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NORTH-EAST ARCTIC HADDOCK: INVESTIGATION OF UNCERTAINTY IN STOCK ASSESSMENT AND IMPROVEMENT PROJECTION

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ABSTRACT

North-East Arctic (NEA) haddock (*Melanogrammus aeglefinus Linne*) is the target species for investigation. In this project, an attempt will be made to improve the methods of estimating inputs for predictions and investigate uncertainty in stock assessment and projection of haddock.

In order to improve current methods of estimating inputs for predictions, alternative methods were compared with the "averaging" methods, which are currently used in the Arctic Fisheries Working Group (AFWG). It was established empirically and supplemented by statistical tests that the "cohort" method gives the best results for predicting weight at age in stock for the youngest age groups in general and all age groups for short-term projection. The retrospective estimates and forecasts of spawning stock biomass, recruitment and fishing mortality in previous years from xADAPT and XSA are slightly different for the period 2000-2006, but working group estimates lie within the bootstrap error distribution.

Suggested algorythms based on the ADAPT framework allow an investigation of part of the ucertainty in stock assessment and projection procedures. Its prototype– programm, ADAPT, can be applied as an alternative approach for estimating of population dynamics of NEA haddock.

Keywords: *stock assessment, projection, weight at age, maturity at age, uncertainty, spawning stock biomass, fishing mortality, reference points, bootstrap error distribution.*

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LIST OF TERMS AND PARAMETERS

Stock assessment	Estimation parameters of population for start of current (assessment) year with back calculation parameters in previous years.
Projection	Predictions of unknown parameters for current year followed by two years (short-term forecast).
$N_{a,y}$	Number of fish in year y at age a.
$M_{a,y}$	Natural mortality at age a in year y.
$F_{a,y}$	Fishing mortality at age a in year y.
$Z_{a,y}$	Total mortality at age a in year y.
$U_{a,y}$	Survey indices.
α	Coefficient of regression.
q_a	Catch ability index at age a (coefficient of regression).
β	Power of regression.
mw@a	Mean weight at age.
msw@a	Mean weight at age in stock.
mcw@a	Mean weight at age in catch.
mat@a	Maturity ratio at age.
SSB	Spawning stock biomass.
Bpa	Precautionary approach reference point – means that SSB above this value can produce strong year classes with high probability.
Blim	Precautionary approach reference point – means that SSB below this value cannot produce strong year classes with high probability.
Fpa, Flim	Corresponding reference values of F set as fishing mortality reference points.
F shrinkage	A procedure, when for each age, the overall estimate of fishing mortality in the final year is a weighted geometric mean of the raised fleet F's.
xAPAPT	Stock assessment and projection model in Excel based on ADAPTive framework described by Gavaris (1988).
XSA	Extended Survivors Analysis - software package (Shepherd 1992), Darby and Flatman 1994) to estimate stock abundance and fishing mortality of cohorts that have entered the fishery.
CV	Coefficient of variances – obtained as standard deviation of parameter divided by average value of same parameter.
N_3	Numbers of fish at age 3 (recruitment).
Fbar	Median fishing mortality for all age groups (for haddock calculated as median of age groups 4-7 (F_{4-7})).
$U_{a,y}$	Observed indices of scientific survey (for ex. catch per unit effort).
$\bar{U}_{a,y}$	Predicted by model indices of scientific survey.
CI	Confidence intervals – means probability that medium estimated values lie between maximal and minimum estimates.

1 INTRODUCTION

1.1 Biological background

The target species for investigation is haddock –(*Melanogrammus aeglefinus Linne)* (Figure 1)*,* a sea boreal fish, which lives in water of normal oceanic salinity in depths of up to 600-650 m at a temperature of 2-10ºC. Haddock is widely distributed in the Northern Atlantic and the western part of the Arctic Ocean.

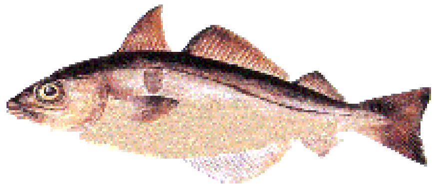


Figure 1: North-East Arctic Haddock – (*Melanogrammus aeglefinus Linne*).

Rather large populations are found in the Barents, Norwegian and Northern seas, off the coast of England, Scotland and Ireland, around Iceland and the Faeroes, in Newfoundland, Nova Scotia and New England. The biggest population lives in the Barents and the Norwegian seas. Tagging experiments from 1930 to1960 (Aleev 1944, Sonina 1969, Maslov 1952) have shown that this population is self-contained with insignificant migration occurring out from that region.

North-East Arctic (NEA) haddock reaches a length of 115 cm, a weight of 9-12 kg and an age of 24 years. The commercial (fishable) stock consists of fish older than 3 years; however the basis of commercial stock is made up of fish from the age of 3 to 6 years. The average size varies from 40 to 65 cm, and the average weight is 1-1.5 kg.

Haddock makes extensive feed and spawning migrations. The basic spawning areas of haddock are situated along a continental slope of the Scandinavian Peninsula from 65 to 73° N (Figure 2). Spawning of haddock is from March to June, and occurs mostlyis at the end of April or the beginning of May.

Eggs are picked up by currents and are carried to the Barents Sea, getting as far as East Murman and the Spitzbergen area. The incubatory period is from one to three weeks. sAdult individuals eat intensively after spawning and begin to move to the north and east along main branches of warm currents (Figure 2A).

Haddock stays in feeding areas prior to the beginning of cold seasonal waters which can begin at the end of October up to the middle of December. The migration of haddock to spawning and wintering places varies from year to year and depends on the size-age structure of the population, conditions of feeding and temperature of the water (Figure 2B).

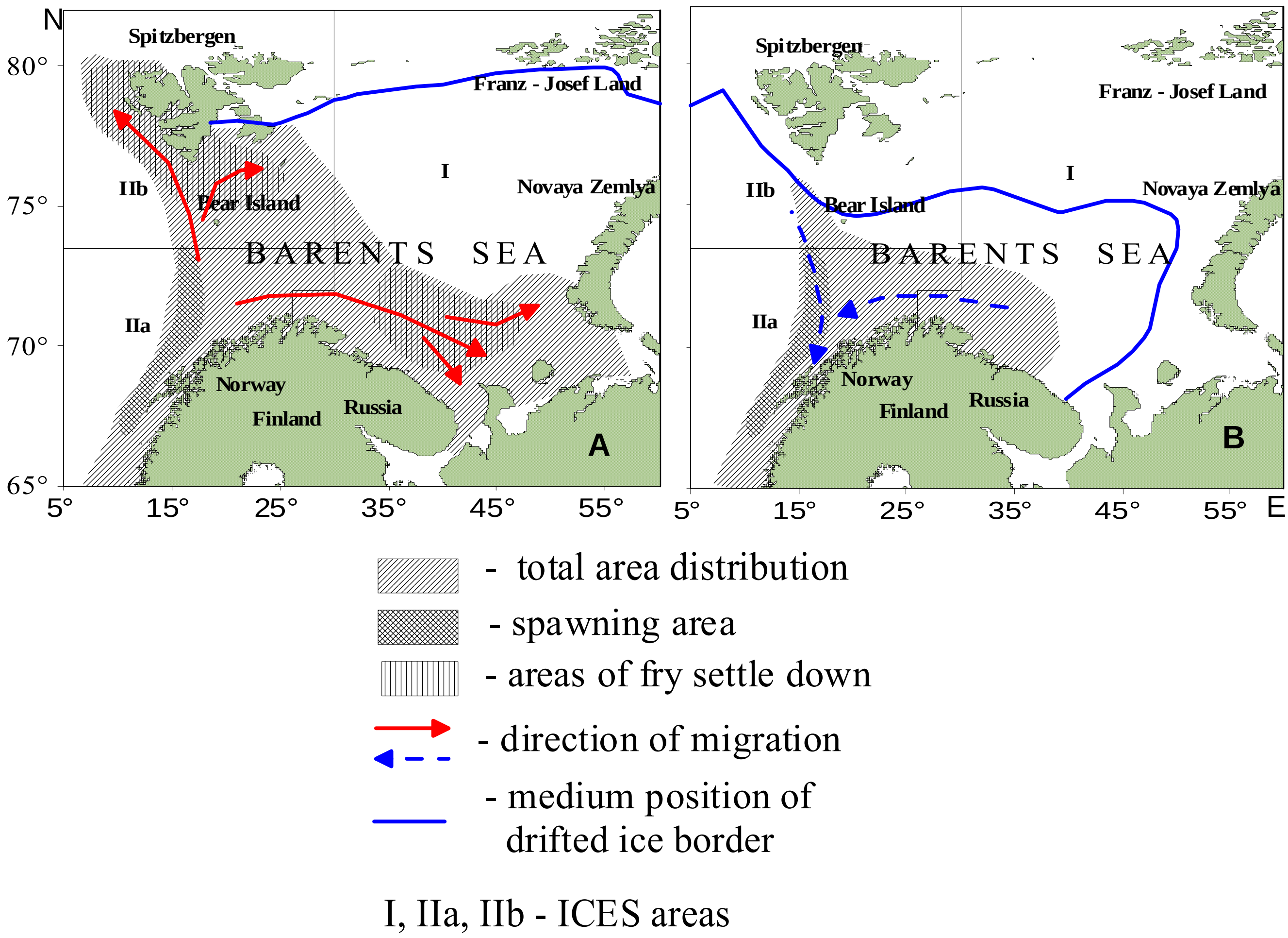
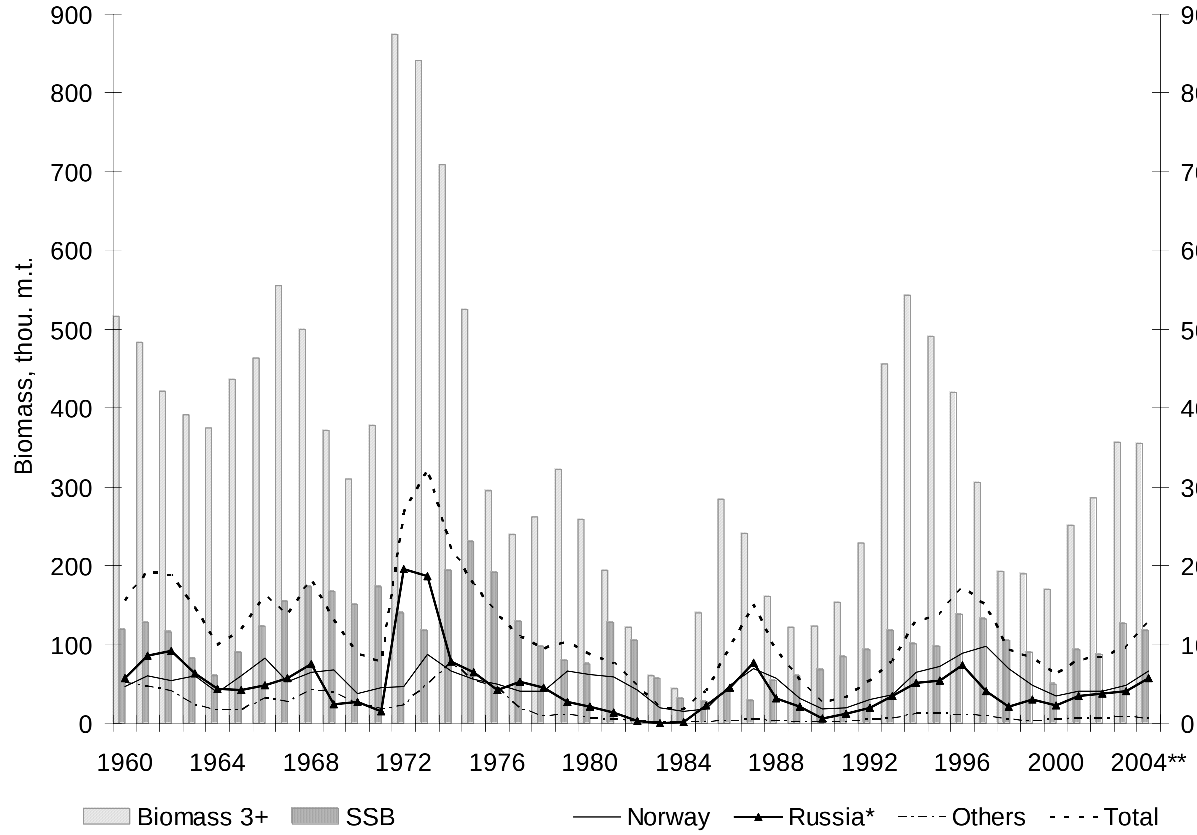


Figure 2: Distribution and migration of haddock in spring-summer (A) and autumn - winter (B) in the Barents Sea.

1.2 Fishery and stocks

Haddock is the second main commercial species, after NEA cod, in the Barents Sea. Since 1960, the total annual catch of this species has ranged from 17 to 322 thousand tons. In recent years, Norway and Russia have accounted for more than 90% of the landings (Figure 3). Haddock are harvested throughout the year. In years when the commercial stock is low they are mostly caught as bycatch in the cod trawl fishery but when the commercial stock is abundant and biomass is high, haddock is targeted directly.

Bottom trawling accounts for approximately 75% of the haddock catches. Conventional gears (mostly longline which is used almost exclusively by Norway) account for most of the rest of the catch. Part of the longline catches are from a directed fishery. The fishery has been restricted by national quotas since 1976.



** - USSR prior to 1991*
***- quota values*

Figure 3: Dynamics of fishable (Biomass 3+), spawning (SSB) stock biomass and total nominal catches of haddock (thousands of tons) from 1960 to2004 (Anon 2004).

Dynamics of the haddock stock are defined by the productivity of its generations, which can considerably differ. There was an increase in the number and stocks of haddock from 2001 to 2004, due to the introduction of some strong year classes. Fishing catches approximately 30% of the stock (Figure 3).

1.3 Annual assessments and management

The haddock stock is assessed annually by the Arctic Fisheries Working Group (AFWG) which gives advices to decision makers the Joint Russian-Norwegian Fishery Commission (JRNFC), and stakeholders, the Arctic Committee of Fisheries Management (ACFM) (Figure 4). This section provides information about the current data gathering and assessment methods used by the AFWG (Anon 2004).

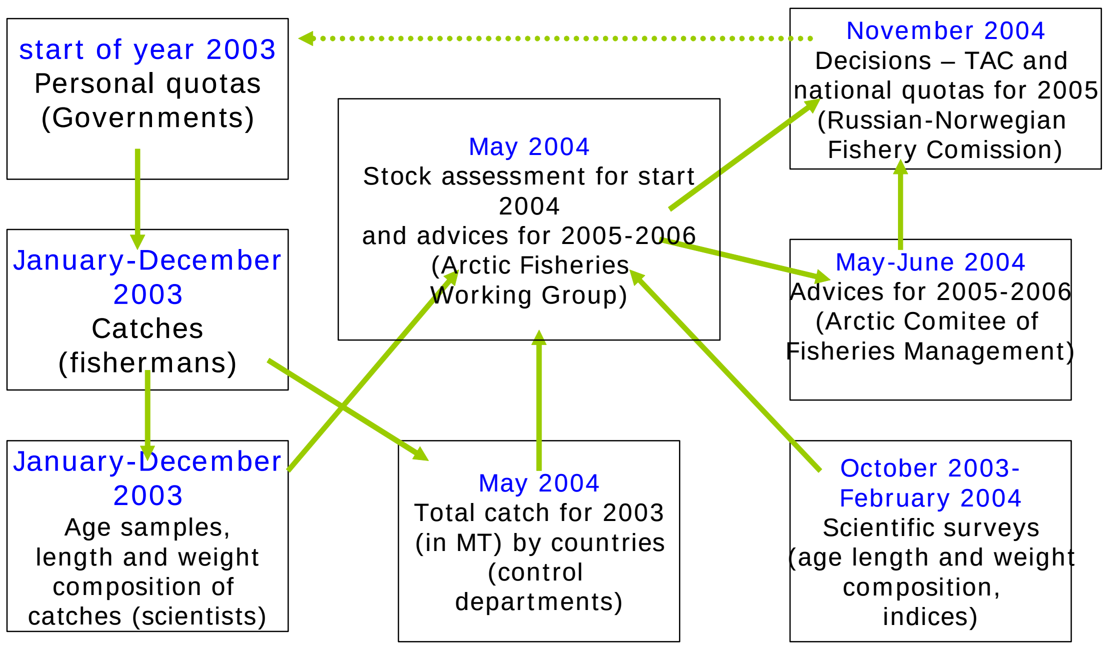


Figure 4: Current management cycles of haddock, with reference to the assessment year 2004.

1.3.1 Measurements

Data from commercial catches

During the year, Russian and Norwegian scientists make length measurements and take age samples from catches onboard commercial vessels. Captains of the vessels or ship owners send information about the size and composition of the catches to control departments and research institutes. All countries, which harvest haddock, send information about commercial catches to AFWG for estimation of the total nominal catch (see Figure 4).

At the AFWG all the data are taken into account for recalculation of the age compositions of the landings (catch-at-age) or (catch in numbers) and the mean weights-at-age in the catches (Appendix 1).

Survey measurements

AFWG used data from two scientific surveys. Firstly, the Russian bottom trawl, an acoustic survey conducted from October to December, which covers the ice-free part of the Barents Sea (Figure 5A). The survey covers the main areas where fry settle down and the commercial fishing takes place in ICES areas I, II a and II b, including the Russian coastal zone.

Secondly, Norway conducts a bottom trawl an acoustic survey in the Barents Sea from January to March, which also covers the ice-free part of the Barents Sea in ICES areas I, II a and II b, including the Norwegian coastal zone. Before 2000, this survey was made without the participation of Russian vessels, while in the three latest surveys Russian vessels have covered important parts of the Russian zone (Figure 5B).

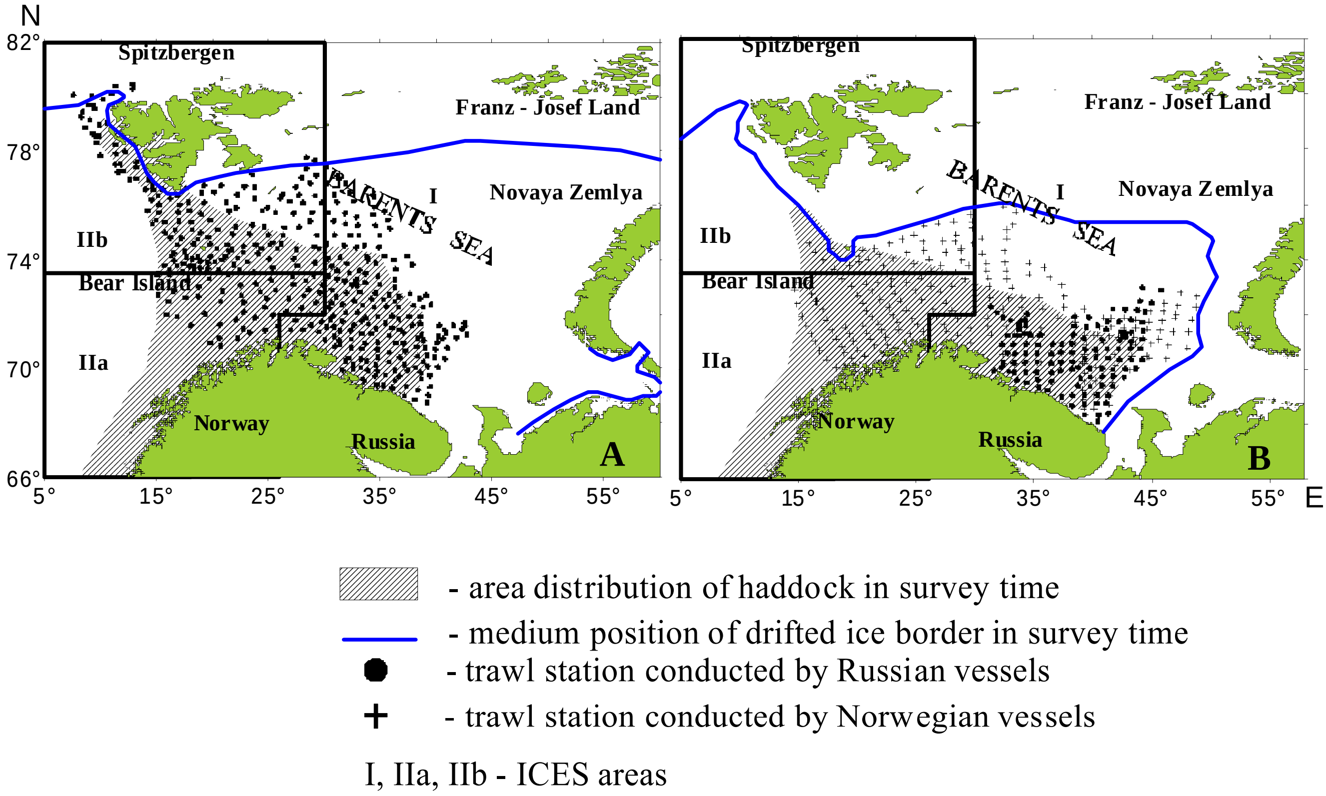


Figure 5: Area of Russian (A) and Norwegian (joint) (B) trawl-acoustic scientific surveys in the Barents Sea.

Data from the survey provide estimates of the mean weight of the fish in the stock (weight at age). Furthermore, survey data is combined with data from catches to calculate the proportion of mature haddock at age, numbers of consumed haddock by NEA cod using data from cod stomach samples, and survey "trawl indices", calculated as relative numbers per age per hour and "acoustic indices" of absolute numbers (in thousands) computed from the acoustic registrations (Appendix 1).

1.3.2 Assessment model

The haddock is assessed using a catch at age model that uses measurements of the number of fish caught in each age group and age based on abundance indices from scientific surveys (see above). Given that the catches are treated as exact, the historical part of the stock estimates (N-values) are in principle the cumulative sum of catches, given certain assumptions of annual natural mortality.

The stock numbers in more recent years are, however, derived from the combined effect of catch at age of the year classes that are in the fisheries and survey information. The uncertainty in the recent estimates is thus greater than the estimates of the historic past due to fewer measurements from each cohort and to sensitivity of various model assumptions.

At present, the AFWG uses the Extended Survivors Analysis (XSA) software package, (Shepherd 1992, Darby and Flatman 1994) to estimate the stock abundance and fishing mortality of the cohorts that have entered the fishery. The numbers of fish which will enter the fishery in the next two years are estimated using the RCT3 software package (Shepherd and Darby*).

Assumptions of weight-at-age in the catch and in the stock, maturity and selection patterns, which are needed in the projection, are derived from ad hoc expert judgement. These data are then the basis for short-term projection procedures (using MFDP software, Anon. 1999), which provides a management option table.

All outputs are point estimates and include estimates of spawning stock biomass (SSB), recruitment, and catch under various fishing mortality scenarios. These point estimates, in relation to defined reference points (that are considered to reflect uncertainty in the assessment), form the basis of the annual advice provided by the ACFM department of the International Council for the Exploration of the Sea (ICES).

The current uncertainty is reflected in the distance between precautionary reference points (lim and pa points). ACFM has adopted a Blim=50,000 tons, an SSB below which only poor year classes have been observed and a Bpa =80,000 tons, which is considered to be the minimum SSB required to provide a 95% probability of maintaining an SSB above Blim, taking into account the uncertainty in the assessment and stock dynamics.

Flim=0.49, the fishing mortality associated with potential stock collapse, and Fpa=0.35, which is the value that is considered to have a high probability of keeping F below Flim (Anon 2003).

2 STATEMENT OF PROBLEM AND OBJECTIVES OF THE PROJECT

2.1 Input data for predictions of catch and spawning stock biomass

Historical assessment is based on measurements of the number of fish caught by age and measurements of age based on survey indices. This provides estimates of fishing mortality in the terminal year and population numbers in the start of the assessment year. The estimated population numbers in the terminal year can easily be projected forwards if information on fishing mortality by age is known (Table 1).

However, in order to provide predictions of future catches as well as estimates of the size of the spawning stock in the following year, it is necessary to estimate the weight at age in the catches and in the stock as well as the maturity at age. In other words, if the assessment year is 2004, measurements on catch weights are only available up to and including the year 2003.

*Work is in ICES Secretariat, year of the edition is unknown

Table 1: Stock assessment and short-term projection flowchart used in AFWG (May 2004).

Information \ Year	1950	…	2002	2003 (terminal year)	2004 (assessment year)	2005 (1st projection year)	2006 (2nd projection year)
Total catch (MT)	known	…	known	known	TAC	forecast	
Mean weight at age in catch	known	…	known	known	forecast	forecast	
Catch at age (mln. spec)	estimated	…	estimated	estimating	forecast	forecast	
Natural mortality (M1)	assumed	…	assumed	assumed	assumed	assumed	
Cod predation (M2)	estimated	…	estimated	estimating	forecast	Forecast	
Weight at age in stock (start of year)	known	…	known	known	known	forecast	forecast
Maturity at age (start of year)	known	…	known	known	known	forecast	forecast
Fishing mortality	estimated (recalculating)	…	estimated (recalculating)	assessing	forecast	forecast	
Numbers of fish at age (start of year)	estimated (recalculating)	…	estimated (recalculating)	estimated (recalculating)	assessing	forecast	forecast
Fishing biomass (start of year)	estimated (recalculating)	…	estimated (recalculating)	estimated (recalculating)	assessing	forecast	forecast
Spawning biomass (start of year)	estimated (recalculating)	…	estimated (recalculating)	estimated (recalculating)	assessing	forecast	forecast

Estimates of catch weight at age are thus needed for 2004 and 2005, the latter being the year for which the advice is given. Similarly, in 2004 measurements of stock weights and maturity at age are only available (from survey measurements) up to and including the year 2004. Estimates of stock weights and maturity at age are thus needed for 2005 and 2006, the latter being the year after the advisory year.

The most common method within ICES working groups has been to use some average of measured weight at age from prior years. A common default is to use the average weight at age from the last three years that measurements are available. In some cases, like for the NEA haddock, ad hoc procedures based on expert judgment, are used to select the reference years from the past for which mean weight in the predictions are estimated from. However, these average based methods ignore any information that may lie in the increase in weight at age of individual cohorts.

It is known that various assumptions about growth and maturity estimates in the predictions may cause significant bias in the projections of stock biomass (Brander 2002). In this project, attempts will be made to improve methods in estimating these auxiliary parameters by using historical measurements of weight at age to predict future weights of cohorts that are currently in the fisheries.

2.2 Uncertainty in the assessment

At present, ICES takes uncertainty in assessement into account by giving advice in relation to defined reference points. In principle ICES has defined Blim as the level of

SSB which produces only poor recruitment (SSB < 50,000 tons) Bpa, on the other hand, is defined as the level of SSB which produces good recruitment with 95% probability. Corresponding values of F are set as fishing mortality reference points.

The distance between Bpa and Blim and Fpa and Flim are 30,000 tons and 0.14 respectively. Thus point estimates of SSB and fishing mortality are evaluated and advice is given in relation to pa-reference points. This is considered to ensure, given the uncertainty, that the advised fishing mortality and resulting spawning stock biomass do not exceed the limit points.

However, point estimates vary depending on the data series used in the assessment and the model assumptions. In other words, changing from moderate (default) shrinkage (SE=0.5) to low shrinkage (SE=1.5) changes the perception of the 2003 SSB from 104,454 to 120,947 tons (16% increase) (Anon. 2004).

In this case it is necessary to investigate differences between reference points, because if possible variation in estimates is higher than that interval stock needs more detailed analysis.

There are several categories of uncertainty in fish science: natural variation, observation errors in input data, model misspecification, uncertainty in transaction of scientific advice into management, imperfect implementation of management strategies and others (Mace and Sissenwine 2002). The current project aims at investigating a part of the uncertainty, i.e. observation errors, given a particular model specification.

The AFWG states that uncertainty may be underestimated and that the difference between Blim and Bpa may be too small (Anon 2004). In this project an attempt will be made to investigate at least part of the uncertainty in the assessment by using bootstrap techniques.

The overall objective is to investigate if current assessment and projection procedures can be improved. Such improvements are expected to be incorporated in AFWG assessments in the future and hopefully improve the scientific advice for North-East Arctic haddock.

3 MATERIALS AND METODS

3.1 Materials

The materials for investigation were the input data for stock assessment and projection which were used by AFWG in 2004 (Anon 2004). These include catch at age, mean weight in stock and catch, maturity ratio for the period 1983 – 2004 and survey indices (Appendix 1, Tables 1-6).

3.2 Methods for improvement of forecast predictions

There are two principal methods used for predictions of mean weight at age (mw@age) (Brander 2002):

Predicting future weight by cohort:

$$mw@age_{a+1,y+1} = mw@age_{a,y} * G$$

(1)

where,
G - growth rate

and predicting future weight from the weight of the same age in previous years:

$$mw@age_{a+1,y+1} = mw@age_{a,y}$$

(2)

For predicting the weight of haddock AFWG traditionally uses different variants of the second method.

For estimations of growth rate - G in the "cohort", the method was fitted into a linear model, which can be described by the following equation (Steinarsson 2004):

$$mw@age_{a} = \alpha * mw@age_{a-1,y-1} + \beta$$

(3)

where,
α – "slope" of regression
β – "intercept" of regression with axis
mw@age $_{a-1,y-1}$ – mean weight at age of the same year class in the previous year

Therefore, G is described in both parameters of regression α and β.

For improvement of the current methods for estimating inputs for predictions, alternative methods were used and complementary statistical tests were made between suggested methods and methods currently used by AFWG.

3.2.1 Weight at age in the stock

Visual comparisons and statistical tests for three different methods for predicting mean weight at age in stock (msw@a) were made. The three methods are:

(1) predicting msw@a using estimated relationships between neighbouring ages in yearclasses (cohorts) (Appendix 2),
(2) using values of msw@a from the previous year (Appendix 2),
(3) using average values of msw@a during the previous three years (Appendix 2, Figures 5-6, Table 3).

These models were run in R and Excel spreadsheets.

The analyses were based on msw@a from the recent assessments of those parameters (Anon 2004). Linear regression models were fitted to estimate the relationship between the mean weight in stock (msw@age) in age groups 2-6 for the period 1983-2004 with msw@a in age groups 1-5 one year previously, one year younger, for the period 1984-2003.

regression parameters α and β were used for calculation "modeled" msw@a for corresponding ages and years for visual comparison.

For statistical comparison of methods, linear regressions were fitted for the same period. The coefficients of determination (R^2) were used for comparing the differences between "observed" and "modeled" msw@a by each method.

3.2.2 Weight at age in the catch

For a prediction of weight at age in the catch (mcw@a) the same procedure was used as for msw@a but included statistical tests of five different methods where mcw@a, as well as msw@a, was used as a predictor.

These are:
(1) predicting mcw@a by using estimated relationships between mcw@a in neighbouring ages in yearclasses (cohorts) (Appendix 3),
(2) using estimated relationships between msw@a and mcw@a for the same year class in neighbouring ages (cohorts)from the previous year (Appendix 3),
(3) using relatonships between mcw@a and msw@a at same age same year (Appendix 3),.
(4) using relationships between modelled mcw@a and observed mcw@a (Appendix 3,),
(5) using average values of mcw@a for the previous three years (Appendix 3).

3.2.3 Maturity ratio

For projection of maturity at age (mat@a), AFWG used the same "averaging" methods as for estimating mean weight in stock. But mat@a is not a directly measured variable. Rather, it is the relationship between mature and immature fish at age in the stock varying from 0 to 1.

In this case maturity ratio and age can been described by the following binominal logistic function

$$P_a = \frac{1}{1+e^{-(\alpha * a+\beta)}} \tag{4}$$

where a – age

For preliminary analysis the theoretical curve of maturity for the period 1984 – 2004 was fitted where proportion maturity was a function of age. For investigation of relationships of the maturity ratio with other parameters of the population, several logistic regressions with a single explanatory variable in addition to age were used. The auxiliary factors were: maturity in the same cohort in the previous year, mean weight in stock, mean weight in catch and number of fish in cohorts at age three. The models used were "three years average" and "equal last year". They are presented here for comparison:

Additional auxiliary factors from equation (4) can be presented as:

$$P_a = \frac{1}{1+e^{-(\alpha * a + \alpha_1 * x + \beta)}} \quad (5)$$

where α_1- regression coefficient of parameter
x – parameter

Analysis of deviation (ANOVA chi-square) was made to compare p-values of the models and differences between modelled and observed values were estimated.

3.3 Methods for assessment uncertainty

3.3.1 Estimation of stock size

The estimates of stock numbers at age (Nay) and fishing mortality at age were made using an ADAPT model set up in Excel. In principle this model is similar to the one described by Gavaris (1988), where catches are treated as being measured without error. The ADAPTive Framework uses a non-linear least-squares fit to calibrate the cumulative catch, given the assumption of natural mortality (the virtual population) against independent indices of abundance. The data used were the estimated catch-at-age from 1979-2003, with age groups 1-11+. The last age group contains all catches equal to and higher than that age and is thus treated as a plus group. The following survey indices were used in the tuning (Appendix 1):

- Russian bottom survey (Fleet 1), year range 1991-2003, age range 0+-7, survey time assumed as start of year 2004, age range 1-8, year range 1992-2004,
- Norwegian acoustic survey (Fleet 2), year range 1990-2004, age range 1-8, survey time as start of year.
- Norwegian bottom trawl survey (Fleet 4), year range 1990-2004, age range 2-9, survey time as start of year.

Estimates of predation of cod on haddock were added as natural mortality (M2) as done by the AFWG. This is in addition to the constant mortality assumption (M1) of 0.2.

In the Excel spreadheet Pope's approximation (Pope 1972) of the transformed Baranov (1918) equation was used:

$$N_{a,y} = N_{a+1,y+1} * e^{M_{a,y}/2 + C_{a,y}} * e^{M_{a,y}/2} \quad (6)$$

Fishing mortality of the oldest true age group (age 10) was derived recursively as the average fishing mortality of the three younger age groups:

$$F_{10,y} = \frac{F_{7,y} + F_{8,y} + F_{9,y}}{3} \quad (7)$$

Fishing mortality of the plus group (age 11+) was set the same as for age 10. Population estimates of the oldest true age group (age 10) and the plus group were then obtained by the transformed Baranov equation:

$$N_{a,y} = \frac{C_{a,y}}{\frac{F_{a,y}}{F_{a,y}+M_{a,y}} * (1-e^{(-(F_{a,y}+M_{a,y}))})} \tag{8}$$

For tuning the relationship between population size and survey was the same as that set by the AFWG 2004. Thus for ages 1-6 a power relationship was assumed:

$$U_{a,y} = \alpha * N_{a,y}{}^{\beta} \tag{9}$$

and for ages 7-9 a proportional relationship was assumed.

$$U_{a,y} = \alpha * N_{a,y} \tag{10}$$

Year class 1996 has consistently been much lower in the survey than in the catches. The AFWG has resolved this by excluding it from tuning but here a special multiplier was added to the relationship between survey and stock size:

$$U^{YC96}_{a,y} = k^{YC96}\alpha_a * N_{a,y}{}^{\beta_a} \tag{11}$$

where k is a parameter estimated by the model. The objective function in the model was:

$$SSE_{MIN} = \sum_{Surveys} \sum_{a} \sum_{y} \frac{\left(\ln U_{a,y} - \ln \hat{U}_{a,y}\right)^2}{\sqrt{2\sigma_a^2}} \tag{12}$$

Survey indices of different age groups are generally measured with different degrees of precision. In the absence of direct information of variance in the survey, a proxy for survey errors was estimated internally in the model. This was done as follows: 1) in the first run the denominator in equation x was set to 1 and an optimal fit was obtained; 2) the standard deviation of the residuals for each age group was calculated; 3) these estimates were then used as a proxy for variance (□) in the objective function for the final fit of the model.

Effectively this means that age groups with higher variances have lower influence in the final population estimates than those with lower variance.

The parameters estimated in the model were thus: numbers of fish at age 1-10 in 2004 and α and β for each age group for each survey.

3.3.2 Predictions

The objective function provides estimates for the population numbers at the start of 2004. Calculation of catch in 2004 and 2005 and population numbers in 2005 and 2006 were done by using the catch and stock equations. Input data for the projection were used to estimate values of msw@a by the “cohort” method for age groups 2-8 average values for the past three years for age groups 9-11+, and estimated values of mcw@a by the “cohort” method for all age groups.

The catches were constrained to a yield of 130,000 tons in 2004 and 117,000 tons in 2005 as set by the AFWG. The selection patterns used was the average of the last three years and the assumed mortality (M1 and M2) set the same as by AFWG.

It should be noted that the plus group in 2004 and onward was estimated using the following equation:

$$N_{a,y} = N_{a-1,y-1} * e^{(-(F_{a-1,y} + M_{a-1,y-1}))} + N_{a,y-1} * e^{(-(F_{a,y-1} + M_{a,y-1}))}$$

(13)

3.3.3 Estimation of uncertainty

Spreadsheets gave the possibility of characterising the uncertainty in the model fit using a bootstrap method (Efron and Tibshirani 1993, Haddon 2001) – re-sampling of the residuals from the observed-predicted tuning indices.

In non-linear least-squares estimates of a solution, estimates of population abundance were chosen that provided the best fit to the tuning indices (Haddon 2001). The residuals of that fit were bootstrapped 1000 times and new values of N produced. The distribution of the associated Fs and SSB provided an indication of variation and the bias (deviations).

Each data set has the same number of observations (n) as the original data set. Recalculating the model to each bootstrap, the data set receives the statistics of interest (probability profile, standard deviations, and confidence intervals) from the results for each model fit. Thus the bootstrap samples were:

$$U_{a,y}^{b} = \hat{U}_{a,y} \left(\frac{U_{a,y}}{\hat{U}_{a,y}} \right)^{boot} \qquad (14)$$

The random sampling was maintained within each survey and each sample consisted of the whole residuals for the randomly selected year.

Spreadsheets gave the possibility of investigating uncertainty in the projection procedure. For this reason, the same procedure as for stock assessment was used. For the projection period 2004-2006 calculations of parameters were based on total allowable catch (TAC) for 2005, which was established by JRNFC in November 2004. Fishing mortality at age was calculated as "TAC constraint" according to the algorithm used in the standard ICES projection software MFDP (Anon 1999). Using standard equations of stock and catch for the projection period were estimated values of numbers of fish in 2005 and 2006 as well as spawning stock biomass and fishing mortality. Selectivity in the years 2004 and 2005 was randomly selected in each run from the selectivity pattern estimated in 2000 to 2003.

For all parameters confidence intervals were estimated and compared with point estimations of N at age 3, F and SSB obtained by AFWG in 2004 (Anon 2004).

4 RESULTS

4.1 Estimation of biological parameters

4.1.1 Weight at age in the stock

The procedure compared the coefficients of determination (R^2) of regressions and sum of squares of the residuals of observed weights versus predicted weights using the "cohort" method, the "previous one year" method, and the "previous three year average" method. The results are presented in Figure 6.

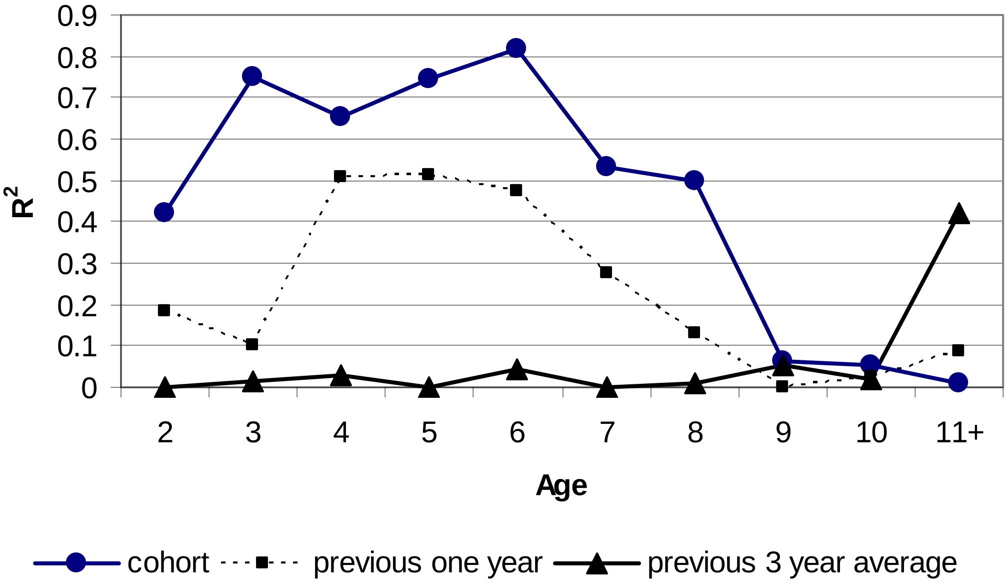


Figure 6: R-square values of regressions between observed and modelled weight at age in the stock (msw@a) using different methods for age groups 3-11+.

The highest R-square values in regressions are observed in the “cohort” method for age groups 3-6, around 0.8. Values were lower for age groups 2 and 7-8, but the p-values were still significant (Appendix 2).

For age groups 9-10 no differences were observed between methods and for age group 11+ (plus group) the highest R-square values are in the “3 year average” method.

The lowest sum of squares of residuals are observed in the “cohort” method for all age groups but differences between the “cohort” and "previous 3 year average" methods for age groups 9-11+ not were significant because the absolute value of errors directly depends on the absolute values of weight and has a tendency to increase with increasing age (Appendix 2).

4.1.2 Weight at age in the catch

Figure 7 shows the differences between the five methods used for investigating mean weight in catch.

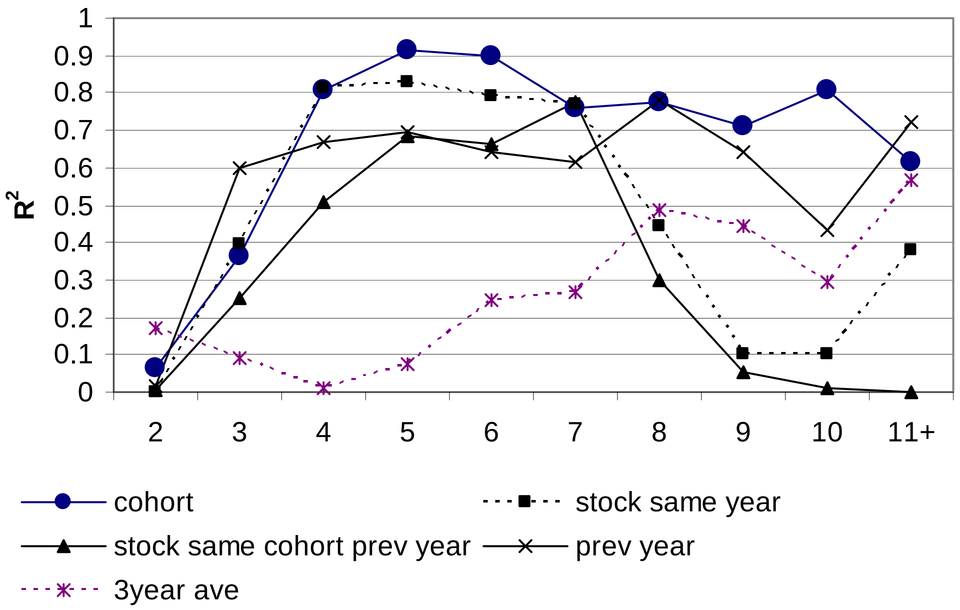


Figure 7: R-square values of regressions between observed and modelled weight at age in the catch (mcw@a) using different methods for age groups 3-11+.

The highest R-square values in the regressions are observed in the “cohort” method for age groups 4-10, around 0.8. The values are lower for age groups 2,3 and 11+, but p-values are not significant for age group 2 (see Appendix 3).

The lowest sum of squares of residuals are observed in the “cohort” method for age groups 2-6. For other age groups, differences in residuals between the “cohort” method and other methods do not have any trends. As addressed above these differences are not significant because the absolute value of errors directly depends on the absolute values of weight and has a tendency to increase with increasing age (Appendix 3).

4.1.3 Maturity ratio

The logistic theoretical curve of the maturity ratio for haddock is given in Figure 8. The figure shows significant differences in maturity at age (mat@a) in 1984 – 2004. Rings represent mean observed values of mat@a in each year for the entire period, curves are the mean values of all observations.

A comparison of statistical p-values from predicted maturity at age with additional explanatory variables is given in Figure 9.

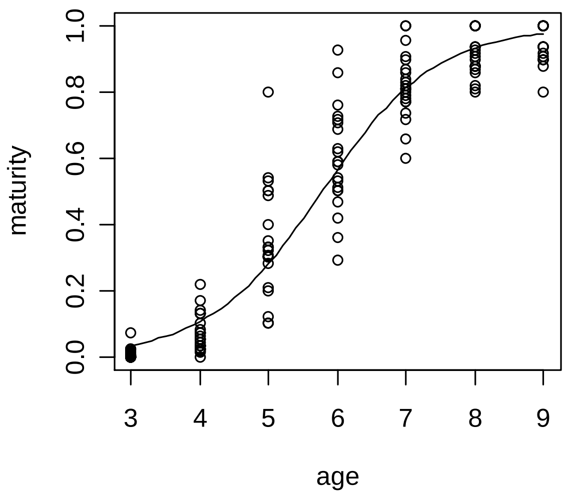


Figure 8: Relationship between maturity and age of haddock from 1984 to 2004.

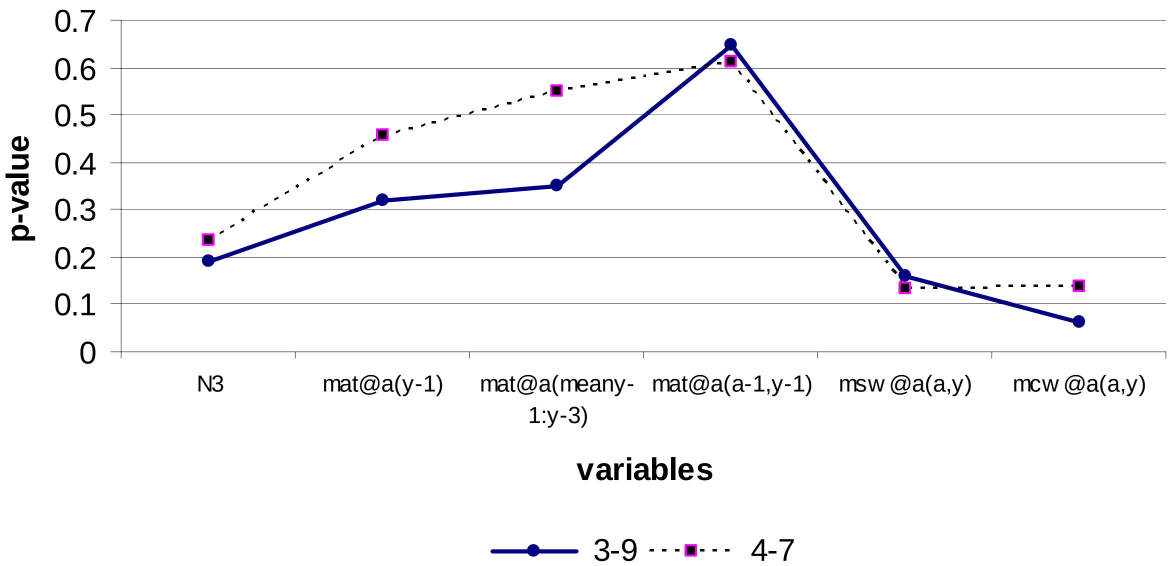


Figure 9: P-values of predicted regressions of mat@a using different explanatory variables for different age ranges.

The highest level of significance (lowest p-value) is observed in logistic regression using mean weight at age in catch as an additional explanatory variable Differences between “observed” and “modelled” maturity at age using the parameters of that regression are significant (Appendix5). It was decided to use values of maturity for predictions from the AFWG report (Anon 2004).

The “best” method for predicting mat@a might be found by doing some sort of 'ad hoc' weighting (such as downweiging years with bad surveys and/or samples from catches, and giving age groups different weights according to how many there generally are in the samples). The numbers behind each proportion would of course be a better choice.

4.2 Stock size and uncertainty

Detailed information on population numbers from 1979 to 2006, values of fishing mortality for the period 1979-2005,bootstrap statistics of the parameters, the number of fish at age at the start of 2004, parameters of regressions between survey indices, and multipliers for the 1996 year class estimated by xADAPT are given in Appendix 5. A summary of the results of the xAPAPT calculations of bootstrap estimations of fishing mortality, numbers of fish at age three (recruits) and SSB are given in Figures 10, 12 and 14. The dark shaded areas show 80% uncertainty and the light shaded areas show 95% uncertainty. Cumulative distribution of the estimates are shown in Figures 11, 13, and 15. These figures enable detailed determination of the probability that the parameters exceed or are below a certain value.

The historical point estimates of SSB, fishing mortality and recruitment from xADAPT are, as expected, the same as those estimated by the AFWG. The historical trends have already been described in section 1.2. Given the constraints in yield for 2004 (130,000 tons) and 2005 (117,000 tons), it is expected that the SSB will most likely continue to increase from a low in 1999 (Figure 10). This is due to expected continuing good recruitment (Figure 14) as well as reasonable fishing mortalities in recent years (Figure 12).

There are no uncertainties in the historical part of the time series since it is assumed that the catches are exact. The uncertainties in the more recent years increase, because of reduced numbers of observations and greater influence of the survey on the current estimates. The point estimates from the final adopted XSA run by the AFWG are slightly different for the period 2000-2006, but the working group estimates lie within the 95% bootstrap error distribution (Figures 10, 12 and 14 and Appendix 5).

Standard deviation (uncertainty) of the estimated SSB value at the start of 2004, according to calculations using the bootstrap procedure, was about 40,000 tons (CV = 0.08). The medium estimate of SSB in 2004 was 131,000 tons and the 95% bootstrap confidence interval is between 112 and 152,000 tons. The medium fishing mortality (Fbar) in 2003 was 0.36 and the 95% bootstrap confidence interval was 0.29 to 0.48 (the bias in the F bootstrap estimates was 8.3 %, CV=0.14).

The 95% bootstrap confidence interval indicates, given the yield constraint for 2004 (130,000 tons), that the Fbar in 2004 is between 0.32 and 0.52 (the mean is 0.39 and the bias in the F estimates is 7.8%, CV=0.15). Accordingly, the estimated SSB value at the start of 2005 is expected to be between 140,000 tons to 219,000 tons (with a median value of 160,000 tons and a bootstrap bias of 0.6 %, CV= 0.10).

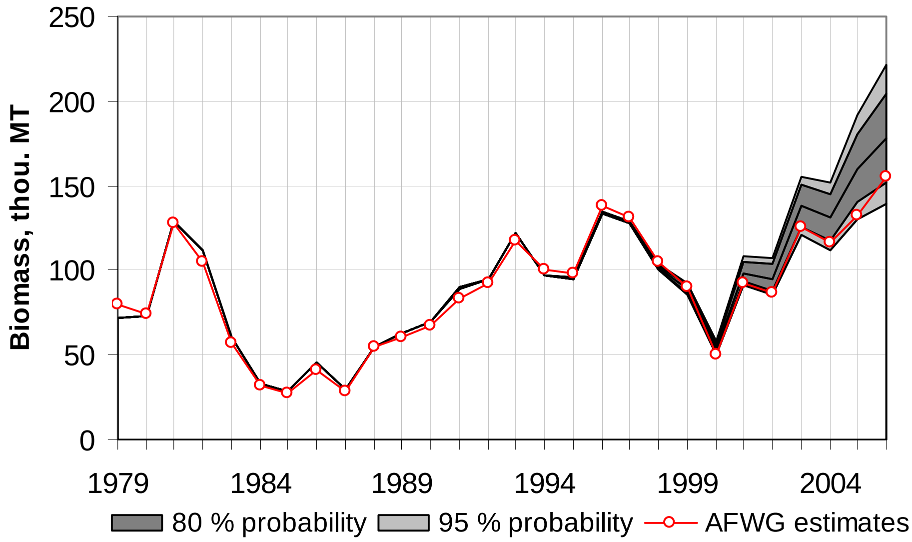


Figure 10: Dynamics of SSB estimated by AFWG and confidence intervals obtained from xADAPT for the period 1979 – 2004 and forecast for 2005-2006.

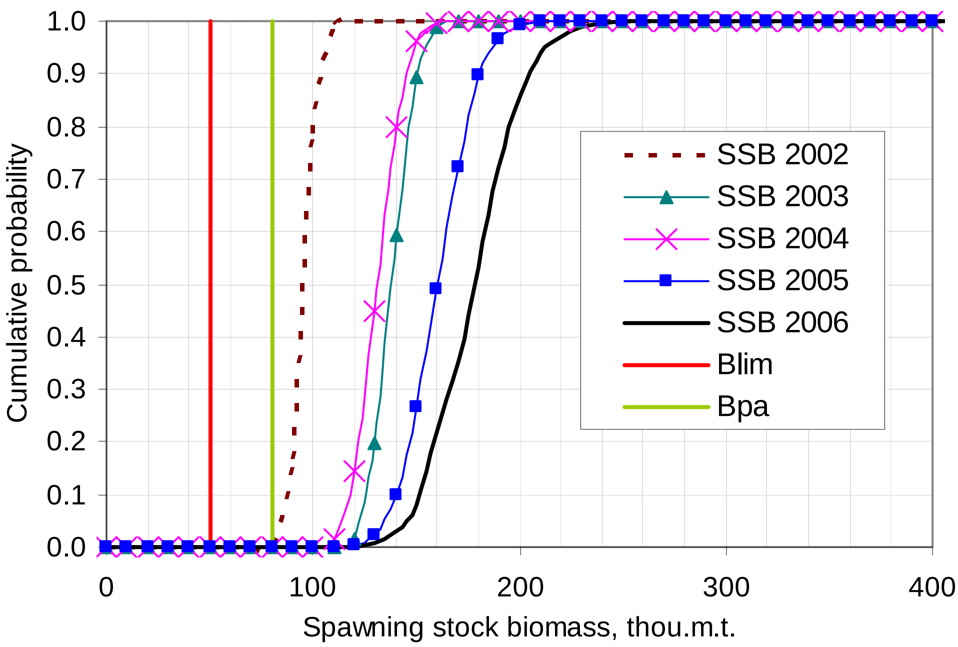


Figure 11: Cumulative probability distribution of SSB obtained from xADAPT for the period 2002 – 2004 and forecast for 2005-2006 in relation with reference points.

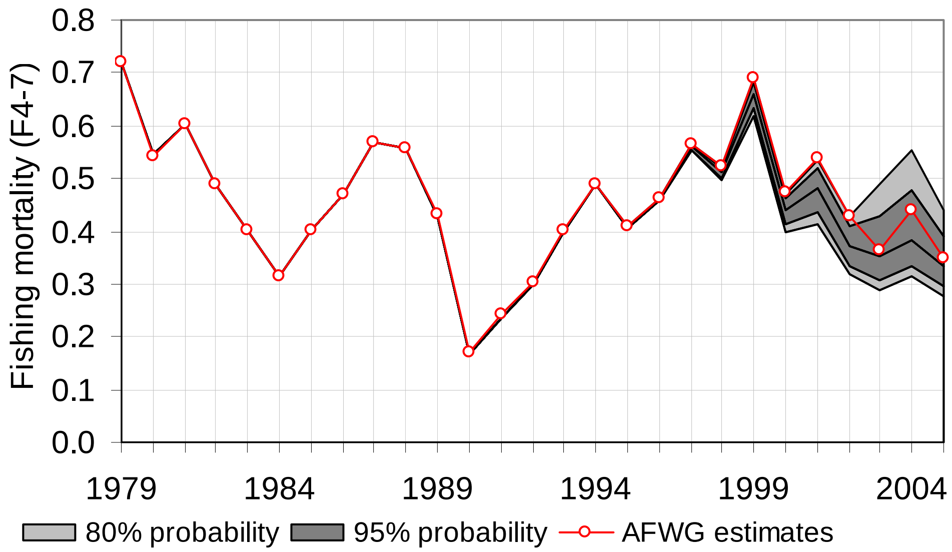


Figure 12: Dynamics of F (age 4-7) estimated by AFWG and confidence intervals obtained from xADAPT for the period 1979 – 2003 and forecast for 2004-2005.

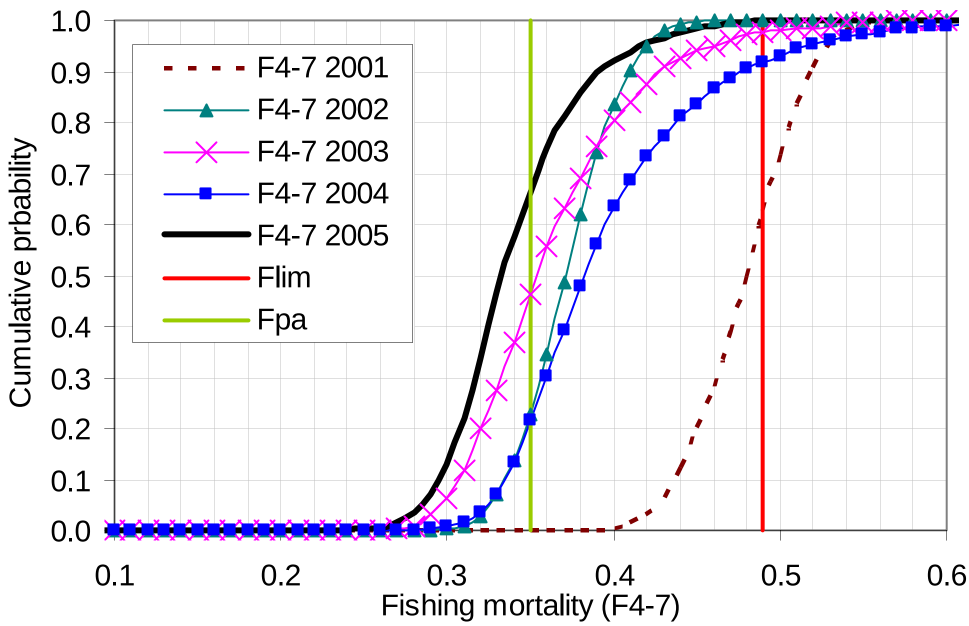


Figure 13: Cumulative probability distribution of SSB obtained from xADAPT for the period 2002 – 2004 and forecast for 2005-2006 in relation with reference points.

The 95% bootstrap confidence interval indicates, given the yield constraint for 2005 (117,000 tons), that the Fbar in 2005 is between 0.28 and 0.49 (the mean is 0.33 and the bias in the F estimates is 0.9 %, CV=0.12). Accordingly, the estimated SSB value at the start of 2006 is expected to be between 139,000 and 221,000 tons (mean value 178,000 tons, bootstrap bias 1.6 %, CV= 0.12).

The results also show trends of mean estimates in F and SSB in resent and projected years. The fishing mortality, after decreasing from 1999 to 2003, stayed more or less at the same level with high probability. Accordingly, spawning stock size has a small tendency to increase from 2000. Insignificant decreasing in 2004 can be explained by the increasing density of the population.

Increasing numbers of fish in the population usually lead to a reduction in the mean weight of haddock as a consequence of increasing food competition between individuals.

The 95% bootstrap confidence interval indicates that variance in recruitment estimates (numbers at age three) increases during the time period. In 2004 varying from 180 to 236 mln spec with a mean value of about 205 mln spec. The expected value of recruitment in 2005 varied from 290 to 471 mln spec with a mean value of about 365 mln spec and in 2006 from 64 to 581 with a mean 236 mln. spec (Figure 14). This means that the incoming year class of 2003 has a lower abundance than the year class of 2002, but these are just preliminary estimates and can be changed using new observations. The probability profile of estimates (Figure 15) shows that a decline in recruitment from 2005 to 2006 is not very likely a true decrease.

Figure 16 demonstrates the uncertainty in estimates of SSB and corresponding F associated with adopted reference points. The dotted line frame in the pictures is matched with imaginary frames between precautionary values of F and SSB.

The 95% bootstrap confidence interval indicates that variances in the estimates also increase during the time, but most of the point estimates lie inside the imaginary "reference point's frame".

In agreement with estimates in the terminal year (F in 2003 and SSB at the start of 2004) we can assume that:

(1) Estimates of spawning stock and F of NEA haddock lies within safe biological limits with high (95%) probability adjusted by ACFM.
(2) The investigated part of uncertainty given by observation errors is comparable to the distance between lim and pa borders of SSB and F.

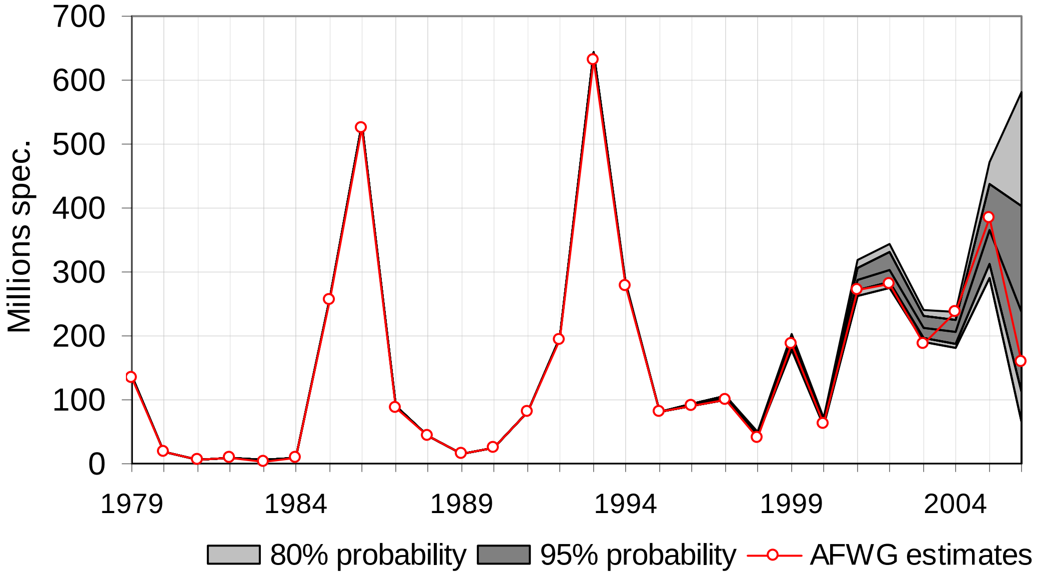


Figure 14: Dynamics of recruitment (N3) estimated by AFWG and confidence intervals obtained from xADAPT for the period 1979 to 2004 and forecast for 2005 to2006.

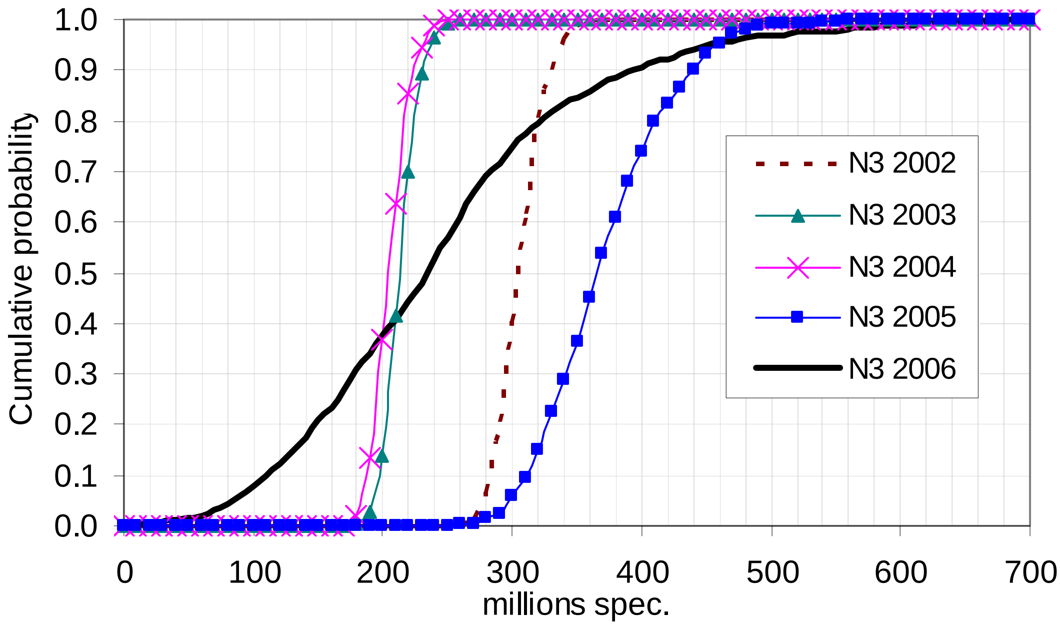


Figure 15: Cumulative probability distribution of recruitment (N3) obtained from xADAPT for the period 2002 to 2004 and forecast for 2005 to 2006

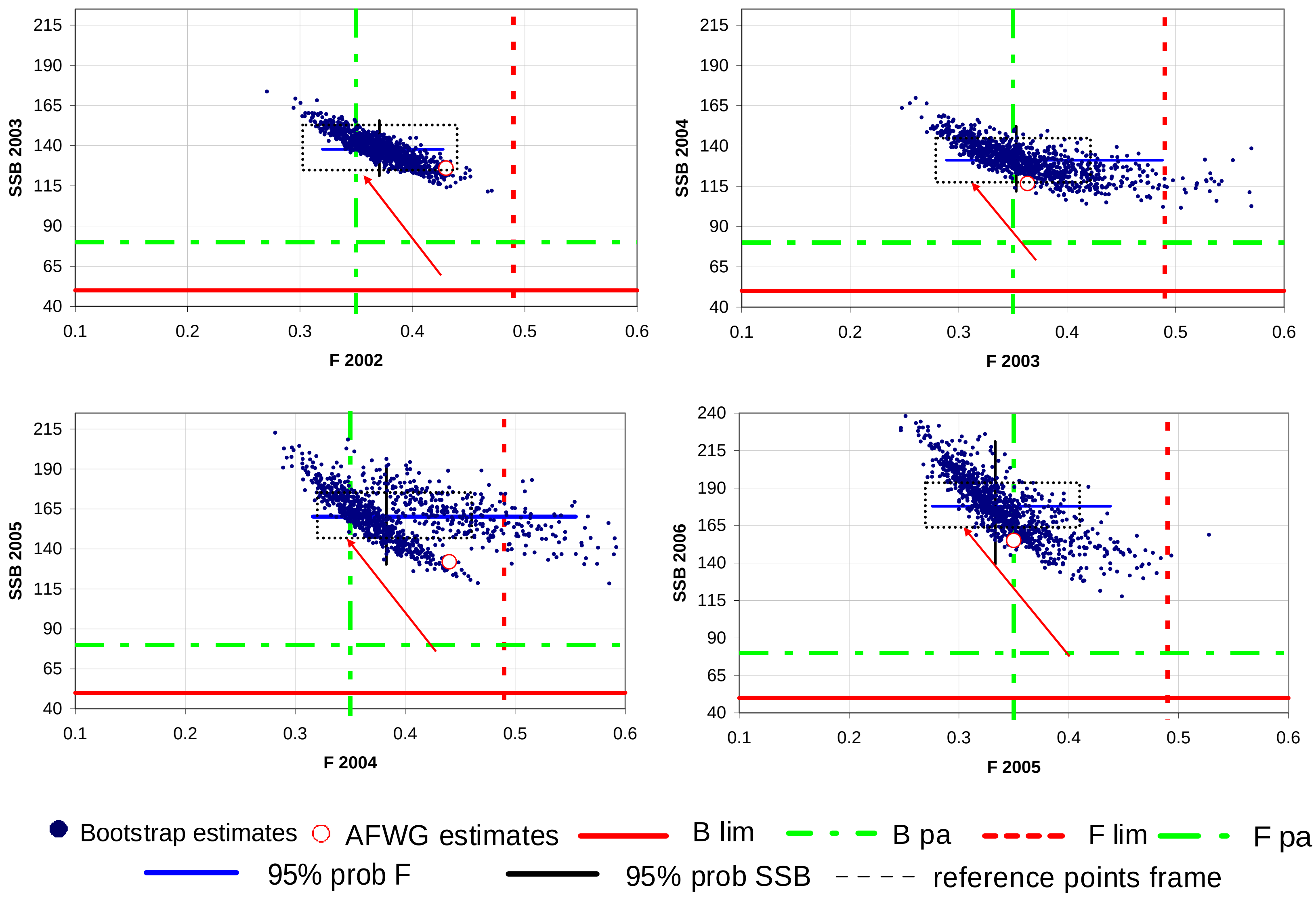


Figure 16: Point estimates of SSB and F in previous year made by AFWG and obtained by xADAPT with 95% confidence intervals in relation with adopted reference points for the period 2002 to 2006.

5 DISCUSSIONS

The methods currently used by AFWG for estimating projection parameters of auxiliary parameters (weights, maturity and selection) are based on variances of the "averaging" principle using expert judgement. Statistical tests showe that the "cohort" method gives the best objective method for short-term predictions of weight at age in stock for the younger age groups and in predicting weight at age in catch for all age groups. The rationale for the "cohort" method is quite clear and the results show us that differences between "observed" and "predicted" weight using the "cohort" method is smaller than using "averaging" methods.

The "cohort" method is analogous to the rationale for estimating numbers at age in the sense that some information about the future weight of the cohort is already measured. In this case, received results using this method can be compatible with projections of abundance of the population, probably, included in regression for the projected number of fish.

The main weakness of the "averaging" approach is distortion of predicted values and significant bias, related with a strong deviation of values, which are in part dependent on year class strength. The first step to reducing that bias was made by AFWG last year, when parameters were estimated as averages of corresponding parameters in the period with similar recruitment. The proposed "cohort" method in this study is a continuation of the previous investigation by AFWG.

For projections of maturity at age, a more realistic approach using logistic binominal regressions is used. Since values of maturity are not absolute values, it is the ratio between mature and immature fish, which varies from 0 to 1.

Some 'F-tests' showed that the mean weight in stock or the mean weight in catch in the same year and age might be a marginally significant addition to predicting maturity at age. Other variables do not seem to improve the fit. But this needs to be addressed in more detail, for example by studying the effect of "weighting" each age as a function of the number of observations.

Mean estimates of SSB obtained by xADAPT are generally higher and estimates of F are somewhat lower than the final point estimates of SSB and F which were adopted by AFWG. This is expected because there are differences in handling of data and in model configurations. The major differences are:

1) In XSA the estimates of the population parameters are done in two steps: the historical values are determined from observations of ages 3 and older but the estimates of the younger ages are determined from separate software, RCT3. In xADAPT all the observations, both recruits and older fishes, were dealt with in the same model setup. The latter should be the preferred option because all available measurements are available for the terminal estimates.
2) XSA is used with shrinkage of the terminal F, but there is no shrinkage in the xADAPT. If there were changes in fishing mortality in the recent past, as observed for the NEA haddock, this assumption of shrinkage will result in higher terminal (2003) F estimates in XSA. And consequently lower estimates of SSB.

3) The weighing of different survey indices is done differently in XSA compared with xADAPT. Further studies are needed to understand how this influences the terminal estimates.
4) The year class 1996 is treated as a missing value in the XSA but is modelled, albeit with a multiplier factor, in xADAPT. The influence of that was not evaluated in this study. It should be noted that although the point estimators differ beteween XSA and xADAPT, the XSA point values lie within the 95% bootstrap confidence interval of xADAPT.

The 95% bootstrap confidence interval in terminal year estimates of SSB obtained by the xADAPT model lies within the distance between the adopted reference points. It must, however, be stressed that the bootstrap confidence interval contains only one part of the total uncertainty in stock assessment, i.e. the uncertainty related to the precision in the estitmates of survey abundance given the model configuration.

However, all models of population dynamics have uncertainties that are related to the assumptions that are made. Uncertainty is unpleasantly commonplace in stock assessment and how best to approach it is a growing and vital part of fisheries modelling (Haddon 2001).

The main weakness of the current methods for stock assessment and projection is the use of several partly different, partly similar models, which use more or less the same input data but receive different estimations of population numbers and fishing mortality. Therefore, the level of uncertainty increases with each step. The suggested method probably allows combining input data and receiving one and only one value for each parameter.

Using the algorithm of the ADAPT framework with the bootstrap procedure allows estimates of at least some part of the uncertainty. It thus provides an opportunity to make statistical tests of differences between the models used in stock assessment and the model assumptions.

The current management strategy of NEA haddock is based on the distance between adopted ACFM lim and pa points. However, those points were established using empirical approaches and should be revised. In this case it is possible to conclude, that the principle of estimation parameters of a population using standard models with the bootstrap procedure can been applied to stock assessment and projection. Furthermore, estimated confidence intervals of parameters can be good for estimating values and intervals between reference points!

This uncertainty analysis, using the bootstrap method, is only the first step in the construction of full analysis of uncertainty in stock assessment. Additional work to more fully characterize all important sources of uncertainty in the assessment process, including modeling errors, should be used to estimate the applicability of the current biological reference points as well as any harvest control rules.

6 CONCLUSION

The choice of "best" method of prediction inputs for projection should be based on careful empirical analysis, using time series analysis. The chosen method will lack credibility if it does not have an obvious rationale, the details of which can be further investigated and verified statistically.

Suggested algorythms based on the ADAPT framework allow an investigation of part of the ucertainty in stock assessment and projection procedures. Its prototype– programm, ADAPT, can be applied as an alternative approach for estimating of population dynamics of NEA haddock.

According to previous investigations, advice to decision makers and stakeholders (JRNFC and ACFM for NEA haddock) can been presented as a decision table(Mace and Sissenwine 2002).

Decision tables can take many forms, but should include a number of alternative system states based on biological and/or economic and/or social criteria as columns. Then a range of possible management actions (e.g. harvest control rules) as rows, with entries in the cells for expected consequences of each management action (for example catch, risk of stock collapse, or employment levels).

The framework should allow for a procedure to make decisions more simple, objective and robust to criticism. Decision makers and stakeholders can then develop a process for weighing the risks and reaching an agreement on the best management actions given all of the uncertainties in the analysis.

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