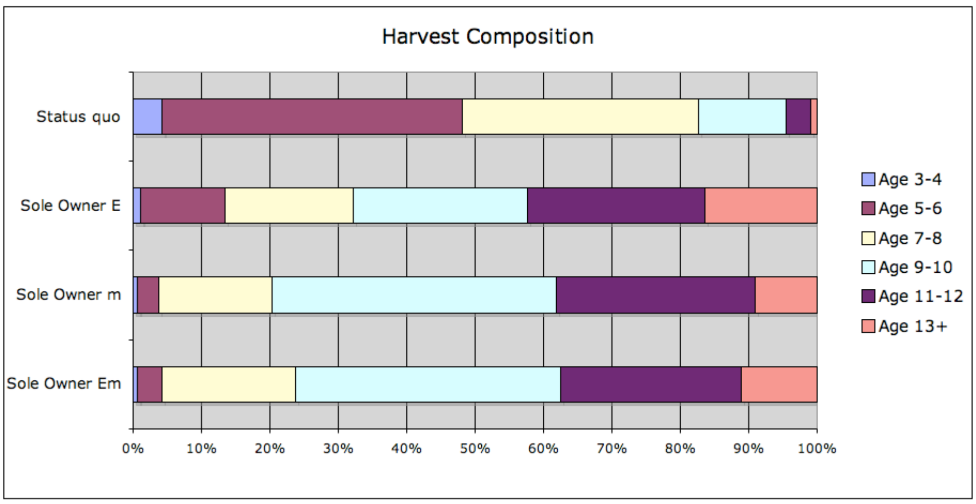
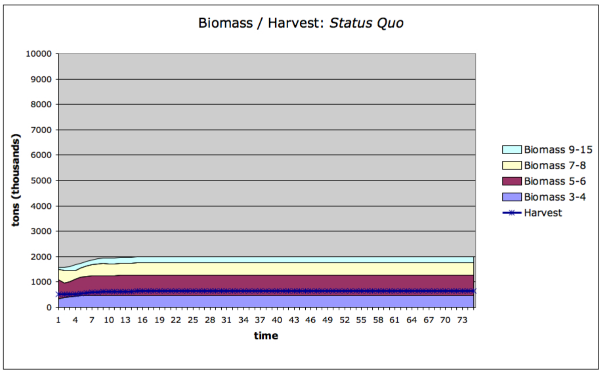
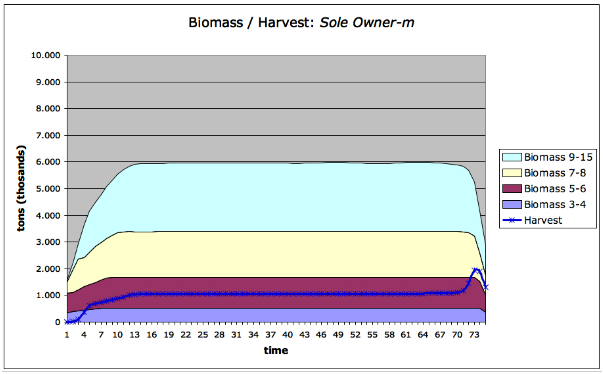


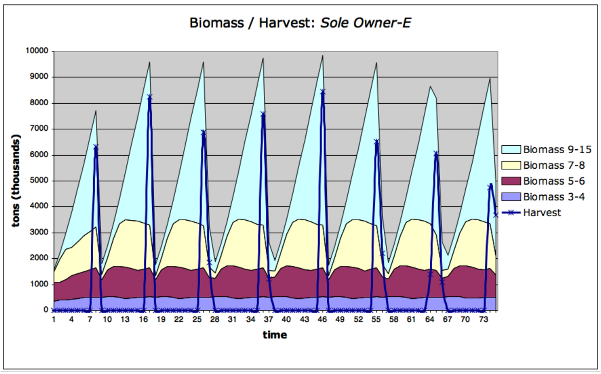
Figure 5: Harvest composition



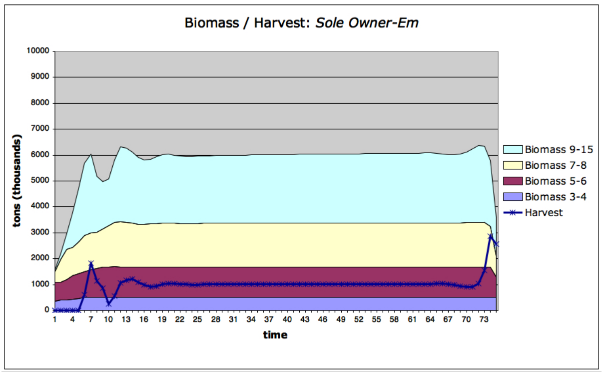
(a) Status Quo



(b) Mesh size is control variable



(c) Effort is control variable



(d) Effort and mesh size are controls

Figure 6: Biomass and harvest for the different scenarios