

EVALUATION OF MAXIMUM LONG-TERM YIELD FOR NORTHEAST ARCTIC COD

by

Yu. Kovalev¹ and B. Bogstad²

¹ *Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk, Russia*

² *Institute of Marine Research (IMR), Bergen, Norway*

1. Introduction

Evaluation of the long-term yield of Northeast Arctic cod (*Gadus morhua*) in a single-species context is the first sub-project in the research program: “Optimal long-term harvest in the Barents Sea ecosystem”, suggested by the Joint Norwegian-Russian Fisheries Commission in 2003. An overview of the sub-projects within this research program is given on the web page <http://www.assessment.imr.no/Request/index.html>.

2. Background

2.1. Evaluation of the proposed harvesting strategy by ICES’ Arctic Fisheries Working Group in 2005

In 2005, the ICES Arctic Fisheries Working Group (ICES, 2005) evaluated the harvesting strategy for Northeast Arctic cod proposed by the Joint Norwegian-Russian Fisheries Commission in 2004. The strategy (see Section 6) was found to be in accordance with the precautionary approach. A biologically detailed population model for cod, CodSim (Bogstad et al., 2004a) was used in that evaluation. CodSim was amended later (Kovalev, 2005) and further improved in the present paper.

However, it is important to search for optimal harvesting strategies, and not only be concerned about whether a harvesting strategy is precautionary. The present paper is a first step in that directions for Northeast Arctic cod.

2.2. Previous analyses of MSY for Northeast Arctic cod

Most studies of MSY (e.g. Nakken et al., 1996; Tretyak, 1987; Kovalev and Korzhev, 2002) have used rather simplistic population biology, with no modelling of density-dependent effects and recruitment only being dependent on SSB. However, we found it appropriate to try to include as much biological knowledge as possible in our population model, as advocated e.g. by Ulltang (1996).

The work by Kovalev (2005) is the only study of MSY for NEA cod after the time series of weight at age and maturity at age was revised in 2001.

3. Methodology for evaluation of MSY

3.1. Simulation approach

Stochastic long-term simulations were carried out in order to evaluate long-term yield, for different harvest strategies and population models. The same population age range (3-13+) and reference F age range (5-10, arithmetic mean) as in the current assessment was used.

3.2. Software

The computer program PROST (Åsnes, 2005) was used for making stochastic long-term simulations for the NEA cod stock based on the population model (CodSim) described in this paper.

3.3. Data used for developing the population model

The time series for weight (in catch and in stock), maturity, fishing mortality and natural mortality at age used in this document were taken from the 2005 report of the ICES Arctic Fisheries Working Group (ICES, 2005). The time series covers the period 1946-2004.

3.4. Model units

The following units are used in this paper:

Individual weight: kg

Recruitment: million individuals

Stock biomass: thousand tonnes

4. Population model for Northeast Arctic cod

4.1. Recruitment

4.1.1. Choice of stock-recruitment relationship

Possible choices for the stock-recruitment relationship include the segmented regression approach, Beverton/Holt and Ricker. ICES (2003) modelled the stock/recruitment relationship for NEA cod using the segmented regression approach. We will extend that in essentially the same way as done by Bogstad et al. (2004a), by including a cyclic term as well as a stochastic term. We thus look for a stock-recruitment relationship of the form shown in Eq. (1):

$$R_3(\text{year} + 3) = f(SSB(\text{year}))e^{A*\sin(\frac{2\pi(\text{year}-1946+\varphi)}{T})+\varepsilon} \quad (1)$$

$$\text{where } f(SSB) = \min(\frac{\alpha}{\beta} SSB, \alpha) \quad (2)$$

The segmented regression function (i.e. only the first term on the right-hand side of equation (1) is included) fit to the data for the year classes 1946-2001 is shown in Fig. 1.

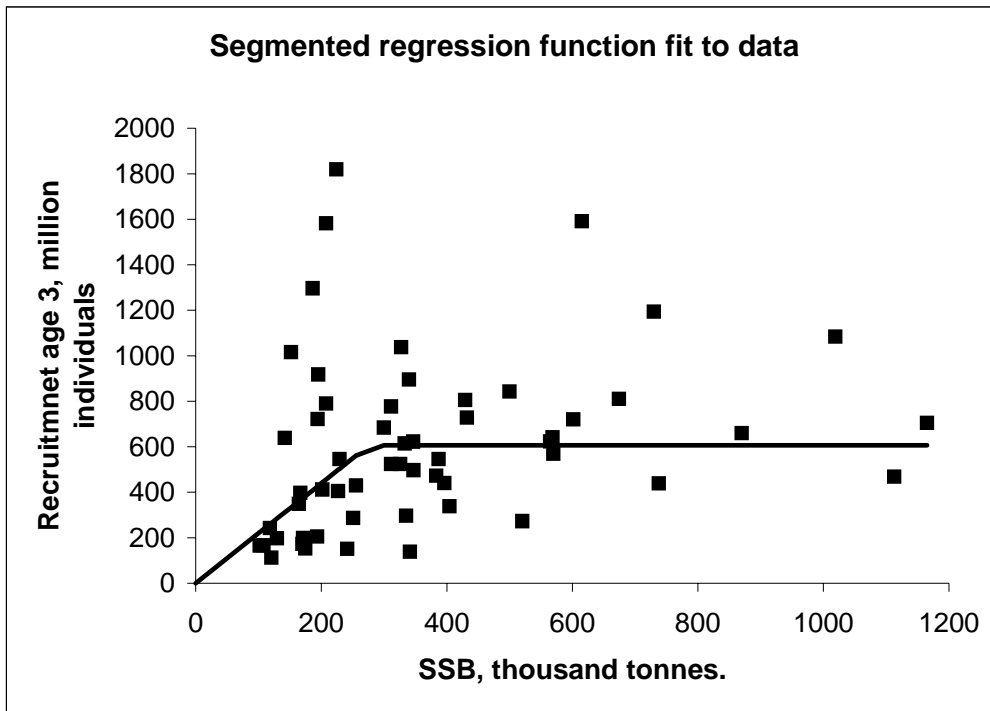


Fig. 1. Segmented regression recruitment function fit to data for spawning stock biomass and recruitment at age 3 (no cannibalism)

4.1.2. Extending the segmented recruitment function by including a cyclic term

Fig. 2 shows the residuals obtained when fitting the segmented regression stock-recruitment relationship. These residuals vary in a cyclic way with time.

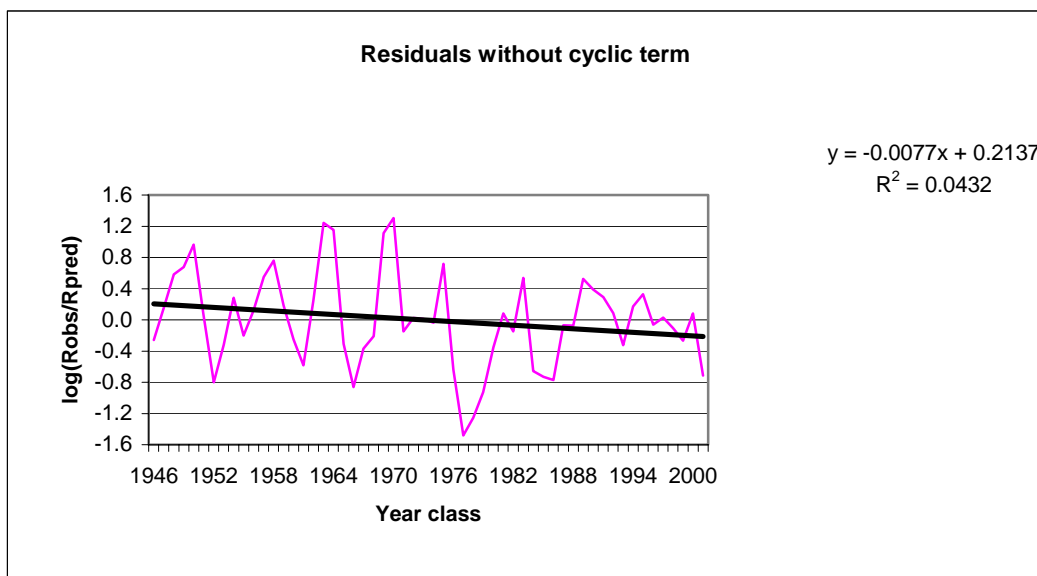


Fig. 2. Time variation of residuals of segmented regression recruitment function

We then tried to include the cyclic term in the exponent in equation (1). The results of the model fit (minimising log SSQ), which was carried out using Solver in Excel, are given in Table 1. The residuals when the cyclic term is included are shown in Fig. 3, and the predicted vs. observed values of recruitment using equation (1) with $\varepsilon = 0$ are shown in Fig. 4. The model does not pick up the outstanding year classes, but still performs fairly well. The time trend is no longer significant ($p > 0.05$).

Table 1. Results of fit of recruitment model

Model	a	b	A	φ	T	ε	Log (SSQ)	proportion of variability explained compared to constant recruitment
Constant recruitment							27.55	0.00
Segmented regression	606	276					19.79	0.28
Segmented regression+ cyclic term	606	276	0.40	-1.97	6.56		15.32	0.44
Segmented regression + cyclic term + stochastic term	599	275	0.40	-1.97	6.56	0.528	15.33	0.44

Several authors (e.g. Ottersen and Stenseth, 2001) have found a good correlation between temperature and recruitment, and there are cyclic variations in temperature. However, reliable long-term (or even medium-term) predictions of temperature variation are not available (Ottersen et al., 2000), and thus we do not include temperature in our recruitment model.

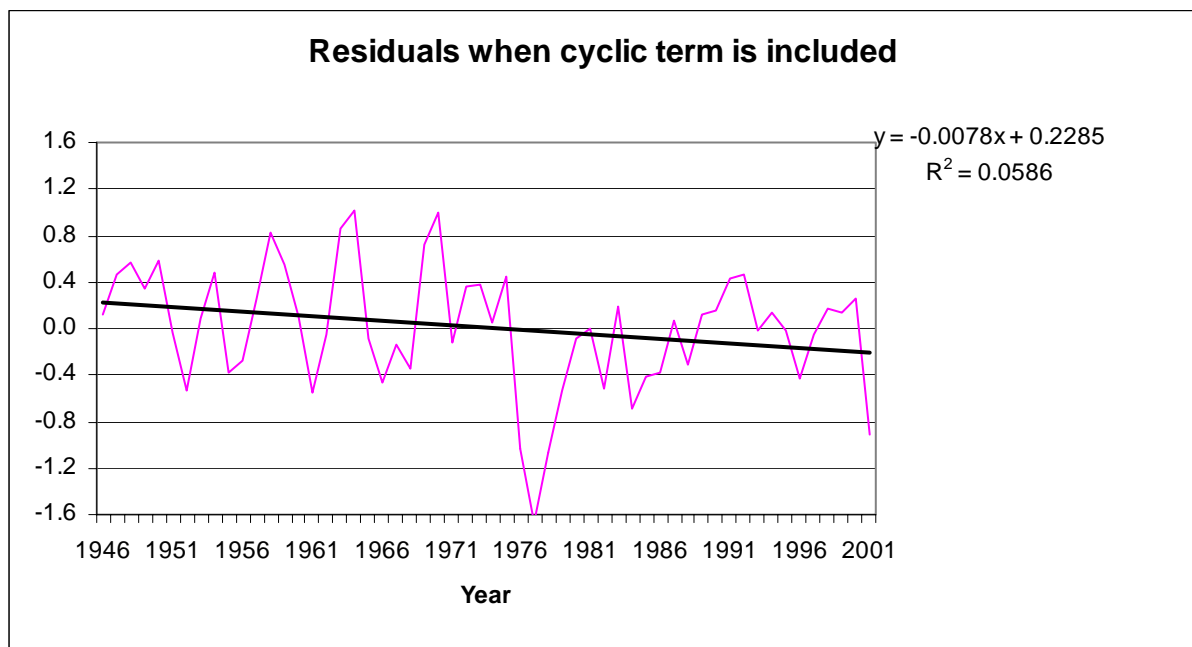


Fig. 3. Residuals when cyclic term is included in the recruitment function

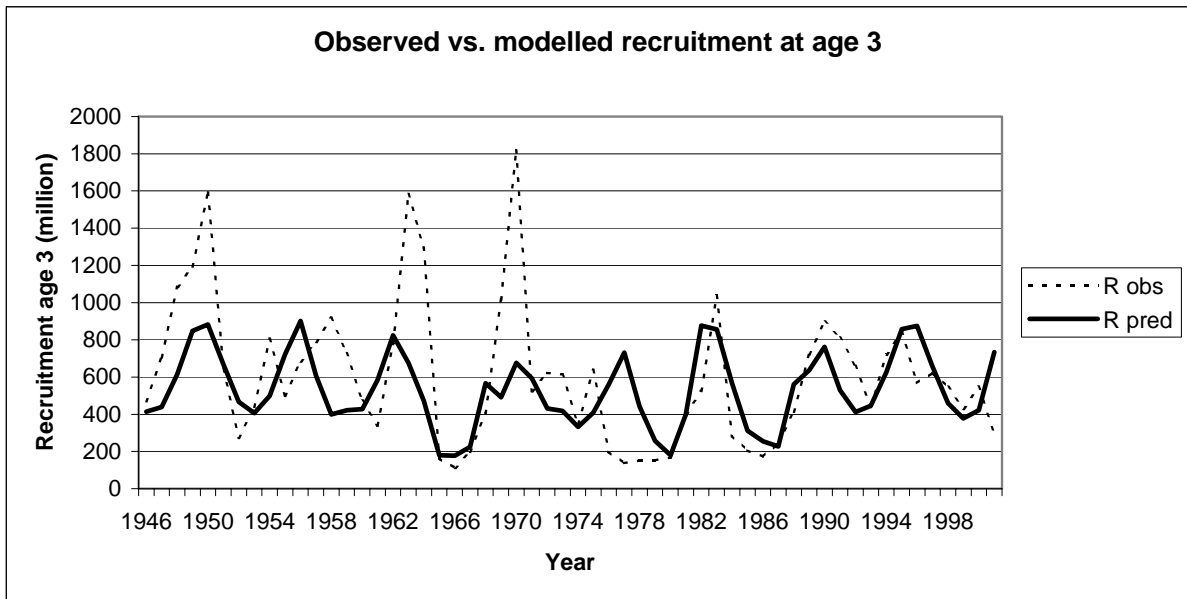


Fig. 4. Observed vs. modelled recruitment when cyclic term is included in the recruitment function

Fig.5 shows the residuals vs. SSB. The residuals are not significantly correlated ($p > 0.05$) with SSB

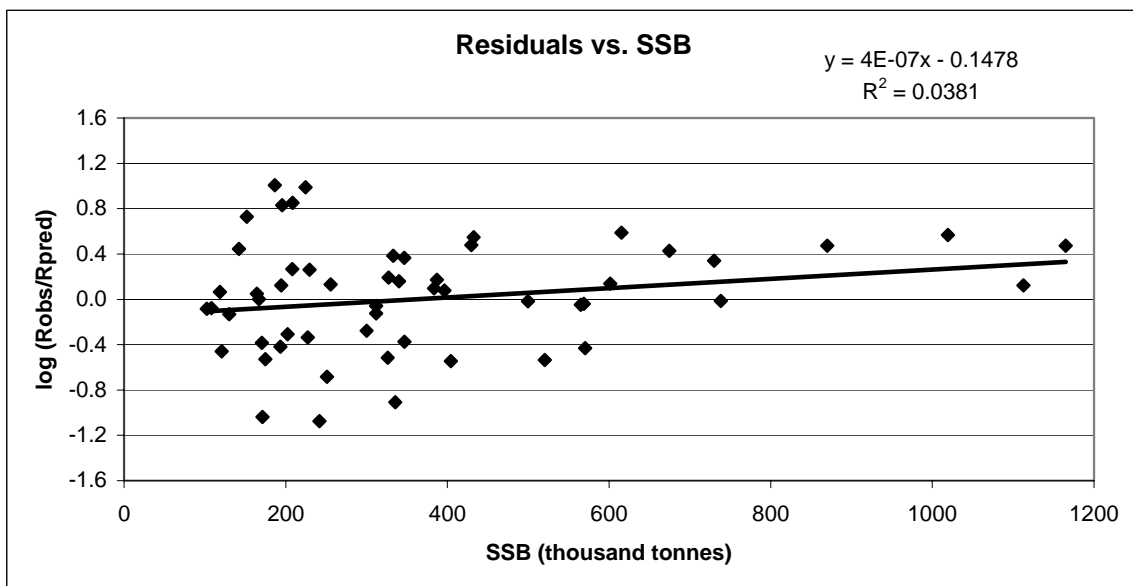


Fig. 5. Dependence of residuals on SSB

4.1.3. Determining the variance in the stock-recruitment function

We then need to determine the stochastic term ε in equation (1). We will follow the approach outlined by Skagen and Aglen (2002). They suggested 3 quality criteria for stochastic stock-recruitment functions:

1. Independence between residuals and SSB
2. Probability coverage
3. The recruitment estimates should be unbiased.

Criterion 1) has been tested for by looking at the deterministic stock-recruitment function (Fig. 5). The residuals are not correlated with SSB, but the variability in recruitment seems to be higher at low SSBs, and this could be modelled by making the variance a function of SSB.

2) is a control that the distribution assumed for the residuals is adequate, while 3) may be used as an additional constraint when finding the parameters of the stock-recruitment function.

Assuming that each of the historic residuals is equally likely, the rank of each of them, divided by the number of observed residuals, gives the empirical cumulated probability of the historical residuals. On the other hand, according to the model that is assumed for the residuals in the prediction, there corresponds a cumulated probability for the value of each observed residual. Each of these model probabilities should be close to the empirical cumulated probability of the same historic residual. The Kolmogorov goodness of fit test is based on this reasoning, and the Kolmogorov test statistic can be derived directly from the pairs of modelled and observed values.

The fit was done using Solver in Excel spreadsheets described by Skagen and Aglen (2002). A constraint on the sum of the difference between modelled and observed recruitments being zero was applied. In the fitting procedure, all the parameters in the stock-recruitment function were re-estimated (Table 1). The parameters a and b in the segmented regression equation (Eq. 1) changed somewhat, but the other parameters were very close to the values estimated using the corresponding deterministic model. Assuming a log-normal distribution, i.e. $\varepsilon = N(0, \sigma)$, $\sigma = 0.528$ gave the best fit to the data. Fig. 6 and 7 show the probability coverage and observed vs. modelled recruitment for this distribution. The fit seems to be rather satisfactory.

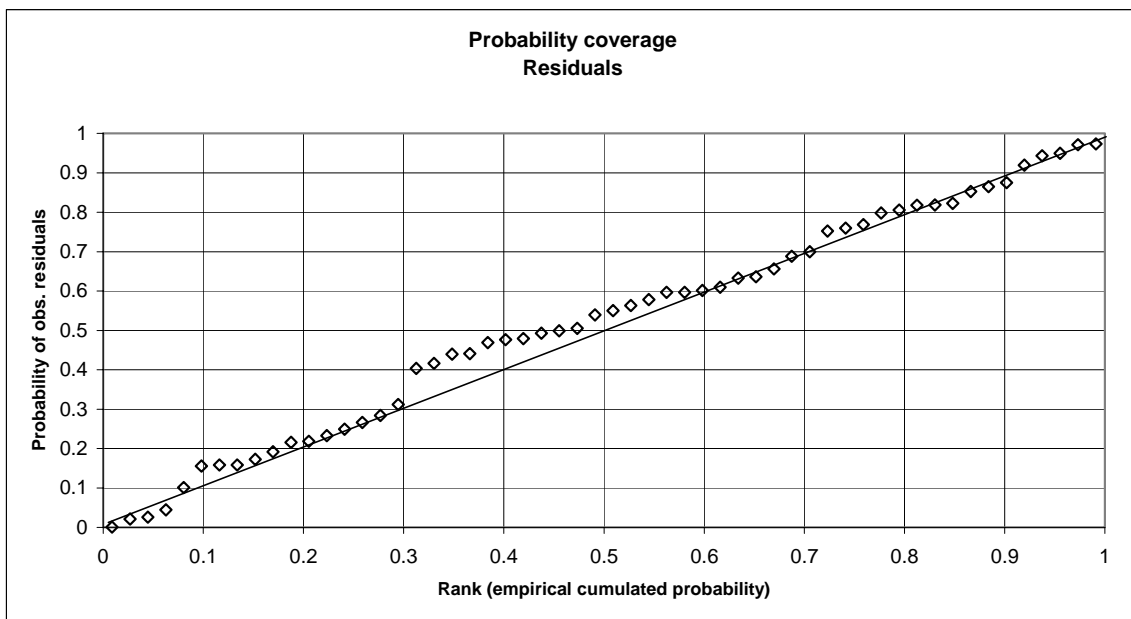


Fig. 6. Probability coverage for stochastic stock-recruitment function

The final test in any case is to take the distribution (or at least the standard percentiles) of recruitments from a long-term prediction and compare with the historic recruitments generated by similar levels of SSB.



Fig. 7. Observed vs. modelled recruitment for stochastic stock-recruitment function.

4.2. Weight and maturity at age

There are several possibilities for modelling this:

- 1) Using a time series average
- 2) To draw randomly weight at age in stock and catch and maturity at age from the entire time series (i.e. draw a year)
- 3) To fit a model for stock size dependence of growth and maturity to the entire time series and to simulate the uncertainty using a statistical model (e.g. normal distributed residuals with estimated σ) or draw randomly observed residuals around fitted trends. For weight at age, the model could e.g. be linearly dependent of total stock biomass (TSB), while for the maturity at age; it could e.g. be assumed to be a sigmoid function of TSB.

Approach 1 does not take the uncertainty in those parameters in account. Approach 2 will overestimate the uncertainty related to changes in those parameters. We have not observed such a wide range of annual changes in values for weight and maturity at age this approach will give. This approach will also give a bias in the results. When F is low, we will overestimate TSB, SSB and yield, when F is high we will underestimate those quantities. In order to avoid that, we will try approach 3). For all approaches, it could be discussed whether the entire time series should be used.

Heino et al. (2002) found that both increase in growth rate and change in age-and sex-specific tendency to mature have contributed to the observed trend towards earlier maturation. Thus, part of the change may represent a fisheries-induced adaptive genetic change. We will not take this into account in our analysis.

4.2.1. Weight at age in the stock

We have used the entire time series (stock weights in 1947-2005 vs. total stock biomass in 1946-2004) to fit a density-dependent model for weight at age (kg) in the stock $ws_{a,y}$ for ages 3-9. The model is of the form

$$ws_{a,y} = \alpha_a TSB_{y-1} + \beta_a \quad (3)$$

where TSB_y is the total stock biomass in year y , a is age and α_a and β_a are constants. The parameters in the regressions are given in Table 2.

It may also be necessary to truncate the range of possible values of cod weight, in order to avoid unrealistic values due to extrapolations. We chose to use the highest/lowest observed values of cod weight at each age as upper/lower bounds in the model.

Table 2. Parameters in regression for density-dependent weight at age in the stock and minimum, maximum and average values

age	α_a	β_a	R^2	p	min observed weight	max observed weight	mean weight
3	0.000011	0.318	0.02	> 0.05	0.19	0.52	0.341
4	-0.000029	0.753	0.02	> 0.05	0.40	1.17	0.692
5	-0.000058	1.373	0.05	> 0.05	0.79	1.82	1.253
6	-0.000118	2.285	0.12	< 0.01	1.48	2.82	2.041
7	-0.000213	3.521	0.21	< 0.01	2.14	4.06	3.079
8	-0.000371	5.190	0.28	< 0.01	2.92	5.83	4.418
9	-0.000703	7.472	0.43	< 0.01	3.65	8.93	6.017
10	-0.001113	10.290	0.42	< 0.01	4.56	12.15	7.990
11	-0.001441	12.404	0.47	< 0.01	5.84	15.03	9.431
12	-0.000888	12.065	0.45	< 0.01	7.08	12.09	10.217
13	-0.001429	15.528	0.59	< 0.01	8.15	14.85	12.563

We see that the relationship for ages 3-5 is insignificant. For those ages TSB will not be used as predictor. The biology and food composition of those age groups is different from that of older ages. We use average values for these age groups, as well as for age 10+, where the data set is less reliable.

For simplicity, we do not include uncertainty from the regression in our simulations.

4.2.2. Weight at age in the catch

Weight at age in catch is modelled as a function of weight at age in stock, using equation (4):

$$wc_{a,y} = \alpha_a ws_{a,y} + \beta_a \quad (4)$$

The values of α_a and β_a for ages 3-8 are given in Table 3. The regressions are based on data from 1983-2004, when observations of stock weights at age from surveys are available.

Weight at age in the catch is calculated directly from weight at age in the stock using equation (4). Uncertainties associated with the regression will not be taken into account. For ages 9 and older weight at age in the catch is set equal to weight at age in the stock.

Table 3. Parameters in regression for weight at age in the catch vs. weight at age in the stock

age	α_a	β_a	R^2	p
3	1.671	0.295	0.59	< 0.01
4	0.927	0.565	0.81	< 0.01
5	0.975	0.495	0.89	< 0.01
6	0.891	0.605	0.89	< 0.01
7	0.794	0.972	0.64	< 0.01
8	0.653	1.933	0.56	< 0.01

4.2.3. Maturity at age

Maturity at age is modeled as a function of weight at age in the stock in the same year:

$$P_{a,y} = P(ws_{a,y}) = \frac{1}{1 + e^{-\lambda_a(ws_{a,y} - w_{50,a})}} \quad (5)$$

Fitting this model for ages 5-10 gave the following results:

Table 4. Parameters in regression for maturity at age vs. weight at age in the stock

age	λ_a	$W_{50,a}$	R^2	Historical mean value
5	2.7551	2.5571	0.338	0.032
6	1.6567	3.2453	0.242	0.121
7	1.7360	3.6743	0.324	0.272
8	1.3006	4.5418	0.380	0.451
9	1.1647	5.4599	0.588	0.626
10	0.6278	5.4517	0.496	0.790

For ages 3-4 we use P=0 and for ages 11+ P=1.

The fit (admittedly not very good) is shown in Fig. 8

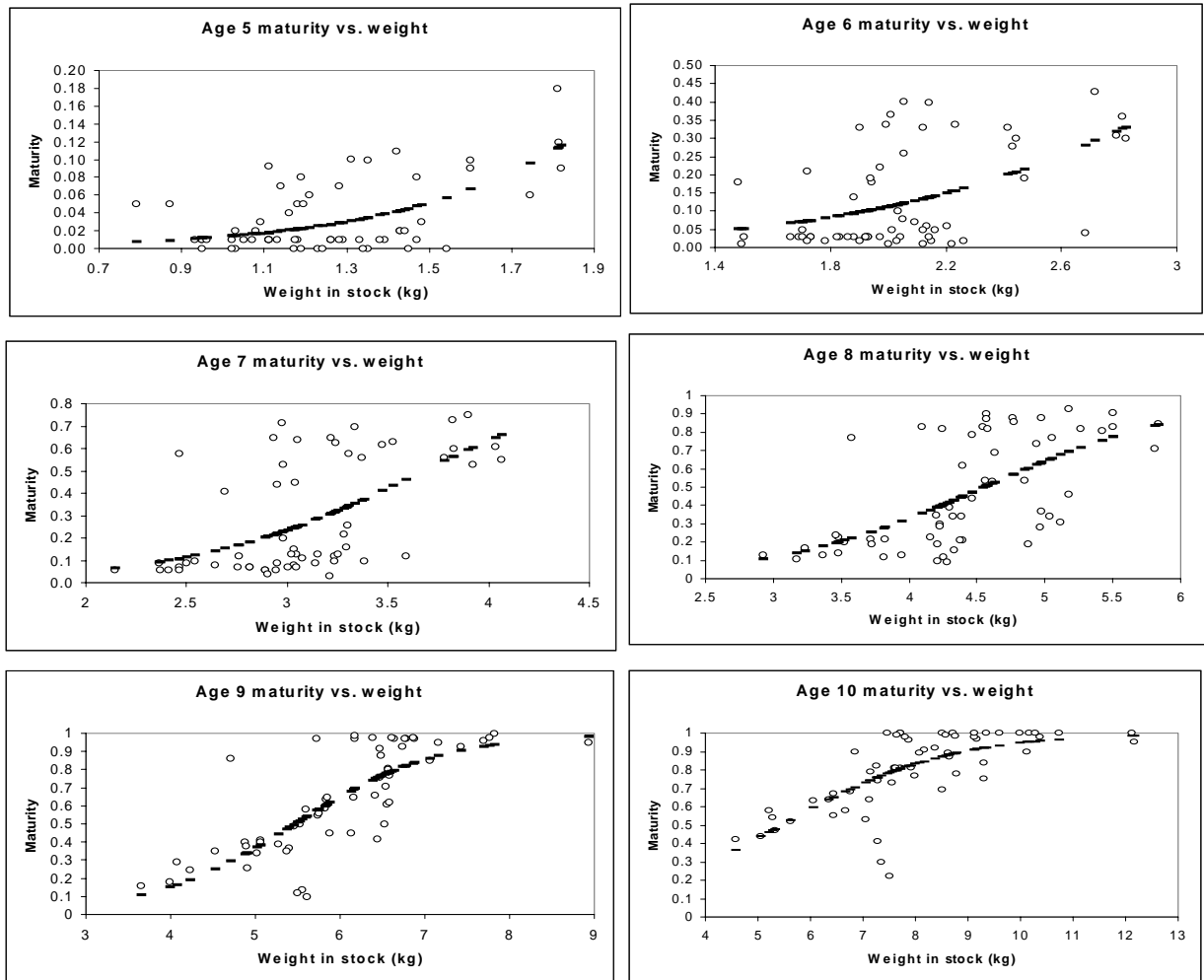


Fig. 8. Maturity at age 5-10 as a function of weight at age in the stock in the same year (open circles). The model described in eq. (5) is also shown (black line)

4.3. Mortality

The (residual) natural mortality (M) was set to 0.2 for all age groups. In addition, cannibalism mortality (M_2) was included in some simulations (see below).

4.3.1. Cannibalism mortality

As mentioned in Section 4.1.1, cannibalism will not be included in our main analysis because the data used to fit our stock-recruitment function does not include cannibalism. However, it is important to have models for cannibalism mortality available so that the effect of cannibalism on the population dynamics can be explored. Natural mortality due to cannibalism (M_2) has been calculated for the period 1984-present, when annual cod stomach content data are available. This mortality can be significant for age 3 and 4 cod (ICES, 2005), and should thus be modelled. Using data for the period 1984-2002, Kovalev (2004) found that cannibalism mortality for age 3 and 4 in year y showed good correlation both with SSB_{y-3} and with the biomass of age 6 and 7 cod in the beginning of year y . The two models can be described by the following formulas:

$$M_{2,y,a} = \alpha_a SSB_{y-3} + \beta_a \quad (6)$$

or

$$M_{2,y,a} = \alpha_a (N_{y,6}W_{y,6} + N_{y,7}W_{y,7}) + \beta_a \quad (7)$$

where the parameter values based on data for the period 1984-2004 are given in Table 5 for equation (6) and in Table 6 for equation (7).

Table 5. Parameters in regression for cannibalism mortality as a function of spawning stock biomass 3 years earlier

Age	α_a	β_a	R^2	p
3	0.000636	-0.123	0.74	<0.01
4	0.000271	-0.064	0.74	<0.01

Table 6. Parameters in regression for cannibalism mortality as a function of the biomass of age 6 and 7 cod in the beginning of the year

Age	α_a	β_a	R^2	p
3	0.000391	- 0.068	0.28	<0.05
4	0.000195	- 0.055	0.38	<0.01

The positive relationship between biomass of age 6 and 7 cod and cannibalism mortality on age 3 and 4 cod can be explained as increasing cannibalism when predator abundance increases. Adding biomass of older ages gave a worse fit. It should be noted, however, that cod predators are usually at least twice as long as cod prey (Bogstad et al. 1994). Since cod growth in length is approximately linear until age 7 (Ozhigin et al. 1995, 1996; Jørgensen 1992), biomass of age 6 and 7 cod does not seem to be the most appropriate measure, particularly as the proportion of cod in the diet of cod increases with increasing cod (predator) length (Bogstad et al., 1994).

The cause and effect between high cannibalism M in one year and high SSB three years before, which gives the strongest correlation, is less clear. A possible interpretation is that cannibalism is higher when SSB and thus recruitment is good. It is also seen from the data that high level of cannibalism coincides not only with high SSB 3 years before but also to some extent with low abundance of capelin (Figure 9).

Thus, in order to properly study the effect of cod cannibalism, a cod-capelin model is needed. In such a model, the following multispecies effects should be included: Effect of capelin abundance on individual growth of cod (Mehl and Sunnanå, 1991), effect of capelin abundance on cod cannibalism, and predation by cod on capelin (Bogstad and Gjørseter 2001). Such an extension of CodSim is planned within the research program: “Optimal long-term harvest in the Barents Sea ecosystem”.

At a later stage, CodSim should also be extended down to age 1 and cannibalism on age 1 and 2 cod could then be modelled explicitly instead of including it in the stock-recruitment relationship. Such work is in progress (Bogstad et al., 2004b).

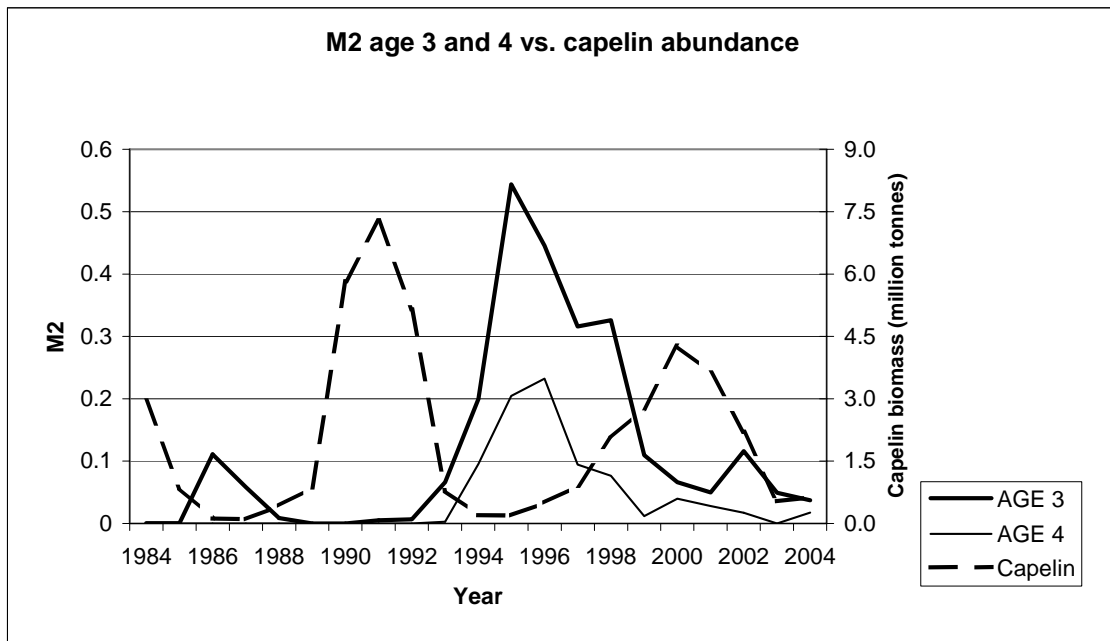


Fig. 9. Cannibalism mortality of age 3 and 4 cod versus capelin abundance (acoustic survey in September) in the same year

It would also be useful to utilise the long time series of qualitative Russian stomach content data for cod (Ponomarenko et al., 1978; Ponomarenko and Yaragina, 1979) in order to investigate how abundance of capelin in cod stomachs affects the level of cod cannibalism.

We decided to make model runs with both cannibalism models, and to apply an upper limit for the level of cannibalism in order to avoid unrealistic values. As an upper limit we chose the highest observed values (rounded): age 3 – 0.6, age 4 – 0.25. The lower limit of M2 was of course set to 0.0.

4.4. Exploitation pattern

The selection pattern used by AFWG 2005 in their prognosis (i.e. the 2002-2004 average) was chosen as the default exploitation pattern S(a) (Table 7). In order to study the effect of changing the exploitation pattern, this pattern was then shifted by 1 age group upwards and downwards.

Table 7. Default exploitation pattern

Age	3	4	5	6	7	8	9	10	11	12	13+
Selection	0.0179	0.1543	0.4643	0.8316	1.1905	1.2805	1.1840	1.0490	0.9404	1.5830	1.5830

Ulltang (1987) and Kvamme and Bogstad (2005) both studied the effect of changing the exploitation pattern on the yield per recruit for NEA cod. Both studies showed that shifting the exploitation pattern towards older fish would increase the yield per recruit.

Since we allow for variable weight-at-age in our model, it would be appropriate to make a weight-dependent selection curve. This could be done e.g. by modifying the commonly used length-dependent selection curve

$$S(a) = (1 + \exp(-4\alpha(l - l_{50})))^{-1} \quad (8)$$

by assuming a constant length-weight relationship and substituting weight for length in equation (8). Such a modification should be introduced in future studies.

5. Modelling of assessment error

Assessment error/bias was not included in these simulations.

6. Choice of harvest control rules to be explored

The harvest control rule suggested by the Joint Norwegian-Russian Fisheries Commission in 2004 is:

- estimate the average TAC level for the coming 3 years based on F_{pa} . TAC for the next year will be set to this level as a starting value for the 3-year period.
- the year after, the TAC calculation for the next 3 years is repeated based on the updated information about the stock development, however the TAC should not be changed by more than +/- 10% compared with the previous year's TAC.
- if the spawning stock falls below B_{pa} , the procedure for establishing TAC should be based on a fishing mortality that is linearly reduced from F_{pa} at B_{pa} , to $F=0$ at SSB equal to zero. At SSB-levels below B_{pa} in any of the operational years (current year, the year before and 3 years of prediction) there should be no limitations on the year-to-year variations in TAC.

$F_{pa}=0.40$ and $B_{pa}=460$ thousand tonnes.

This rule was evaluated by the AFWG in 2005, and found to be precautionary. (ICES, 2005).

In this paper, we will explore a rule of this kind, but will concentrate on studying fixed F strategies (same F applied irrespective of stock size, no stabilizing elements).

The rule for determining the reference F level (F_{5-10}) is then:

$$\left\{ \begin{array}{ll} F(y) = \frac{SSB(y)}{B_{pa}} F_1 & \text{if } SSB(y) < B_{pa} \\ F(y) = F_1 & \text{if } SSB(y) > B_{pa} \end{array} \right. \quad (9)$$

and the fishing mortality at age is given by

$$F(y, a) = S(a)F_1 \quad (10)$$

7. Choice of model runs

7.1. Default settings (Run 1)

Initial data were taken from the 2005 AFWG assessment (ICES, 2005) and the population model described in Section 4 was used from 2006 onwards. Simulations were carried out for a 100-year period (2006-2105). The mean yield over the last 80 years of the period was used for evaluation of MSY. 2000 simulations were carried out in each case, and a 100% limit on annual TAC change was applied.

For all runs, the reference F was varied from 0 to 1.2 in steps of 0.05. Density-dependent weight at age was assumed, and weight at age in catch and maturity at age was assumed to depend on weight at age in the stock. No cannibalism was assumed. The default exploitation pattern (2002-2004 average) was used.

7.2. Exploring rules of the type evaluated by ICES in 2005

In Run 2, we explored strategies with a reduction of F below B_{pa} (i.e. of the type outlined in Section 6).

7.3. Changing population dynamics model and exploitation pattern

Runs were made both with (Run 1) and without (Run 3) density-dependence in weight at age (and thus in weight at age in catch and maturity at age). Also, 3 different exploitation patterns (the default pattern and this pattern shifted 1 age group upwards and downwards) were explored (Run 1, 4 and 5). Runs were also made with both cannibalism functions (Run 6 and 7). For technical reasons, such runs could at present only be made without uncertainty in recruitment. Cyclic recruitment is included, however.

Table 8. Overview of runs

Run no.	Harvest strategy	Fishing pattern	Density-dependence	Cannibalism
1	Fixed F	AFWG2005	Yes	No
2	JRNC rule	AFWG2005	Yes	No
3	Fixed F	AFWG2005	No	No
4	Fixed F	AFWG 2005 shifted 1 age upwards	Yes	No
5	Fixed F	AFWG 2005 shifted 1 age downwards	Yes	No
6	Fixed F	AFWG 2005	Yes	Function 1
7	Fixed F	AFWG 2005	Yes	Function 2

8. Results and discussion

The results of Run 2, using the JRNC rule for various F levels above B_{pa} (F_1 in eq. 9) are shown in Figure 10. It is seen that for F_1 values above 0.5, the realized mean F will be much lower than F_1 because SSB will be below B_{pa} in many cases.

Figures 12-13 only show the SSB/TSB for F values from 0.2 upwards. The reason for this choice is that for lower Fs, SSB and TSB are well outside the observed range (e.g. about 10 million tonnes SSB and 15 million tonnes TSB at F=0), and showing SSB/TSB for the F range 0.0-0.2 would make the plots less informative for moderate and high F values because all the curves will then be close to the Y-axis for such values.

Figure 11 shows that the MSY is around 900 000 tonnes in all cases. The yield curve is relatively flat on top in all cases. All curves except the curve where the exploitation pattern is shifted one age group upward show a sharp decrease at high F values, when recruitment starts decreasing (Figure 14). The reason why this is not seen when the exploitation pattern is shifted towards older fish, is that such a pattern gives a much lower exploitation of the youngest fish so that some fish will always mature before being caught.

Figure 11 also shows that the yield starts to decrease sharply for F values above about 0.7, when density-dependence is not included. This is in good accordance with ICES (2003) who found a F_{lim} value of 0.74 in an analysis where density-dependence was ignored.

Figure 15 shows the yield as a function of F for cannibalism functions 1 and 2. Cannibalism function 1 shows a peak in yield at about F=0.7, while cannibalism function 2 gives a yield curve with about the same shape as the curves without cannibalism. Both curves show a much lower maximum yield (about 600 thousand tonnes) than the curves without cannibalism (about 900 thousand tonnes). It should be noted that stochastic recruitment would shift the peak somewhat towards lower Fs, because SSBs below the breakpoint in the segmented regression would occur more often than in simulations without stochasticity.

F values around 0.3-0.4 seem to be optimal. This is in accordance with earlier work (e.g. Nakken et al., 1996; Kovalev and Korzhev, 2002).

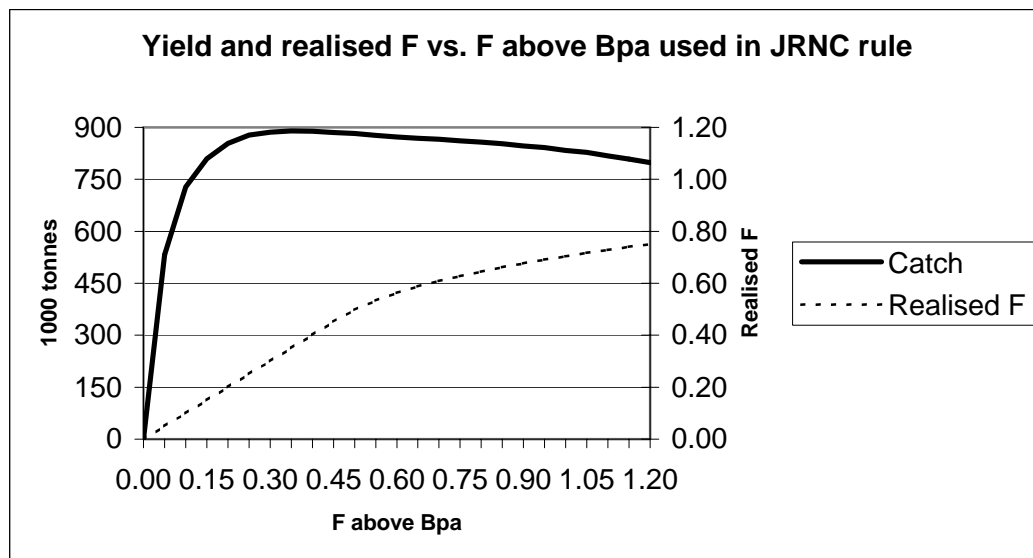


Fig. 10. Average catch and realized F for the period 2026-2105 using the JRNC rule

It should also be noted that the MSY measured in economic value will be found at lower F values than the MSY measured in biomass, because catch costs are higher at low stock sizes and because larger cod is better paid than smaller cod.

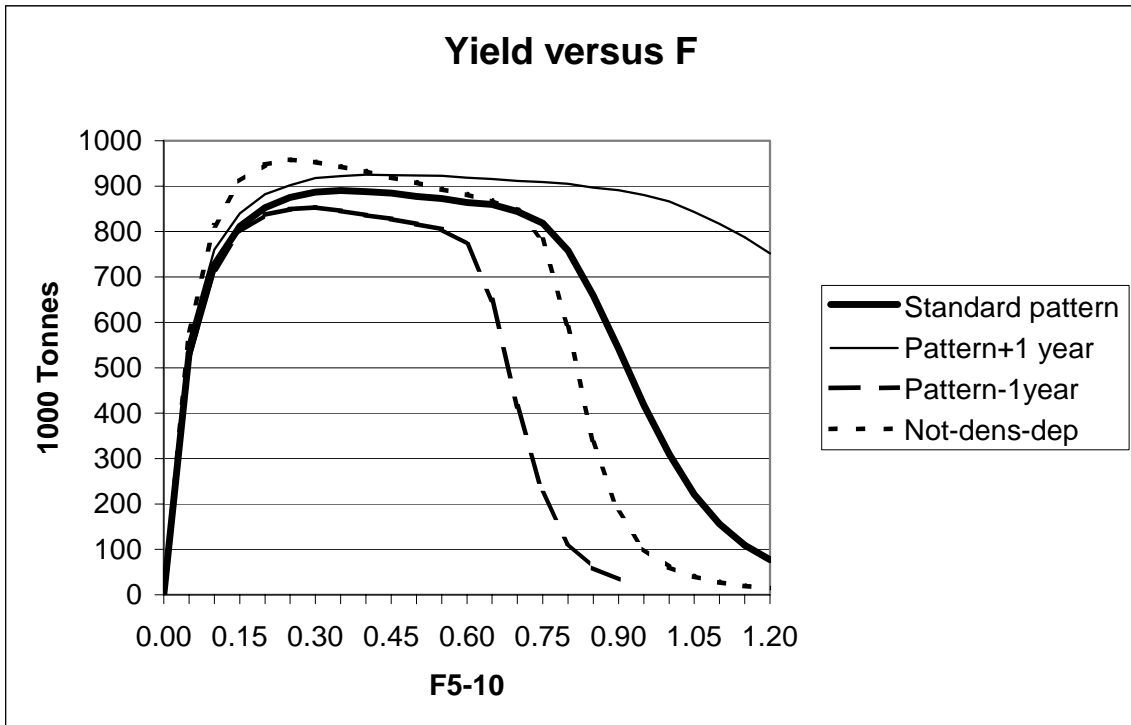


Fig. 11. Average catch for 2026-2105 as a function of fishing mortality for different exploitation patterns and population models

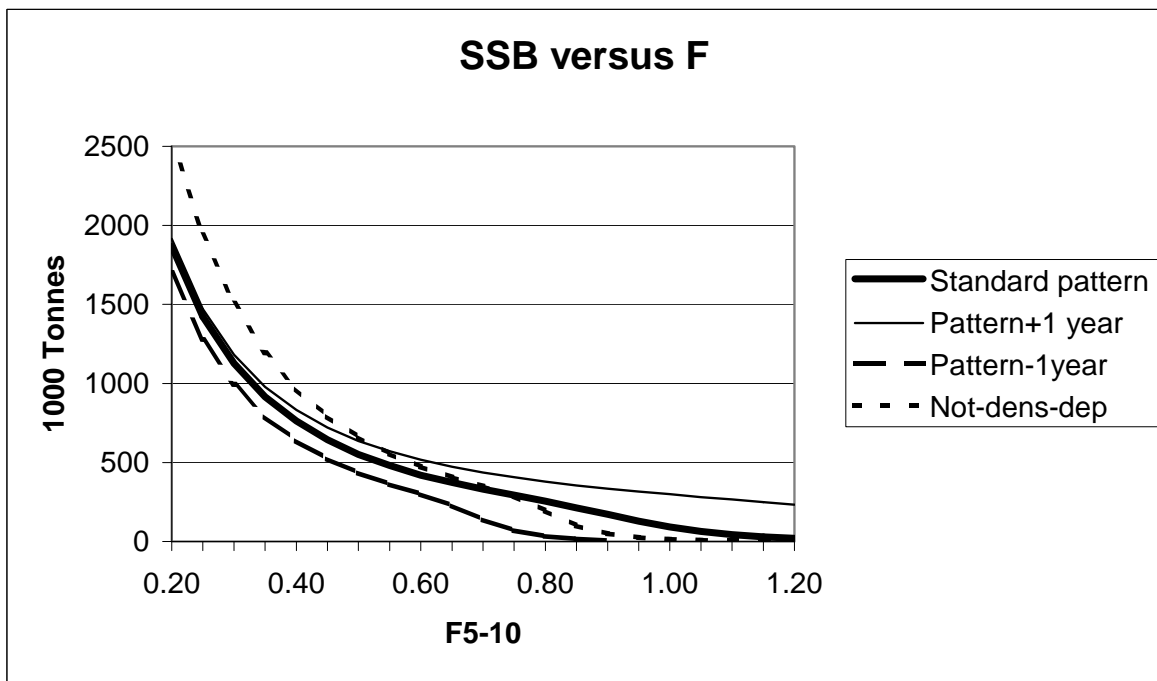


Fig. 12. Average spawning stock biomass for 2026-2105 as a function of fishing mortality for different exploitation patterns and population models

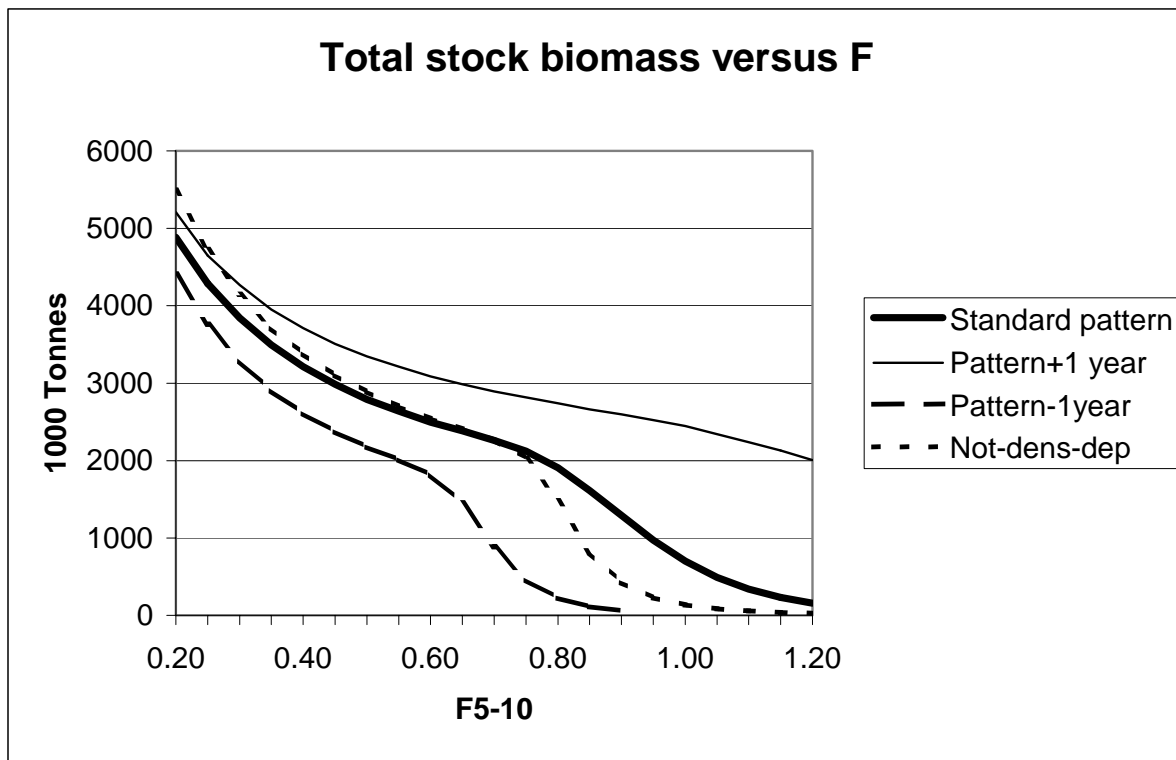


Fig. 13. Average total stock biomass for 2026-2105 as a function of fishing mortality for different exploitation patterns and population models

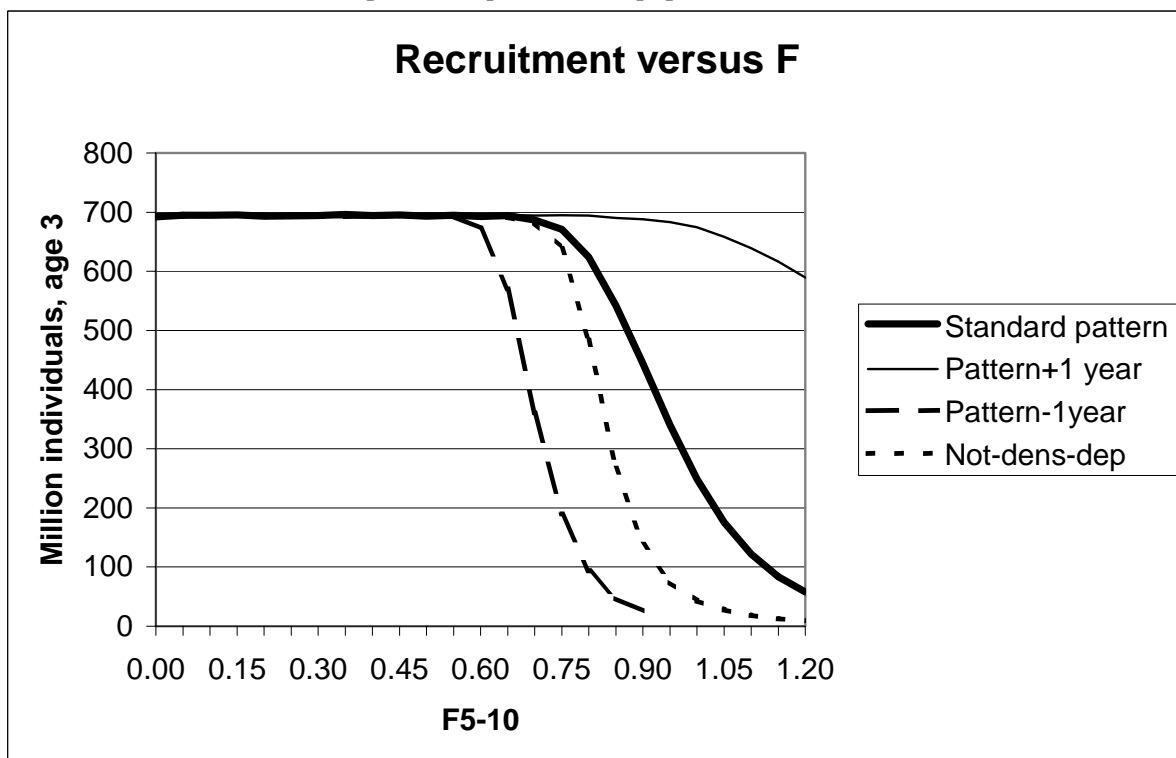


Fig. 14. Average recruitment for 2026-2105 as a function of fishing mortality for different exploitation patterns and population models

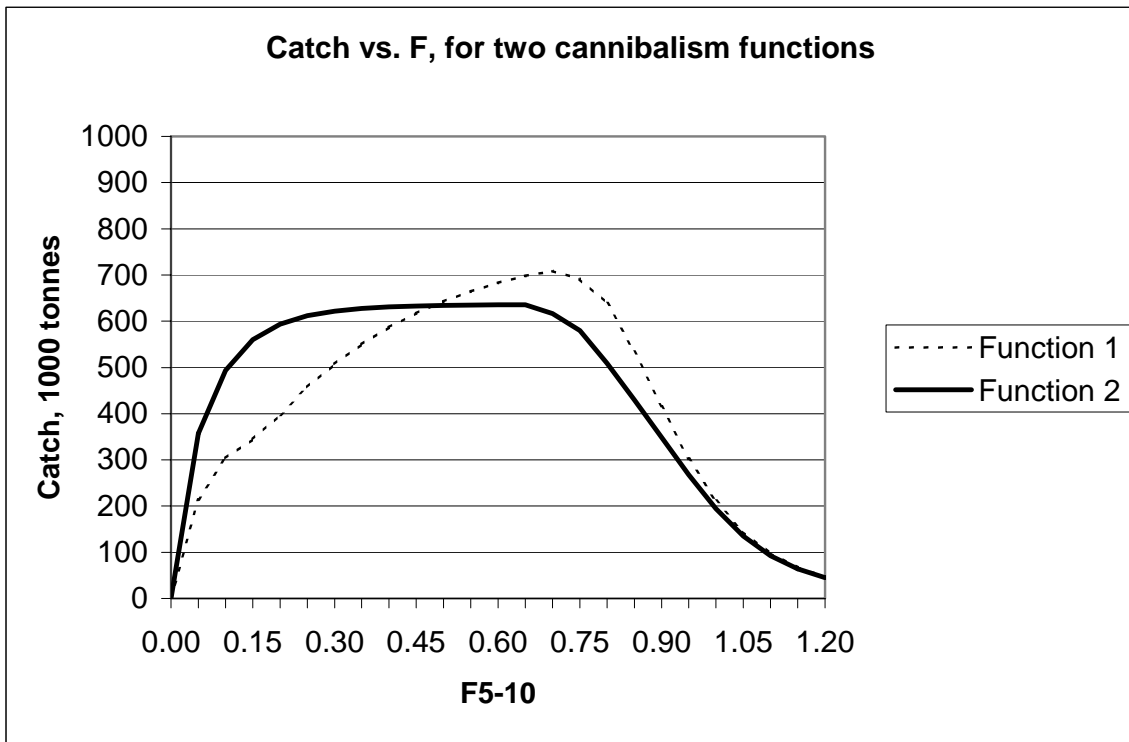


Fig. 15. Average catch for 2026-2105 as a function of fishing mortality for different cannibalism functions

Kvamme and Bogstad (2005) showed that the loss of yield when F is increased above F_{max} is slightly higher when an age-length structured model is used, and that the effect of fishery on mean weight-at-age and maturity-at-age is significant.

9. Further work

The single-species population model for cod presented in this paper may be extended e.g. by extending the age range down to age 1(0) or by adding length structure (see Bogstad et al. (2004b) for a description of a cod model extended down to age 1(0) and including age and length structure). Also, more biological knowledge may be used, e.g. by using the total egg production (TEP) instead of SSB to describe the recruitment potential of the cod stock. The main reason for doing so is that the correlation between TEP, and recruitment at age 3 for Northeast Arctic cod is stronger than the correlation between spawning stock biomass and recruitment (Marshall et al. 2003). Maturity at age (size) as well and mortality at age after maturation differ significantly by sex (Jakobsen and Ajiad 1999, Ajiad et al. 1999) and this should also be taken into account.

We have also recognized that changes in the natural mortality of cod in the plus group could substantially shift F_{msy} to the left/right as the proportion of older fish in stock when F is low will increase considerably. Is it realistic that the population will consist mainly of plus group (cod older than 12 years)? We do not think so, but probably we have not enough data to predict this situation correctly. Such uncertainty of cod population behavior should, however, be taken into account when a long-term maximum yield strategy is implemented in practice.

Model changes (e.g. using a Beverton-Holt instead of a segmented regression stock-recruitment relationship) may alter the perception of maximum long-term yield as well as of how the yield and the fishing mortality are related.

Time series of catch at age should be updated by including discards (see e.g. ICES 2005, Tab. 3.31).

10. References

- Ajiad, A.M., Jakobsen, T., and Nakken, O.** 1999. Sexual difference in Maturation of Northeast Arctic Cod. *J. Northw. Atl. Fish. Sci.* 25: P.1-15.
- Bogstad, B., Aglen, A., Tjelmeland, S., Åsnes, M. N., Kovalev, Y., and Yaragina, N.A.** 2004a. Evaluation of the proposed harvest control rule for Northeast Arctic cod. Appendix to Report of the Arctic Fisheries Working Group, Copenhagen 4-13 May 2004. ICES C.M. 2004/ACFM: 28. – 475 pp.
- Bogstad, B., and Gjørseter, H.** 2001. Predation by cod (*Gadus morhua*) on capelin (*Mallotus villosus*) in the Barents Sea: implications for capelin stock assessment. *Fisheries Research* 53: 197-209.
- Bogstad, B., Howell, D., and Åsnes, M.N.** 2004b. A closed life-cycle model for Northeast Arctic Cod. ICES C.M.2004/K:26. – 26 pp.
- Bogstad, B., Lilly, G. R., Mehl, S., Pálsson, Ó. K., and Stefánsson, G.** 1994. Cannibalism and year-class strength in Atlantic cod (*Gadus morhua* L.) in Arcto-boreal ecosystems (Barents Sea, Iceland and eastern Newfoundland). *ICES mar. Sci. Symp.* 198: P.576-599.
- Heino, M., Dieckmann, U., and Godø, O.R.** 2002. Reaction norm analysis of fisheries-induced adaptive change and the case of the Northeast Arctic cod. *ICES C. M.* 2002/Y:14. – 14 pp.
- ICES** 2003. Report of the Study Group on Biological Reference Points for Northeast Arctic Cod, Svanhovd, Norway 13-17 January 2003. *ICES C. M.* 2003/ACFM:11. – 39 pp.
- ICES** 2005. Report of the Arctic Fisheries Working Group, Murmansk, Russia 19-28 April 2005. *ICES C.M.* 2005/ACFM:20. – 564 pp.
- Jakobsen, T., and Ajiad, A.M.** 1999. Management Implications of Sexual Differences in Maturation and Spawning Mortality of Northeast Arctic Cod. *J. Northw. Atl. Fish. Sci.* 25: P.125-131.
- Jørgensen, T.** 1992. Long-term changes in growth of Northeast Arctic cod (*Gadus morhua* L.) and some environmental influences. *ICES J. mar. Sci.* 49: P.263-277.
- Kovalev, Yu. A.,** 2004. Predicting natural mortality due to cannibalism for Northeast Arctic cod. WD10, AFWG 2004.
- Kovalev, Yu. A.,** 2005. Evaluation of maximum sustainable yield for Northeast Arctic cod using single species population model. *Problems of Fisheries.* (in press).
- Kovalev, Yu. A., and Korzhev, V.A.** 2002. The model of the Lofoten – Barents Sea cod fisheries management. *Problems of fisheries.* Vol. 3. № 2(10): P.264-276. (In Russian)
- Kvamme, C., and Bogstad, B.** 2005. The effect of including length structure in yield-per-recruit estimates for Northeast Arctic cod (*Gadus morhua* L.). *ICES Journal of Marine Science* (accepted).
- Marshall, C.T., O'Brien, L., Tomkiewicz, J., Marteinsdóttir, G., Morgan, M.J., Saborido-Rey, F., Köster, F., Blanchard, J.L., Secor, D. H., Kraus, G., Wright, P., Mukhina, N.V., and Björnsson, H.** 2003. Developing alternative indices of

- reproductive potential for use in fisheries management: case studies for stocks spanning an information gradient. *J. Northw. Atl. Fish. Sci.* 33: P.161-190.
- Mehl, S. and Sunnanå, K.** 1991. Changes in growth of Northeast Arctic cod in relation to food consumption in 1984-1988. *ICES mar. Sci. Symp.* 193: P.109-112.
- Nakken, O., Sandberg, P., Steinshamn, S.I.** 1996. Reference points for optimal fish stock management. A lesson to be learned from the Northeast Arctic cod stock. *Marine Policy* 20(6): P.447-462.
- Ottersen, G., and Stenseth, N.C.** 2001. Atlantic climate governs oceanographic and ecological variability in the Barents Sea. *Limnol. Oceanogr.* 46(7): 1774-1780.
- Ottersen, G., Ådlandsvik, B., and Loeng, H.** 2000. Predicting the temperature of the Barents Sea. *Fisheries Oceanography* 9: P.121-135.
- Ozhigin, V.K., Tretyak, V.L., Yaragina, N.A. and Ivshin, V.A.** 1995. Growth of Arcto-Norwegian cod in dependence of environmental conditions and feeding. *ICES C.M.1995/P:10. Theme Session on Causes of Observed Variations in Fish Growth.* – 22 pp.
- Ozhigin, V.K., Tretyak, V.L., Ivshin, V.A., and Yaragina, N.A.** 1996. Growth of Arcto-Norwegian cod. – Murmansk: PINRO Press. – 82 pp. (In Russian).
- Ponomarenko, V.P., Ponomarenko, I. Ya., and Yaragina, N.A.** 1978. Consumption of Barents Sea capelin by cod and haddock in 1974-1976. *ICES C. M.* 1978/G:23.–22 pp.
- Ponomarenko, I. Ya. and Yaragina, N. A.** 1979. Seasonal and year-to-year variations in the feeding of the Barents Sea cod on Euphausiacea in 1947-1977. *ICES CM* 1979/G:17 – 20 pp.
- Skagen, D.W., and Aglen, A.** 2002. Evaluating precautionary values of fishing mortalities using long-term stochastic equilibrium distributions. Annex 7(WD 7) in: *ICES Study Group on the Further Development of the Precautionary Approach to Fishery Management, Copenhagen 2-6 December 2002.* *ICES C. M.* 2003/ACFM:09.– 144 pp.
- Tretyak, V.L.** 1987. Methodical recommendations on regulation of single species fishery (exemplified by Arcto-Norwegian cod). Murmansk: PINRO Press, 1987. – 37 pp. (In Russian).
- Ulltang, Ø.** 1987. Potential Gains from Improved Management of the Northeast Arctic Cod Stock. *Fisheries Research* 5: P.319-330.
- Ulltang, Ø.** 1996. Stock assessment and biological knowledge: can prediction uncertainty be reduced? *ICES J. mar. Sci.* 53: P.659-675.
- Åsnes, M.N.** 2005. Prost User Guide. WD2, *ICES AFWG* 2005. (Also available at www.assessment.imr.no/).