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# Updates to a Northern Cod (*Gadus morhua)* State-Space Integrated Assessment Model

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## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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## ABSTRACT

The stock assessment model developed for Northern cod (Cadigan 2015) is updated with more recent data, for review at the 2015 Fisheries and Oceans Canada (DFO) Northern Cod Framework Review Meeting. The model was modified to include age information for tagged fish and information on the monthly fraction of total fishery catches taken each year which is used to infer exploitation rates of tagged fish in the year they were released. Additional options were added to model the variability in fishing mortality experience by groups of tagged fish, to model changes in catchability of the Sentinel 5.5 in mesh gillnet catch rates, and to include total fishery catch bounds in weight. Several model formulations were presented to illustrate potential sensitivity of model results to assumptions. Detailed results were provided in accordance with the Terms of Reference of the Framework meeting.

**Mise à jour d’un modèle d’évaluation intégré de type état-espace pour la morue du Nord (*Gadus morhua*)**


## RÉSUMÉ

Le modèle d’évaluation du stock élaboré pour la morue du Nord (Cadigan 2015) est mis à jour avec des données plus récentes aux fins d’examen à la réunion d’examen du cadre sur la morue du Nord de Pêches et Océans Canada (MPO) de 2015. Le modèle a été modifié pour inclure des renseignements sur l'âge pour les poissons marqués et sur la proportion mensuelle de prises totales faites chaque année; ces renseignements sont utilisés pour déduire les taux d'exploitation de poissons marqués durant l'année où ils ont été remis à l'eau. Des options supplémentaires ont été ajoutées afin de modéliser la variabilité de la mortalité par pêche subie par les groupes de poissons marqués, de modéliser les changements dans la capturabilité selon les taux de prise dans les relevés sentinelles au filet maillant (maillage de 5,5 po), et d'inclure le poids total des prises dans les limites de captures. Plusieurs formules de modèle ont été présentées afin d’illustrer la sensibilité possible des résultats du modèle aux hypothèses. Les résultats détaillés ont été fournis conformément au cadre de référence de la réunion sur le cadre.

# INTRODUCTION

Cadigan (2015) presented a state-space integrated assessment model for Northern cod (*Gadus morhua*), which I refer to in this document as NCAM, that utilized much of the existing information on the productivity of this stock, including DFO offshore bottom-trawl survey indices, inshore gillnet indices, inshore acoustic biomass estimates, fishery catch age-composition information, partial fishery landings information, and some tagging information. By integrating much of the information in one model, Cadigan (2015) addressed problems that are difficult to deal with using data sources individually, such as estimating fishing (F) and natural mortality (M) rates separately and accounting for changes in the spatial distribution of the stock. The purpose of developing this model was to provide projections of the impacts of various levels of future fishery catches on the continued recovery of this stock. Cadigan (2015) is referred to as C15 for simplicity in the remainder of this document.

The major focus of this update of NCAM is to extend the model from the 1983-2012 period in C15 to 1983-2014, and include new survey and fishery information for 2013-14. Also, all of the tagging information for this stock was not used in C15 because it was not available at that time. In this update I use much more of the tagging data that has been collected for Northern cod, which is approximately twice as much data compared to C15. In particular, additional (to C15) information from tagging experiments around the time of the fishing moratorium in 1992 will be used to provide more information on stock dynamics during that period of rapid change. Also, data from more recent (i.e. 2008-14) tagging experiments will be used to improve estimates of stock size and mortality rates during the past few years. All of the tagging data was considered but not all experiments will be used because of low sample sizes or other problems with some experiments. About 3% is not used. This will be described in more detail below.

Another change is the way the tagging data is included in NCAM. C15 used information on the average length of fish tagged in an experiment to approximate the average age of tagged fish when captured in subsequent years, and then matched this with corresponding average fishing mortality for those ages. This procedure was complicated. Individual information on tagged fish were available for this update and I use a conceptually much simpler approach involving estimating the age of tagged fish based on their length-at-release and time-at-liberty. The tagging data are then summarized in an age-disaggregated format and used directly in NCAM, as described in the Methods section. The estimation of the age of tagged fish is described in Cadigan and Konrad (2016). I also explore an alternative likelihood component for the tagging data, to further simplify the model and produce better diagnostics on the model fit to the tagging data. An improved method to account for the exploitation of tagged fish in the release year is also implemented.

Northern cod are recovering and the age-distribution of the stock, sampled in surveys and commercial fisheries, has been expanding. This is the motivation for another change in the NCAM update compared to C15, which is to expand the modelled ages from 2-12 to 2 -14 to account for the expanding age-distribution. This is only an interim solution for the expanding age distribution.

C15 found that there was a major conflict between the Sentinel gillnet indices and the DFO RV surveys and tagging data. The sentinel indices were at about the same level in 2010-12 as in 1997-99, whereas the DFO RV surveys increased substantially. The NCAM model could not reconcile these differences and C15 omitted the Sentinel gillnet indices from the model estimation because of uncertainty about how these fixed gear catch rates related to the stock as a whole. In this update I include the Sentinel gillnet indices but with a model adjustment to account for a change in catchability (described below).

Some other minor adjustments to the NCAM model were also made which are described below. The model was modified to provide the output (including standard errors) requested in the Terms of Reference for the 2015 Northern Cod Framework Review Meeting. The model was also extended to incorporate potential offshore acoustic survey estimates. This will be illustrated with a hypothetical example.

# METHODS

The NCAM model was described in detail in CD15 and this description will not be repeated in this paper. Basic model settings are briefly indicated and model changes are described in more detail.

## BASIC SETTINGS

- model ages and years: 2 to 14, 1983 to 2014.
- no plus group.
- DFO RV indices, ages 2-14, 1983-2014.
- Sentinel gillnet (5.5 in mesh) indices for 3K+3L combined, ages 3-10, 1995-2014.
- DFO RV catchability (*q*) constrained to be equal for ages 6 to 14.
- DFO RV indices in 2004 are not used because of problems with survey coverage that year.
- DFO RV survey measurement error is fixed to have a standard deviation of 0.5 in 1986 (i.e. a year effect), so that the index for this year has little weight in model fitting
- DFO RV indices with values of zero are assumed to be < 0.005.
- means for the autocorrelated *M*'s (Eqn. 3 in C15), $m_2 = 0.5$, $m_3 = 0.3$, $m_{4+} = 0.2$.
- M's coupled for ages 8+.
- lower bound on total catch weight = reporting landings.
- upper bound on total catch weight = 1.5 x reported landings during 1983-92, and 2 x reported landings during 1993-2014.
- Smith Sound acoustic biomass estimate represents age 5+ biomass with equal catchability of all ages > = 5.
- Smith Sound campelen bottom trawl age compositions assumed to have catchability (scaled to one) $q_2 = 0.7$, $q_3 = 0.9$, $q_{4+} = 1$.
- Reported tag-recaptures for years-at-liberty 0-9, by experiment and age-at-release for experiments conducted during 1997-2014 in 2J3KL. Only experiments with greater than 70 fish tagged in total were used and only experiments and ages with at least 10 fished tagged were used.
- Tag reporting rates estimated using high-reward information (see Konrad et al. 2015) declined from 84% in 1997 to 65% in 2014.
- Tag loss applied using Kirkwood's model and parameters in Healey and Brattey (2006).
- The same selection criteria were used for old tagging experiments conducted during 1983-96 (i.e. more than 70 fish tagged, more than 10 tagged in an age class). However, the return period was restricted to years-at-liberty 0-5, the same as Myers et al. (1996), because

of their assumption that report rates were the same in all years-at-liberty for these experiments.

- Tag reporting rates + additional initial tagging mortality (see next bullet) + short-term tag loss (i.e. θ in Myers et al. 1996) estimated by experiment prior to 1997. These early experiments did not include high-reward tagging to provide information to estimate reporting rates. θ is estimated within NCAM for each experiment separately.
- For all tagging experiments during 1983-2014, short-term tagging survival was assumed to be 97% for experiments conducted in November-June, and 78% for experiments conducted in July-October (see Brattey and Cadigan 2003). This was the same for all gears types used to catch fish for tagging.

## MODEL CHANGES

### Population Dynamics

In C15 the recruitments were treated as uncorrelated lognormal random variables with a standard deviation fixed at one. This subjective choice affects the uncertainty of projections. In the updated NCAM formulations this parameter is estimated.

### Tag Component

Age-based tag returns are included in the model using a simplified method compared to C15. If $N_{x,a,y}$ tagged fish from experiment *x* survive to year *y* and are age $a$, then the size of the tagged population in year *y+1* is modelled as

(1) $$N_{x,a+1,y+1} = N_{x,a,y} \exp\left(-F_{x,a,y} - M_{a,y} - \gamma_y\right),$$

where $F_{x,a,y}$ is the experiment, age, and year specific fishing mortality rate experienced by the tagged fish, $M_{a,y}$ is the age and year specific natural mortality rates that is estimated by NCAM, and $\gamma_y$ is the tag loss rate which depends on the time-at-liberty of a fish. I use Kirkwood's model for tag loss. If a fish is at-liberty for the time interval *Δt* then the probability that the fish still retains its tag is

(1.1) $$\Gamma(\Delta t) = \left(\frac{\beta_1}{\beta_1 + \beta_2 \Delta t}\right)^{\beta_1}.$$

This is a monotone decreasing function of *Δt*. I assume that $M_{a,y}$ is the same for all fish (including those tagged), but I do not make a similar assumption about *F*.

For each experiment, fish were tagged in specific geographic locations and the *F* they experienced was likely different from the stock as a whole. C15 assumed these differences were random such that

(2) $$\log\left(F_{x,a,y}\right) \sim N\left\{\log(F_{a,y}), \sigma_{fx}^2\right\}.$$

The tag catch at age ($C_{x,a,y}$) was modelled using the common Baranov catch equation,

(3) $$C_{x,a,y} = N_{x,a,y}\left\{1 - \exp\left(-Z_{x,a,y} - \gamma_y\right)\right\} \frac{F_{x,a,y}}{Z_{x,a,y} + \gamma_y},$$

where *Z* = *F* + *M* is the total mortality rate. Only a fraction of *F* and *Z* were applied in the year of release, depending on the fraction of the total annual catch that was taken before the fish were released. For convenience I used some approximate values for this fraction (see Results section) but this can be easily estimated in the future using monthly catch statistics. This is different than C15 who simply used the fraction of year that the fish was tagged. However, this will usually not correspond well to how much *F* the tagged fish experienced in the release year. For example, in recent years fish tagged in June experienced (on average) practically all the annual exploitation that occurred because the fishery has not started until after June. In C15 only half of *F* was applied to fish tagged in June.

Hence, the main differences between the updated NCAM model and C15 are the use of age-disaggregated tag catch data and the amount of *F* applied in the year of release. A simplified assessment model is used that treats tag catch-at-age the same as fishery catch-at-age, except that the tag catch comes from a population whose size we know something about (i.e. number released) when tagging mortality has been estimated whereas the fishery catch comes from a population whose size is unknown and must be estimated.

The Terms of Reference for the 2015 Northern Cod Framework Review Meeting requested that model results be provided, including parameter estimates and predictions of random effects. It is particularly important in state-space models that process error random effects be examined. This is considered further in the Discussion. For the most part process errors were examined in C15, although not always on their own, but in conjunction with fixed-effect population parameters. The exception was the *F* deviations in Eqn. (2), $U_{x,a,y} = \log(F_{x,a,y}) - \log(F_{a,y})$. These were not examined in C15 and this is a deficiency in that paper. There are a great many of these random effects; in the current model formulation there are 8,597 of these and it is difficult to examine them all. In this paper I also do not do this explicitly. However, I investigate a model formulation that does not involve *U* random effects and I examine the tag-return residuals from this model. This is similar to interpreting predictions of the *U* random effects, and perhaps more relevant to stock assessment.

C15 assumed that, conditional on $U_{x,a,y}$, the tag-returns were Poisson distributed. C15 assumed that $U_{x,a,y} \overset{iid}{\sim} N(0, \sigma_{fx}^2)$ with $\sigma_{fx}^2$ the same for all experiments during 1983-2012. In the update NCAM I use a different $\sigma_{fx}^2$ for the 1983-96 and 1997-2014 periods. In either case this is similar to a Poisson-Lognormal (Poi-LN) mixture distribution that does not have a closed-form marginal distribution (e.g. Cameron and Trivedi 2013) and whose marginal mean depends on the model predicted tag-return and the lognormal transformation bias which involves $\sigma_{fx}^2$. When random effects are not of direct interest (i.e. like nuisance parameters) then it may be better to examine marginal residuals based on the distribution of the response with those random effects "integrated out". Marginal residuals may be better for identifying model mis-specification that could be masked by random effects. C15 only examined conditional residuals.

A more common approach to model count data with Poisson over-dispersion is the Poisson-Gamma mixture model. This has a closed form marginal distribution, namely the Negative Binomial (NB). I have added this option to NCAM. The NB distribution has a mean parameter $\mu$ and an over-dispersion parameter. In the formulation I use, the over-dispersion parameter is *k*, where the NB variance is $\mu + \mu^2/k$. I assume tag-returns are NB distributed with means derived using Eqns. (1) and (3) but with $F_{x,a,y}$ replaced by $F_{a,y}$; that is, the same *F*'s are applied to all experiments and between-experiment variation in *F*'s is simply modeled as Poisson over-dispersion in tag-returns. I estimate two *k* parameters for 1983-96 and 1997-2014. This model does not have *U* random effects which simplifies estimation of other parameters. However, the Poi-LN and NB approaches are more different in NCAM than with simple iid data with either LN or LogGamma over-dispersion because of the time-series nature of the model. One advantage of the NB approach is that marginal residuals are easily derived.

## Fishery Landings

Landings estimates are available and these were used to provide lower and upper bounds on the total fishery catch. Model predicted total landings were derived from mid-year stock biomass-at-age, summed over ages 2-14. Mid-year stock weights were estimated using a new growth model described in Cadigan (2016). C15 used total catch abundance at ages 2-12 for this purpose which is another difference in the updated NCAM model compared to C15.

The bounds used on total catch weights are subjective and perhaps not too realistic because we know for certain that recent landings are too low because they do not include recreational catches. I investigate the sensitivity of model results to the catch bounds using higher values: lower bound on total catch weight = 1.5 x reporting landings and the upper bound = 3 x reporting landings. These same bounds were used for all years.

## Surveys

The expansion of the age range of the model to 2-14 is straightforward. However, I also extended the DFO RV autumn bottom trawl survey indices to ages 2-14. Prior to 1990 the survey index usually included cod at these ages, although since 1991 cod at these ages have been rarely caught, the exception being at age 13 in 2013-14. The DFO RV indices are included using the same likelihood component as C15. This involved a censored likelihood component for indices with values of zero. There are more zeros in the DFO RV indices now compared to C15 because of the inclusion of ages 13-14. The survey indices are shown in model output figures below. Residual plots are based on observed (not log) minus expected, divided by the standard deviation (i.e. CV x mean).

C15 found that the NCAM model fit the 3KL sentinel gillnet indices very poorly. This index has an overall trend that is substantially different than the DFO RV index (see Fig. 1). The sentinel index is based on fixed station sites that are distributed very close to the coastline in 3KL. The index is derived from a catch rate model that does not explicitly account for the area that a site represents. Hence, this index will be sensitive to the amount of cod that migrate inshore in the summer to feed, and where the migration occurs. I hypothesize that changes in migration patterns (timing, location) and the size of offshore spawning components may be affecting the catchability of the Sentinel index. I address this using catchability year effects. Let $q_{s,a,y}$ be the Sentinel gillnet index catchability for age a fish in year y. I assume

(4) $$\log(q_{s,a,y}) = \log(q_{s,a}) + \log(q_{s,y}),$$

where $q_{s,a}$ is a fixed age effect parameter to estimate and $q_{s,y}$ is a random year effect which we assume has zero mean and is a random walk over time. Hence, in this approach the age-composition information of the index is utilized directly but the index trends over years are not.

The final formulation I investigate includes a hypothetical offshore acoustic survey of some spawning aggregations of Northern cod in 2014. I assume the biomass estimate is 500 Kt with a CV of 15%. I assume this is a partial biomass estimate of the whole stock, and this information is included via a censored likelihood component. Let $X_A$ denote the acoustic survey SSB estimate for stock area *A* which is a subset of the entire stock area. If the survey was for the entire stock area, which we denote simply as *X*, then the log-likelihood component for it, assuming LN error with $Var\{\log(X)\} = \sigma_X^2$, is $log(\sigma_X^{-1}\varphi_N[\{\log(X) - \log(SSB(\theta))\}/\sigma_X])$,

where $\varphi_N$ is the probability distribution function (pdf) of a *N(0,1)* random variable and *SSB(θ)* is the model value for *SSB*. This is based on $\Pr\{X = \log(SSB) + dx\}$. However, the actual survey is only for a subset of the stock area and we assume it provides a partial estimate (i.e. a stochastic lower bound). The log-likelihood for this partial estimate is based on $\Pr\{X \geq X_A\}$ and is

(5) $$log(1 - \Phi_N[\{\log(X_A) - \log(SSB(\theta))\}/\sigma_X]),$$

where $\Phi_N$ is the cumulative distribution function (CDF) for a *N(0,1)* random variable. If $X_A \ll SSB(\theta)$ then $\{\log(X_A) - \log(SSB(\theta))\}/\sigma_X$ << *0* , $1 - \Phi_N[\{\log(X_A) - \log(SSB(\theta))\}/\sigma_X] \approx 1$ and Eqn. (5) will be approximately zero. Hence, $X_A$ will not contribute to the log-likelihood for $\theta$ parameter values that result in *SSB(θ)* >> $X_A$, but otherwise it will. In a sense Eqn. (5) penalizes against values of *SSB(θ)* < $X_A$ but not for values of *SSB(θ)* > $X_A$. I assume the survey occurs mid-year and the model value of *SSB* in Eqn. (5) is based on projecting beginning of year *SSB* to mid-year assuming constant *F* within the year.

## FORMULATIONS

Four model formulations are investigated and results presented:

1. C15+: Updated formulation of C15;
2. NB: C15+ but with NB approach to tag-returns;
3. NB_LC: NB but with higher bounds on total catch weight; and
4. NB_ACO: NB and hypothetical offshore acoustic survey.

In accordance with the Terms of Reference, the results presented include measures of fit (negative log-likelihood and AIC), many graphical displays of residuals and model fit, most parameter estimates with CV's, graphs of predictions of random effects, and graphs and tables for estimates of total abundance (age 2+), recruitment (age 2 or 3), total biomass (ages 2+ and 3+), SSB, F (averaged over both ages 4-6 and ages 7 9), M, and q's. Retrospective analyses were conducted for 2005 -14. It was not sensible to do a retrospective analysis of the NB_ACO NCAM, for obvious reasons.

The NCAM model was developed to provide catch advice. Although the exact value of catches are not assumed to be known, the model estimates these catches and therefore it is possible to do catch projections based on these estimated catches. These projections were done assuming constant catch scenarios for the next 5 years, where catches are assumed to be a multiple of the estimated 2014 catch. Projections were performed using multipliers ranging from 0.5 to 1.5, with increments of 0.1. Projected recruitment was assumed to be the geometric mean of 2012-14 recruitment at age 2. Note that NCAM models recruitment as deviations from two mean values (before and after 1993) so recent recruitment estimates will be "shrunk" towards mean recruitment since 1993. Hence, it is more appropriate to use the geometric mean recruitment during 2012-14 for projections, compare to the case when recruitment is estimated freely with no shrinkage and very high uncertainty in recent values.

A small model error was discovered during the framework meeting; this involved how the partial M was computed to apply to tagged fish in their year of release. This was based on the fraction of the catch that remained to be caught. This fraction is appropriate to apply to F but not M. The fraction of M should have been based on the fraction of year remaining when the fish were tagged. This was corrected during the framework meeting and the effect of this error was examined for one model formulation. Results on the effect for other formulations will be included in the meeting Proceedings document.

# RESULTS

## DATA INPUTS

Most of the survey and catch data will be present elsewhere so I focus on providing a few summaries of the tagging data. A broad overview of the releases and recaptures is shown in Fig. 2a. The data selected for input into the NCAM model, after deleting experiments with less than 70 fish tagged, and ages with fewer than 10 fish tagged, are summarized in Tables 1a-c. Illustrative approximations of the cumulative fraction of the total annual catch taken each month are shown in Figs. 2b,c. This information was used to approximate the fraction of $F$ for tagged fish in the year they were released. If $ff$ was the cumulative fraction of catch taken by the month of release, then $(1\text{-}ff)xF$ was the fishing mortality applied. Improvements in the calculation of $ff$ are considered in the Discussion.

I first present key results from each model formulation. Figures comparing these formulations and results from C15 are presented later (Figs. 23a,b).

## C15+: UPDATED FORMULATION OF CADIGAN (2015)

Some estimates of model parameters and key derived stock size and mortality rates are shown in Table 2 and Figs. 3a,b. Mature biomass is estimated to be 190,000 tonnes in 2014, which is 29% of the model value of Blim (653,000 tonnes). Blim in the base model in C15 was 621 Kt. Average $M$ (ages 5+) was 0.26 in 2014 but $F$'s were low so that average $Z$ (ages 5+) was only slightly higher than $M$. Age specific estimates are presented in Appendix II Tables. Mortality rates are also shown in Fig. 4, indicating a spike in $M$ during 1990-94.

DFO RV survey $q$'s increased until age 6 (Fig. 5a) and they were assumed to be constant for older ages. The maximum swept-area $q$ was 1.03 indicating that all of the stock was available to the survey in many years. However, a large change in $q$ occurred during 1995-2007 (Fig. 5b) when there was a relatively large over-wintering aggregation of cod in Smith Sound in the inshore. These fish would not have been available to the DFO RV autumn survey. The Sentinel gillnet (5.5 in mesh) catch rate $q$'s had a domed shaped pattern (Fig. 5c), which is to be expected.

Projections results are illustrated for the 0.5, 1.0, and 1.5 times multipliers (Figs. 6a-c). The stock is estimated to continue to grow for all catch scenarios, with little difference between the projection scenarios because the F's are low. The stock will be around 40% of Blim in 2016 (Fig. 6b) at almost 300,000 tonnes (Fig. 6c) which is a 40% increase compared to 2014 mature biomass.

There is a small retrospective pattern in mature biomass in this formulation of NCAM (Figs. 7a,b) which is different from C15. The pattern is for estimates of mature biomass to slightly increase as more years of data are added to the model. There is a more pronounced retrospective pattern in recruitment. However, there are no strong retrospective patterns in mortality rate estimates (Fig. 7b).

The aggregate fit to the DFO RV survey index is reasonable (Fig. 8a). There is high between-year variability in the index during 1983-91 that the model cannot account for. It is unlikely that the stock size fluctuated as much as the survey index during this period. Otherwise, the model tracks the aggregate survey index fairly well, except that it does not increase as much as the index during 2013-14. Reasons for this are explored later in this document. The model has high flexibility to fit the Sentinel gillnet index well, and this is the result (Fig. 8b). Total catch weight is estimated to be within the data bounds (Fig. 8c) each year. During 2010-14 the reported landings are estimated to be about 85% of total catch. The model fits the Smith Sound acoustic biomass estimates fairly well (Fig. 8d). However, the biomass in Smith Sound was estimated to be higher than the survey during 1997-99 which was not the case in C15.

Residuals from model fits to the age-disaggregated survey data, which are used for model estimation, do not indicate major problems (Figs. 9a,b) such as large year effects, although the residuals are mostly positive for the last four cohorts which is similar to C15. Note that by construction residuals are always negative for indices with values of zero. There are age and year patterns in residuals that the model does not account for (Figs. 9c,d). The model fits the catch age composition information well (Fig. 9e). The fits to the age composition information from the Smith Sound acoustic surveys (Fig. 9f) are not as good, and are substantially worse than C15.

The model used a substantial amount of tagging information: 8,597 year and age specific capture events from 200 tagging experiments, involving the reported capture of 10,463 tagged cod from 105,903 releases. NCAM fit these data very well (Fig. 10a). Aggregate fits were very close to observed values (Figs. 10b,c). Aggregate fits across ages for each experiment are illustrated in Figs. 11a,b. The full set of results were provided to the Framework Review Meeting. Fits were good for most experiments. Age-specific fits were also provided.

The ability of NCAM to fit tagging data well is not surprising because the model has substantial flexibility to do this because the tagging F's are modelled for each experiment and age via random effects. I have not examined how much adjustment (i.e. random effect deviations) to total stock F's were required to achieve this good fit, nor whether these deviations indicate model mis-specification. This will be addressed in the next model formulation.

## NB: C15+ AND NB APPROACH TO TAG-RETURNS

The main motivation for this formulation is for diagnostic purposes, to examine if there is potential model mis-specification in the tagging component of NCAM, or if results are sensitive to how the tagging data are incorporated in the model. Only results for this purpose will be presented.

This model fit better than C15+ (Table 2) with a substantially lower value of AIC. Biomass (both mature and total) estimates were slightly lower (Table 2; Fig. 12) but stock status relative to Blim was very similar to the C15+ model. The difference in observed and predicted tag-returns (Fig. 13a) is larger than the C15+ model as expected because in C15+ the tagging F's were allowed to vary across experiments. However, the marginal tag return residuals in Fig 13a had similar variability to the conditional residuals in Fig. 10a. A most notable difference is the consistently higher model predictions of tag-returns during 2007-14 compared to observations (Fig. 13b). This is considered further in the Discussion. This pattern was hardly apparent in Fig. 10b. Another difference is the tendency of the model to slightly under-predict tag-returns in the release year and then to very slightly over-predict returns in subsequent years-at-liberty (Fig. 13c).

## NB_LC: HIGHER BOUNDS ON TOTAL CATCH WEIGHT

In this formulation the lower bounds on total catch weights were 1.5 times reported, and the upper bounds were 3 times reported, for all years. Setting the bounds is subjective and the motivation for this formulation was to assess the sensitivity of results to these subjective model specifications.

The results (Table 2, Figs. 14a,b) demonstrate that the scale of the biomass estimates is sensitive to the catch bounds, although the mortality rate estimates are much less sensitive. Retrospective variation in models results (Fig. 15a,b) were about the same as C15+. Total catch weights were usually estimated to be within the data bounds (Fig. 16). The discrepancy between observed and model predicted tag-returns during 2007-14 (Fig. 17) was similar to the NB model (Fig. 13b). The NB_LC model fit the 1983-96 tag-returns better, as evidence by the higher NB $k$ parameter estimate for these experiments (Table 2). Recall that in NB formulation I use, the variance function of the mean ($\mu$) is $\mu + \mu^2/k$, so when $k$ is smaller this indicates more variability.

## NB_ACO: NB AND INCLUDING A HYPOTHETICAL OFFSHORE ACOUSTIC SURVEY

The final formulation included a hypothetical 2014 offshore acoustic survey mature biomass estimate of 500 Kt with a CV of 15%. I assumed this was a partial biomass estimate of the whole stock, and this information was included via a censored likelihood component.

First note that because this model included additional data, the negative log-likelihood and AIC in Table2 were not comparable to the other NCAM formulations.

The addition of this survey estimate resulted in higher biomass estimates (Table 2; Figs. 18a,b) compared to the C15+ and NB models, and lower estimates of M for the last few years. The stock is estimated to be 34% of Blim. Projections (Figs. 19a-c) were more optimistic as well, with the mature biomass projected to be 520 Kt (80% of Blim) in 2017 compared to around 325 Kt (50% Blim) for the NB formulation.

This formulation resulted in a slightly better for to the DFO RV index (Table 2; Fig. 20a) but a slightly worse fit to the Sentinel gillnet index (Table 2; Fig. 20b). However, the model over-predicted catches at older ages in the DFO RV index in 2014 (Fig. 21). This was not the case for the C15+ (Fig. 9c) and NB models.

There was a similar discrepancy between observed and model predicted tag-returns during 2007-14 (Fig. 22) compared to the NB model (Fig. 13b).

However, the model did not fit the offshore acoustic survey estimate well. The upper 95% confidence limit (276 Kt) from NCAM was considerable less than the hypothetical acoustic survey estimate of 500 Kt. Additional modifications of model assumptions seem to be required to better fit such an acoustic survey estimate (see Discussion).

## COMPARISON OF ALL MODELS

Although the scale of mature biomass estimates varied across model formulations (Figs. 23a,b) the stock status relative to Blim was much more stable. The formulation that results in the highest estimate of SSB relative to Blim is NB_ACO which included a hypothetical 2014 offshore acoustic survey mature biomass estimate of 500 Kt. Mortality rates (M and F) were similar among the various update NCAM formulations but these were considerably different than C15, presumably because of the use of substantial additional tagging data in the updates models.

## ADDITIONAL MODELS PRESENTED AT THE FRAMEWORK MEETING

As mentioned above, a small error was discovered in NCAM related to how much M was applied to tagged fish in the year they were released. Fixing this error had little impact on NB model results (Fig. 24). Results for other models were not reviewed during the framework meeting but will be provided in an appendix of the proceedings document for completeness.

None of the above models were able to fit the recent increase in the DFO RV survey index; more specifically, the increase at young ages. Model residuals are mostly positive for the 2009-12 cohorts (e.g. Figs. 9a,c). There seems to be two reasons for this. The first is that recruitment is modelled as a simple random effect with two mean values (pre- and post-moratorium) and model estimates of recent recruitment will tend to be “shrunk” to the post-moratorium mean unless there is strong evidence otherwise. The second reason is that the fishery age-compositions have not indicated the same magnitude of increases in recent recruitment (e.g. Fig. 9e).

I investigated two changes to the NCAM formulation to better fit the recent trend in the DFO RV index. The first was to fix the recruitment standard deviation ($\sigma_R$) at one to essentially freely estimate recruitment. The second was to increase the fishery age-composition standard deviation ($\sigma_P$). In C15 and the above model runs this was fixed for ages 2-3 to be 3x the estimated common $\sigma_P$ value for ages 4-8. The $\sigma_P$ for ages 9-14 was fixed to be 2x$\sigma_P$. Increasing $\sigma_P$ for ages 2-3 will reduce the influence of these ages. Neither of these changes on their own produced a better fit to the age-aggregated DFO RV index. A model with both of these changes did result in a somewhat better fit (compare Fig. 25a with Fig. 8a), but at the expense of fitting the commercial age 2-3 compositions (compare Fig. 25b with Fig. 9e). This run is for sensitivity purposes only.

## DISCUSSION

An integrated state-space stock assessment model for Northern cod (NCAM; Cadigan 2015) has been updated to incorporate more of the data on the productivity of this stock; in particular, much more of the existing tagging data is used. However, integrating tagging data in a stock assessment model is not common (for exceptions see Eveson et al. 2012, and Goethel et al. 2015) and the best way to do this for Northern cod requires additional research. In the interim, I suggest the NB NCAM formulation is the better approach because it fits the survey, commercial catch, and tagging data better. A potential dis-advantage of the C15+ formulation is potential masking of model mis-specification but this could be better understood by a thorough examination of the tagging *F* random deviations. A concern is that these deviations are masking something else, like a decrease in tag reporting rates. These issues require further study.

There is a discrepancy between model estimates and observations of the number of tags returned in recent years (i.e. since 2007), with less observed than model predicted. This could indicate a reduction in reporting rates; however, it may also indicate over-estimation of exploitation rates. This was not apparent in C15 nor in tag-return residual diagnostics from the C15+ model formulation. This was because these discrepancies were accounted for by the tagging *F* random deviations (i.e. *U* deviations). This potential mis-specification was "masked", although this may have been apparent by looking at appropriately aggregated *U* diagnostics such as these random effects aggregated over return years. There is a potential that random effects like *U* can account for uncertainty in model mis-specification such as incorrect reporting rates, but this needs to be validated, probably on a case-by-case basis. Obviously it is more desirable not to mis-specify reporting rates and consequently produce more accurate and precise estimates of stock size and mortality rates.

Two likelihood equations were investigated to include tagging data in NCAM. Both approaches were based on the assumption or rationale that the F experienced by tagged fish will vary across experiments, because of spatial and seasonal variations. In reality both F and M vary spatially and seasonally and experiment-specific M's could be modelled similar to Eqn. (2); however, I have not investigated this for an update of NCAM. The two plausible approaches produced only slightly different stock size estimates. The NB approach only included variation in the current *F* applied to the tagged population. The size of this population is estimated using only the total stock *F* histories and not tagging experiment *F* histories like in C15 and C15+.

Tagged fish do not experience the full annual *F* in their year of release. Using a rough approximation of the fraction of total annual catch taken before fish were tagged to adjust how much *F* the tagged fish experience resulted in a substantial improvement in the fits of all models compared to first versions models that simply used the fraction of the year remaining after tagging to adjust F. The latter adjustment is based on the assumption of constant F throughout the year which is definitely not the case for Northern cod since 1992. Annual estimates of the monthly cumulative distribution of catches may produce further improvements in model fit.

Estimates of $\sigma_{fx}$ for 1983-96 (0.42) and 1997-14 (0.65) from the C15+ model are smaller than the combined estimate in C15 (0.99). This indicates that the estimated ages of tagged fish and improvements in partial *F*'s applied during the year of release have helped to explained additional variation in tag-return data.

The NCAM model estimates parameters for tagging experiments during 1983-96 that represent the combined effects of reporting rates, initial tagging mortality, and short-term tag loss. This θ parameter (see Myers et al. 1996) is estimated separately for each experiment. The consequence of this is that the overall magnitude of tag-returns does not provide information on mortality rates. Only the rate of decline of recaptures with years-at-liberty provides mortality rate information. This is analogous to mortality information that comes from a survey catch curve analysis. This is a substantial deficiency in these early tagging experiments that results in a loss of exploitation rate information because the percent of tags returned is not informative about harvest rates since the size of the tagged population available to fisheries is unknown due to unknown tagging mortality.

If there are substantial concerns about the accuracy of recent reporting rate estimates (i.e. Konrad et al. 2015) or mortality during tagging then the θ parameters could also be estimated for each of the 1997-2014 experiments or some subset of them. This would require the return period to be more restricted than the 9 years used in all model formulations presented here. This would reduce information about M and would also basically mean that the tagging experiments of the last few years are uninformative about exploitation rates because their time-series would be too short to infer mortality rates. This may be a useful area for additional investigations.

Data from 200 tagging experiments were used in this update of the NCAM model. The tagging component of the model may be improved by combining some results from experiments that were conducted at similar times and locations. This could improve estimation of between-experiment variations in fishing mortality. There will likely be temporal and spatial dependencies in differences in F's among experiments, and there is probably high correlation in tagging F's among ages. These dependencies could be utilized to improve the model.

The random walk on total stock fishing mortality rates has the same temporal auto-correlation at all ages. If catches of young cod in commercial fisheries happen by mistake then we may expect less auto-correlation at these ages. It may be useful to model the temporal dependencies at young and old ages differently.

The Sentinel gillnet (5.5 in mesh) index has been included in all model formulations in this working paper. There is uncertainty about how the catch rates from this index relate to the stock as a whole. The index is based on fixed station sites that are distributed very close to the coastline in 3KL. The index is derived from a model that does not explicitly account for the area that a site represents. Hence, this index will be sensitive to the amount of cod that migrate inshore in the summer to feed, and where the migration occurs. I hypothesize that changes in the size of offshore stock components and how they migrate to the inshore may be affecting the catchability of the Sentinel index. This was addressed in the update of NCAM by using auto-correlated (i.e. random walk) year effects in catchability. The intended consequence of this change in the catchability model is that the overall trends in the index should have little effect on model results, but the age composition information will – even though the 5.5 inch mesh gillnet samples only a few age classes effectively. The efficacy of this approach requires further investigation although I highly doubt the model results are influenced much by including this index.

The censored likelihood components for total catch weights, DFO RV indices with zero values, and the hypothetical acoustic biomass estimate of some offshore components, seem to cause estimation problems with TMB. It seems to create flat areas in the likelihood surface for some parameter values and the inner optimization of random effects sometimes fails. Another possible cause is the Laplace approximation. This requires further study and investigation with simpler “toy” problems with censored likelihood components.

All NCAM model formulations produced results that are fairly consistent with offshore acoustic estimates of spawning components in Rose and Rowe (2015) during 1990-2014. This is based on comparing model estimates of mature biomass with the estimates in Rose and Rowe (2015). The NCAM model estimates are similar to theirs which makes sense under the assumption that the acoustic biomass estimates are partial estimates, or estimates (with uncertainty) of part of the stock, but nonetheless represent a large part of the stock. I have assumed that the acoustic biomass estimates are for mature fish. If they include some immature fish then this comparison is still valid because the survey estimates of mature biomass will be less than the values in Rose and Rowe (2015), and the NB NCAM estimates are almost always greater than Rose and Rowe (2015) estimates.

However, one year projections indicate there will be a large inconsistency if the 2015 acoustic biomass estimate is considerably larger than the acoustic survey estimate for 2014. I expect that additional modifications of model assumptions will be required to better fit a high 2015 survey value. This could involve assumptions about additional and recent changes in the catchability of the DFO RV survey at older ages, or the level of fishery catches.

It is nevertheless useful to include all the offshore acoustic biomass estimates in NCAM even if the estimates during 1990-2014 (as lower bounds on mature biomass) are already consistent with the model. Although including the acoustic survey information prior to 2015 may have little impact on NCAM, if they provide additional validation of the model then that is useful. Age composition information is also collected during the acoustic surveys of spawning components and this information should be included as well. However, it is not clear to me how to do this because it is not clear if there are sufficient numbers of tows conducted to reliably estimate the age compositions of the spawning components surveyed, or how these age compositions relate to the stock as a whole.

There is additional and highly relevant information on survival rates (ergo natural mortality rates) from acoustic tagging (i.e. telemetry) studies that should be included in the model and this is a useful area for future research.

Uncertainty in projections is large; however, model estimates of population size in the final model year seem much more precise at older ages and this does not seem like an important source of uncertainty in projections. Model estimates of recruitment in the last two years are more uncertain and this is likely an important source of uncertainty when these year classes reach maturity in projections. In many stock assessments it is the only source of uncertainty in projections, apart from uncertainty about initial stock size. Uncertainty about M can also be important and in this assessment this uncertainty is accounted for. However, the process error standard deviation for $M$ ($\sigma_{\delta}$) is estimated to be almost 50% lower than the recruitment standard deviation ($\sigma_R$) so the second source still seems like the most important one. Reducing these sources of error requires more knowledge about the factors affecting the reproduction and mortality processes for this stock. However, there is also large estimation uncertainty in the size of recent recruitment. Additional recruitment indices may reduce this estimation uncertainty. DFO RV survey catches at age one should be investigated to see if this information could improve the estimation of recruitment. Also, there is a comprehensive juvenile survey in an important nursery area in the inshore (i.e. Newmans Sound) and these data should also be investigated to see if they can improve recruitment estimates for the entire stock.

An important assessment issue that needs to be investigated for Northern cod is reference points. The NCAM models all indicate substantial temporal variation in reproduction and mortality processes for Northern cod, and this is important to consider when determining reference points and sustainable harvest rates. Additional catch and tagging data exist for 1959-82 and it will be useful if the NCAM model could be extended back into this time period to better understand the temporal variability of these productivity processes. Further investigation of the body growth and maturation processes will also help better understand how these processes may change in the future. All of this may impact what are sustainable levels of fishing for Northern cod.

The variety of tagging (conventional, acoustic, satellite) and survey (inshore, offshore fall, and spawning surveys) data available for this stock may mean that it is possible to reliably implement some type of spatial or meta-population assessment model, and this may be a fruitful area for future research. Hence, there is much scope for additional stock assessment research on Northern cod.

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# APPENDIX I – TABLES

*Table 1a. Total number of fish tagged and released (Rel), recaptured and returned (Ret), and percent returned (%) for selected tagging experiments and release ages in NAFO Divisions 2J, 3K, and 3L.*

| Exp | Rel | Ret | % | Exp | Rel | Ret | % | Exp | Rel | Ret | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8302 | 981 | 178 | 18.1 | 8610 | 140 | 15 | 10.7 | 9004 | 788 | 121 | 15.4 |
| 8303 | 1992 | 325 | 16.3 | 8701 | 769 | 124 | 16.1 | 9005 | 1001 | 145 | 14.5 |
| 8305 | 220 | 31 | 14.1 | 8702 | 497 | 60 | 12.1 | 9101 | 1531 | 475 | 31.0 |
| 8306 | 101 | 17 | 16.8 | 8703 | 686 | 94 | 13.7 | 9102 | 1735 | 74 | 4.3 |
| 8307 | 318 | 24 | 7.5 | 8704 | 598 | 100 | 16.7 | 9103 | 131 | 0 | 0.0 |
| 8401 | 490 | 17 | 3.5 | 8705 | 491 | 96 | 19.6 | 9104 | 1115 | 3 | 0.3 |
| 8402 | 290 | 3 | 1.0 | 8801 | 949 | 100 | 10.5 | 9105 | 982 | 74 | 7.5 |
| 8403 | 1695 | 291 | 17.2 | 8802 | 587 | 140 | 23.9 | 9106 | 989 | 54 | 5.5 |
| 8404 | 132 | 23 | 17.4 | 8803 | 497 | 56 | 11.3 | 9107 | 1387 | 88 | 6.3 |
| 8405 | 150 | 28 | 18.7 | 8804 | 495 | 59 | 11.9 | 9108 | 84 | 3 | 3.6 |
| 8406 | 200 | 32 | 16.0 | 8805 | 499 | 33 | 6.6 | 9201 | 2048 | 5 | 0.2 |
| 8407 | 783 | 82 | 10.5 | 8806 | 738 | 101 | 13.7 | 9202 | 5478 | 48 | 0.9 |
| 8501 | 488 | 75 | 15.4 | 8807 | 473 | 51 | 10.8 | 9203 | 1047 | 40 | 3.8 |
| 8502 | 1075 | 141 | 13.1 | 8901 | 888 | 33 | 3.7 | 9302 | 1031 | 28 | 2.7 |
| 8503 | 358 | 15 | 4.2 | 8902 | 519 | 23 | 4.4 | 9501 | 488 | 20 | 4.1 |
| 8504 | 189 | 13 | 6.9 | 8903 | 545 | 34 | 6.2 | 9502 | 204 | 24 | 11.8 |
| 8505 | 271 | 59 | 21.8 | 8904 | 498 | 45 | 9.0 | 9503 | 2005 | 110 | 5.5 |
| 8506 | 172 | 56 | 32.6 | 8905 | 234 | 31 | 13.2 | 1997003 | 581 | 62 | 10.7 |
| 8604 | 94 | 3 | 3.2 | 8906 | 1427 | 60 | 4.2 | 1997007 | 681 | 183 | 26.9 |
| 8605 | 77 | 9 | 11.7 | 8908 | 283 | 9 | 3.2 | 1997009 | 460 | 73 | 15.9 |
| 8606 | 1489 | 298 | 20.0 | 9001 | 1187 | 52 | 4.4 | 1997010 | 302 | 45 | 14.9 |
| 8607 | 282 | 39 | 13.8 | 9002 | 67 | 0 | 0.0 | 1997011 | 74 | 15 | 20.3 |
| 8608 | 722 | 119 | 16.5 | 9003 | 284 | 1 | 0.4 | 1997012 | 253 | 24 | 9.5 |

*Table 1b. Total number of fish tagged and released (Rel), recaptured and returned (Ret), and percent returned (%) for selected tagging experiments and release ages in NAFO Divisions 2J, 3K, and 3L.*

| Exp | Rel | Ret | % | Exp | Rel | Ret | % | Exp | Rel | Ret | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1997013 | 211 | 31 | 14.7 | 1999030 | 437 | 75 | 17.2 | 2001020 | 119 | 21 | 17.6 |
| 1997014 | 598 | 66 | 11.0 | 1999031 | 264 | 75 | 28.4 | 2001021 | 1686 | 456 | 27.0 |
| 1997016 | 189 | 21 | 11.1 | 1999033 | 95 | 3 | 3.2 | 2001023 | 153 | 26 | 17.0 |
| 1998007 | 100 | 22 | 22.0 | 1999034 | 96 | 5 | 5.2 | 2001026 | 987 | 146 | 14.8 |
| 1999006 | 717 | 201 | 28.0 | 1999035 | 197 | 16 | 8.1 | 2002005 | 86 | 1 | 1.2 |
| 1999007 | 369 | 83 | 22.5 | 1999038 | 130 | 24 | 18.5 | 2002010 | 905 | 185 | 20.4 |
| 1999008 | 294 | 46 | 15.6 | 1999042 | 498 | 86 | 17.3 | 2002011 | 143 | 33 | 23.1 |
| 1999009 | 63 | 19 | 30.2 | 1999044 | 466 | 81 | 17.4 | 2002013 | 132 | 24 | 18.2 |
| 1999010 | 214 | 38 | 17.8 | 2000005 | 85 | 2 | 2.4 | 2002015 | 1608 | 263 | 16.4 |
| 1999011 | 100 | 22 | 22.0 | 2000014 | 329 | 74 | 22.5 | 2002017 | 254 | 41 | 16.1 |
| 1999012 | 637 | 198 | 31.1 | 2000015 | 271 | 32 | 11.8 | 2002018 | 583 | 74 | 12.7 |
| 1999013 | 212 | 40 | 18.9 | 2000018 | 312 | 39 | 12.5 | 2002019 | 93 | 18 | 19.4 |
| 1999014 | 210 | 26 | 12.4 | 2000019 | 1030 | 150 | 14.6 | 2002022 | 88 | 5 | 5.7 |
| 1999015 | 156 | 24 | 15.4 | 2000020 | 182 | 54 | 29.7 | 2002023 | 981 | 122 | 12.4 |
| 1999016 | 349 | 56 | 16.0 | 2000021 | 203 | 25 | 12.3 | 2003001 | 469 | 7 | 1.5 |
| 1999017 | 291 | 59 | 20.3 | 2000023 | 244 | 20 | 8.2 | 2004001 | 911 | 68 | 7.5 |
| 1999018 | 240 | 36 | 15.0 | 2000024 | 96 | 35 | 36.5 | 2005001 | 664 | 50 | 7.5 |
| 1999019 | 150 | 19 | 12.7 | 2000027 | 164 | 13 | 7.9 | 2005002 | 163 | 8 | 4.9 |
| 1999024 | 188 | 26 | 13.8 | 2000028 | 128 | 9 | 7.0 | 2005003 | 96 | 10 | 10.4 |
| 1999025 | 570 | 176 | 30.9 | 2001012 | 464 | 74 | 15.9 | 2006001 | 374 | 32 | 8.6 |
| 1999026 | 179 | 85 | 47.5 | 2001015 | 705 | 115 | 16.3 | 2006003 | 86 | 2 | 2.3 |
| 1999028 | 481 | 72 | 15.0 | 2001018 | 659 | 203 | 30.8 | 2006004 | 383 | 19 | 5.0 |
| 1999029 | 175 | 23 | 13.1 | 2001019 | 877 | 111 | 12.7 | 2006005 | 1337 | 74 | 5.5 |

*Table 1c. Total number of fish tagged and released (Rel), recaptured and returned (Ret), and percent returned (%) for selected tagging experiments and release ages in NAFO Divisions 2J, 3K, and 3L.*

| Exp | Rel | Ret | % | Exp | Rel | Ret | % | Exp | Rel | Ret | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2006006 | 480 | 57 | 11.9 | 2008013 | 105 | 4 | 3.8 | 2012008 | 273 | 3 | 1.1 |
| 2006007 | 1281 | 119 | 9.3 | 2009002 | 1159 | 59 | 5.1 | 2012010 | 498 | 10 | 2.0 |
| 2006008 | 919 | 50 | 5.4 | 2009004 | 595 | 31 | 5.2 | 2012011 | 117 | 2 | 1.7 |
| 2006009 | 468 | 31 | 6.6 | 2009006 | 219 | 37 | 16.9 | 2013003 | 1039 | 19 | 1.8 |
| 2006010 | 254 | 25 | 9.8 | 2009008 | 460 | 15 | 3.3 | 2013004 | 794 | 21 | 2.6 |
| 2006011 | 298 | 24 | 8.1 | 2009009 | 99 | 2 | 2.0 | 2013008 | 291 | 2 | 0.7 |
| 2006012 | 634 | 31 | 4.9 | 2009010 | 526 | 25 | 4.8 | 2013011 | 60 | 0 | 0.0 |
| 2007001 | 1117 | 2 | 0.2 | 2010002 | 254 | 8 | 3.1 | 2014002 | 431 | 15 | 3.5 |
| 2007002 | 90 | 7 | 7.8 | 2010003 | 201 | 9 | 4.5 | 2014005 | 132 | 0 | 0.0 |
| 2007003 | 270 | 13 | 4.8 | 2010007 | 214 | 4 | 1.9 | 2014006 | 911 | 3 | 0.3 |
| 2007006 | 502 | 24 | 4.8 | 2010008 | 171 | 3 | 1.8 | 2014007 | 470 | 4 | 0.9 |
| 2007009 | 537 | 45 | 8.4 | 2010009 | 616 | 32 | 5.2 | 2014008 | 1034 | 9 | 0.9 |
| 2007015 | 120 | 3 | 2.5 | 2010010 | 122 | 4 | 3.3 | 2014009 | 89 | 0 | 0.0 |
| 2007016 | 973 | 55 | 5.7 | 2010013 | 228 | 8 | 3.5 | 2014010 | 336 | 1 | 0.3 |
| 2008001 | 2257 | 70 | 3.1 | 2011003 | 107 | 15 | 14.0 | 2014011 | 525 | 0 | 0.0 |
| 2008002 | 92 | 4 | 4.3 | 2011004 | 86 | 7 | 8.1 | 2014013 | 1071 | 0 | 0.0 |
| 2008003 | 609 | 21 | 3.4 | 2011005 | 97 | 5 | 5.2 | - | - | - | - |
| 2008007 | 530 | 37 | 7.0 | 2011006 | 527 | 8 | 1.5 | - | - | - | - |
| 2008008 | 313 | 10 | 3.2 | 2011007 | 540 | 12 | 2.2 | - | - | - | - |
| 2008009 | 444 | 42 | 9.5 | 2011009 | 251 | 14 | 5.6 | - | - | - | - |
| 2008010 | 185 | 13 | 7.0 | 2011010 | 268 | 16 | 6.0 | - | - | - | - |
| 2008011 | 369 | 26 | 7.0 | 2012003 | 264 | 10 | 3.8 | - | - | - | - |
| 2008012 | 422 | 26 | 6.2 | 2012006 | 318 | 7 | 2.2 | - | - | - | - |

*Table 2. Estimates of model parameters, stock size and mortality rates in 2014. Models are: 1) C15+: Updated formulation of Cadigan (2015); 2) NB: C15+ but with NB approach to tag-returns; 3) NB_LC: NB but with higher bounds on total catch weight; 4) NB_ACO: NB and hypothetical offshore acoustic survey. Tag VP indicates tagging standard deviation parameters, which are $\boldsymbol{\sigma_{fx}}$ for the C15+ model with Lognormal between experiment variation in F's, and the NB k over-dispersion parameters for the NB, NB_LC, and NB_ACO models. nll is the negative log-likelihood, and AIC is Akaike's Information Criterion.*

| Quantity | C15+ est | C15+ CV (%) | NB est | NB CV (%) | NB_LC est | NB_LC CV (%) | NB_ACO est | NB_ACO CV (%) |
|---|---|---|---|---|---|---|---|---|
| Index: $\sigma_{RV}$ | 0.398 | 6 | 0.393 | 7 | 0.416 | 8 | 0.395 | 7 |
| Index: $\sigma_{SN}$ | 0.411 | 7 | 0.410 | 7 | 0.392 | 7 | 0.414 | 7 |
| YE RW: $\sigma_{SN\_RW}$ | 0.199 | 25 | 0.190 | 26 | 0.221 | 24 | 0.198 | 25 |
| Age comps: $\sigma_P$ | 0.229 | 8 | 0.234 | 8 | 0.238 | 8 | 0.234 | 8 |
| tag VP -96 | 0.413 | 7 | 7.619 | 15 | 8.435 | 16 | 7.783 | 16 |
| tag VP 97+ | 0.653 | 4 | 2.381 | 8 | 2.330 | 8 | 2.408 | 8 |
| PE: $\sigma_\delta$ | 0.246 | 16 | 0.241 | 17 | 0.249 | 17 | 0.244 | 17 |
| $F\ RW$: $\sigma_F$ | 0.581 | 5 | 0.554 | 5 | 0.573 | 5 | 0.571 | 4 |
| SS: $\sigma_D$ | 0.700 | 18 | 0.711 | 19 | 0.678 | 22 | 0.688 | 18 |
| Rec: $\sigma_R$ | 0.410 | 22 | 0.395 | 23 | 0.380 | 23 | 0.402 | 22 |
| $PE: \varphi_{\delta,age}$ | 0.893 | 5 | 0.896 | 5 | 0.892 | 5 | 0.901 | 4 |
| $PE: \varphi_{\delta,yr}$ | 0.818 | 10 | 0.815 | 10 | 0.810 | 10 | 0.808 | 10 |
| $SS: \varphi_{D,yr}$ | 0.894 | 5 | 0.891 | 5 | 0.888 | 6 | 0.892 | 5 |
| $SS: \varphi_{D,age}$ | 0.864 | 6 | 0.869 | 6 | 0.886 | 6 | 0.872 | 6 |
| $F\ RW: \varphi_{F,age}$ | 0.791 | 6 | 0.796 | 7 | 0.821 | 6 | 0.812 | 6 |
| Blim (Kt) | 653 | 6 | 647 | 6 | 1129 | 10 | 697 | 6 |
| $SSB_{2014}$ (Kt) | 190 | 9 | 178 | 9 | 299 | 12 | 239 | 7 |
| $SSB_{2014}$/Blim | 0.292 | 10 | 0.276 | 10 | 0.265 | 10 | 0.344 | 9 |
| total $B_{2014}$ (Kt) | 268 | 9 | 248 | 9 | 416 | 12 | 330 | 8 |
| $q_{full}$ | 1.031 | 4 | 1.073 | 4 | 0.607 | 11 | 0.967 | 5 |
| $\bar{Z}_{2014}$ | 0.278 | 38 | 0.272 | 38 | 0.254 | 40 | 0.156 | 44 |
| $\bar{M}_{2014}$ | 0.259 | 41 | 0.251 | 41 | 0.234 | 43 | 0.139 | 49 |
| $\bar{F}_{4-6,2014}$ | 0.008 | 21 | 0.009 | 21 | 0.008 | 21 | 0.008 | 21 |
| $\bar{F}_{7-9,2014}$ | 0.040 | 17 | 0.042 | 16 | 0.041 | 17 | 0.035 | 16 |
| nll/AIC | 8520 | 17267 | 8508 | 17242 | 8522.462 | 17271 | 8532.462 | 17291 |

Notes: PE – process error; SS – Smith Sound; YE – year effects; RW – random walk

## APPENDIX II – TABLES - AGE SPECIFIC ESTIMATES

*Table A1. Northern cod stock size estimates (Est) and 95% confidence intervals (L,U) from the **C15+** NCAM.*

| Year | Biomass (3+; Kt) Est | Biomass (3+; Kt) L | Biomass (3+; Kt) U | SSB (Kt) Est | SSB (Kt) L | SSB (Kt) U | SSB/Blim (%) Est | SSB/Blim (%) L | SSB/Blim (%) U | Recruits (age 3 x10^6) Est | Recruits (age 3 x10^6) L | Recruits (age 3 x10^6) U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 1129 | 968 | 1317 | 522 | 453 | 602 | 80 | 70.5 | 90.7 | 676 | 514 | 891 |
| 1984 | 1354 | 1108 | 1654 | 582 | 480 | 707 | 89.3 | 76.1 | 104.7 | 977 | 682 | 1401 |
| 1985 | 1512 | 1281 | 1785 | 667 | 566 | 786 | 102.2 | 90.5 | 115.4 | 753 | 539 | 1051 |
| 1986 | 1551 | 1301 | 1847 | 646 | 543 | 769 | 99 | 87.3 | 112.4 | 375 | 272 | 518 |
| 1987 | 1544 | 1259 | 1895 | 715 | 576 | 887 | 109.5 | 93 | 129 | 368 | 254 | 534 |
| 1988 | 1278 | 1069 | 1528 | 704 | 582 | 852 | 107.9 | 92.8 | 125.6 | 471 | 338 | 658 |
| 1989 | 1250 | 1062 | 1473 | 731 | 611 | 875 | 112.1 | 95.8 | 131.2 | 699 | 501 | 974 |
| 1990 | 1352 | 1112 | 1643 | 654 | 527 | 812 | 100.2 | 81 | 124 | 867 | 556 | 1351 |
| 1991 | 1024 | 850 | 1235 | 413 | 334 | 511 | 63.3 | 50.1 | 79.8 | 359 | 235 | 549 |
| 1992 | 596 | 457 | 778 | 230 | 175 | 302 | 35.2 | 26.4 | 47 | 316 | 184 | 543 |
| 1993 | 152 | 111 | 208 | 63 | 43 | 94 | 9.7 | 6.5 | 14.6 | 86 | 50 | 147 |
| 1994 | 46 | 33 | 65 | 19 | 13 | 28 | 2.9 | 2 | 4.4 | 28 | 15 | 53 |
| 1995 | 23 | 18 | 29 | 10 | 8 | 13 | 1.6 | 1.2 | 2.1 | 17 | 12 | 24 |
| 1996 | 31 | 25 | 37 | 15 | 13 | 19 | 2.4 | 1.9 | 3 | 18 | 11 | 30 |
| 1997 | 37 | 32 | 42 | 19 | 17 | 22 | 2.9 | 2.5 | 3.5 | 21 | 14 | 33 |
| 1998 | 48 | 42 | 54 | 29 | 26 | 32 | 4.4 | 3.8 | 5.1 | 27 | 18 | 40 |
| 1999 | 53 | 49 | 58 | 35 | 32 | 37 | 5.3 | 4.7 | 6 | 26 | 18 | 37 |
| 2000 | 59 | 51 | 68 | 33 | 30 | 36 | 5 | 4.4 | 5.8 | 42 | 25 | 70 |
| 2001 | 49 | 43 | 56 | 25 | 23 | 28 | 3.8 | 3.3 | 4.4 | 34 | 22 | 54 |
| 2002 | 44 | 37 | 52 | 22 | 19 | 24 | 3.3 | 2.8 | 3.9 | 34 | 20 | 56 |
| 2003 | 45 | 37 | 54 | 23 | 20 | 26 | 3.5 | 2.9 | 4.1 | 37 | 23 | 59 |
| 2004 | 43 | 35 | 54 | 21 | 17 | 26 | 3.2 | 2.5 | 4.1 | 39 | 29 | 52 |
| 2005 | 69 | 57 | 83 | 26 | 22 | 31 | 4 | 3.2 | 4.9 | 69 | 51 | 93 |
| 2006 | 98 | 83 | 117 | 39 | 33 | 46 | 6 | 4.9 | 7.2 | 36 | 26 | 50 |
| 2007 | 127 | 106 | 151 | 73 | 61 | 87 | 11.2 | 9.2 | 13.6 | 45 | 32 | 65 |
| 2008 | 142 | 118 | 170 | 95 | 78 | 116 | 14.6 | 11.7 | 18.2 | 55 | 37 | 82 |
| 2009 | 128 | 106 | 154 | 80 | 66 | 97 | 12.3 | 10 | 15.2 | 50 | 32 | 76 |
| 2010 | 129 | 105 | 157 | 76 | 63 | 93 | 11.7 | 9.5 | 14.5 | 57 | 38 | 85 |
| 2011 | 124 | 104 | 147 | 74 | 62 | 89 | 11.4 | 9.3 | 14 | 50 | 36 | 70 |
| 2012 | 151 | 129 | 177 | 88 | 75 | 104 | 13.5 | 11.2 | 16.3 | 68 | 49 | 95 |
| 2013 | 200 | 170 | 234 | 129 | 110 | 152 | 19.8 | 16.5 | 23.8 | 43 | 30 | 62 |
| 2014 | 268 | 225 | 320 | 190 | 160 | 227 | 29.2 | 24 | 35.5 | 85 | 53 | 136 |

*Table A2. Northern cod mortality rate estimates (Est) and 95% confidence intervals (L,U) from the* ***C15+*** *NCAM.*

| Year | $\bar{F}_{4-6}$ Est | $\bar{F}_{4-6}$ L | $\bar{F}_{4-6}$ U | $\bar{F}_{7-9}$Est | $\bar{F}_{7-9}$L | $\bar{F}_{7-9}$U | $\bar{M}_{5+}$Est | $\bar{M}_{5+}$L | $\bar{M}_{5+}$U | $\bar{Z}_{5+}$Est | $\bar{Z}_{5+}$L | $\bar{Z}_{5+}$U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 0.116 | 0.086 | 0.155 | 0.366 | 0.291 | 0.459 | 0.200 | 0.200 | 0.200 | 0.451 | 0.403 | 0.504 |
| 1984 | 0.106 | 0.077 | 0.145 | 0.402 | 0.306 | 0.529 | 0.261 | 0.131 | 0.519 | 0.476 | 0.335 | 0.677 |
| 1985 | 0.132 | 0.105 | 0.166 | 0.474 | 0.389 | 0.578 | 0.242 | 0.126 | 0.463 | 0.527 | 0.393 | 0.707 |
| 1986 | 0.133 | 0.097 | 0.182 | 0.444 | 0.348 | 0.566 | 0.245 | 0.129 | 0.466 | 0.488 | 0.345 | 0.689 |
| 1987 | 0.150 | 0.120 | 0.189 | 0.453 | 0.368 | 0.557 | 0.418 | 0.240 | 0.728 | 0.660 | 0.471 | 0.924 |
| 1988 | 0.199 | 0.150 | 0.264 | 0.388 | 0.307 | 0.492 | 0.277 | 0.151 | 0.508 | 0.572 | 0.429 | 0.764 |
| 1989 | 0.133 | 0.098 | 0.180 | 0.418 | 0.322 | 0.542 | 0.243 | 0.130 | 0.454 | 0.545 | 0.404 | 0.735 |
| 1990 | 0.148 | 0.112 | 0.197 | 0.373 | 0.288 | 0.484 | 0.600 | 0.397 | 0.908 | 0.868 | 0.653 | 1.155 |
| 1991 | 0.252 | 0.195 | 0.327 | 0.652 | 0.509 | 0.835 | 0.843 | 0.602 | 1.181 | 1.259 | 0.979 | 1.618 |
| 1992 | 0.173 | 0.132 | 0.226 | 0.512 | 0.372 | 0.704 | 2.056 | 1.581 | 2.674 | 2.305 | 1.826 | 2.910 |
| 1993 | 0.149 | 0.102 | 0.216 | 0.358 | 0.213 | 0.603 | 2.417 | 1.881 | 3.105 | 2.628 | 2.095 | 3.296 |
| 1994 | 0.077 | 0.047 | 0.126 | 0.217 | 0.116 | 0.404 | 1.748 | 1.255 | 2.435 | 1.871 | 1.390 | 2.519 |
| 1995 | 0.027 | 0.021 | 0.034 | 0.108 | 0.073 | 0.158 | 0.377 | 0.198 | 0.719 | 0.418 | 0.236 | 0.742 |
| 1996 | 0.046 | 0.038 | 0.056 | 0.115 | 0.085 | 0.156 | 0.372 | 0.213 | 0.650 | 0.454 | 0.291 | 0.708 |
| 1997 | 0.018 | 0.013 | 0.026 | 0.065 | 0.046 | 0.091 | 0.286 | 0.187 | 0.439 | 0.324 | 0.221 | 0.474 |
| 1998 | 0.058 | 0.046 | 0.073 | 0.158 | 0.136 | 0.183 | 0.372 | 0.243 | 0.570 | 0.487 | 0.356 | 0.666 |
| 1999 | 0.083 | 0.066 | 0.103 | 0.305 | 0.274 | 0.340 | 0.435 | 0.316 | 0.598 | 0.639 | 0.515 | 0.792 |
| 2000 | 0.076 | 0.061 | 0.096 | 0.217 | 0.188 | 0.250 | 0.846 | 0.682 | 1.049 | 0.988 | 0.826 | 1.183 |
| 2001 | 0.146 | 0.117 | 0.183 | 0.310 | 0.260 | 0.370 | 0.646 | 0.492 | 0.850 | 0.887 | 0.731 | 1.077 |
| 2002 | 0.076 | 0.057 | 0.101 | 0.324 | 0.263 | 0.398 | 0.539 | 0.372 | 0.779 | 0.704 | 0.529 | 0.936 |
| 2003 | 0.011 | 0.008 | 0.015 | 0.110 | 0.088 | 0.137 | 0.800 | 0.523 | 1.221 | 0.845 | 0.567 | 1.260 |
| 2004 | 0.008 | 0.005 | 0.013 | 0.090 | 0.062 | 0.131 | 0.371 | 0.192 | 0.715 | 0.403 | 0.222 | 0.733 |
| 2005 | 0.010 | 0.007 | 0.016 | 0.076 | 0.053 | 0.110 | 0.353 | 0.191 | 0.655 | 0.386 | 0.219 | 0.678 |
| 2006 | 0.023 | 0.016 | 0.033 | 0.160 | 0.122 | 0.209 | 0.363 | 0.230 | 0.571 | 0.426 | 0.288 | 0.631 |
| 2007 | 0.021 | 0.015 | 0.029 | 0.093 | 0.071 | 0.122 | 0.468 | 0.286 | 0.764 | 0.503 | 0.318 | 0.795 |
| 2008 | 0.026 | 0.018 | 0.036 | 0.095 | 0.074 | 0.122 | 0.696 | 0.488 | 0.993 | 0.746 | 0.535 | 1.041 |
| 2009 | 0.014 | 0.009 | 0.020 | 0.072 | 0.055 | 0.094 | 0.558 | 0.376 | 0.828 | 0.599 | 0.414 | 0.865 |
| 2010 | 0.010 | 0.006 | 0.015 | 0.057 | 0.043 | 0.077 | 0.607 | 0.381 | 0.968 | 0.637 | 0.410 | 0.991 |
| 2011 | 0.012 | 0.008 | 0.017 | 0.078 | 0.058 | 0.104 | 0.365 | 0.211 | 0.634 | 0.407 | 0.248 | 0.666 |
| 2012 | 0.007 | 0.005 | 0.011 | 0.056 | 0.042 | 0.076 | 0.220 | 0.117 | 0.412 | 0.246 | 0.140 | 0.432 |
| 2013 | 0.008 | 0.006 | 0.012 | 0.045 | 0.033 | 0.060 | 0.211 | 0.109 | 0.406 | 0.234 | 0.129 | 0.424 |
| 2014 | 0.008 | 0.005 | 0.012 | 0.040 | 0.029 | 0.055 | 0.259 | 0.116 | 0.576 | 0.278 | 0.131 | 0.590 |

*Table A3. Northern cod abundance-at-age estimates (millions) from the **C15+** NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 1611.6 | 676.5 | 405.0 | 282.7 | 83.2 | 50.9 | 59.6 | 34.2 | 17.5 | 3.5 | 1.2 | 0.5 | 0.4 |
| 1984 | 1337.5 | 977.5 | 500.1 | 319.1 | 193.1 | 52.2 | 30.3 | 34.2 | 17.7 | 9.1 | 2.0 | 0.8 | 0.3 |
| 1985 | 657.7 | 753.1 | 676.7 | 379.1 | 218.8 | 115.1 | 27.1 | 15.8 | 16.5 | 9.3 | 4.6 | 1.1 | 0.5 |
| 1986 | 646.0 | 375.4 | 533.4 | 523.8 | 247.8 | 125.8 | 55.1 | 13.4 | 8.0 | 7.9 | 4.3 | 2.0 | 0.6 |
| 1987 | 1007.5 | 368.2 | 267.5 | 418.4 | 359.2 | 138.7 | 65.1 | 26.3 | 6.9 | 3.6 | 3.9 | 2.0 | 1.0 |
| 1988 | 1143.0 | 471.1 | 222.4 | 190.4 | 261.7 | 164.6 | 58.2 | 27.5 | 10.5 | 2.8 | 1.7 | 1.5 | 0.9 |
| 1989 | 1317.3 | 698.7 | 335.2 | 167.0 | 128.5 | 141.3 | 85.3 | 28.3 | 13.3 | 5.6 | 1.6 | 0.9 | 0.8 |
| 1990 | 913.2 | 867.0 | 521.3 | 264.0 | 119.2 | 73.9 | 71.9 | 41.6 | 14.5 | 6.3 | 2.9 | 0.8 | 0.5 |
| 1991 | 911.3 | 358.7 | 436.0 | 315.5 | 135.4 | 47.3 | 26.8 | 20.9 | 11.9 | 4.4 | 2.0 | 0.8 | 0.3 |
| 1992 | 527.8 | 315.9 | 154.3 | 224.3 | 113.5 | 31.5 | 8.3 | 3.0 | 2.1 | 1.4 | 0.5 | 0.2 | 0.1 |
| 1993 | 112.0 | 86.2 | 64.1 | 41.3 | 28.7 | 7.7 | 1.2 | 0.4 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 |
| 1994 | 77.5 | 28.0 | 22.5 | 17.8 | 3.8 | 1.5 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1995 | 35.2 | 17.1 | 7.3 | 8.3 | 2.8 | 0.5 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1996 | 59.0 | 18.3 | 11.2 | 5.7 | 5.6 | 1.8 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1997 | 57.6 | 21.4 | 9.3 | 8.3 | 3.6 | 3.6 | 1.1 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1998 | 54.6 | 26.7 | 12.3 | 7.1 | 5.9 | 2.7 | 2.6 | 0.8 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1999 | 73.6 | 26.0 | 14.9 | 8.6 | 4.0 | 3.7 | 1.7 | 1.8 | 0.5 | 0.1 | 0.0 | 0.0 | 0.0 |
| 2000 | 86.9 | 42.2 | 16.0 | 10.5 | 4.4 | 1.9 | 1.9 | 1.0 | 1.1 | 0.3 | 0.1 | 0.0 | 0.0 |
| 2001 | 81.4 | 34.0 | 14.9 | 7.6 | 3.0 | 1.5 | 0.8 | 1.1 | 0.6 | 0.7 | 0.2 | 0.0 | 0.0 |
| 2002 | 78.8 | 33.6 | 13.3 | 7.0 | 2.6 | 1.2 | 0.7 | 0.5 | 0.6 | 0.4 | 0.4 | 0.1 | 0.0 |
| 2003 | 74.4 | 37.2 | 14.6 | 7.1 | 3.2 | 1.3 | 0.6 | 0.4 | 0.3 | 0.4 | 0.2 | 0.3 | 0.1 |
| 2004 | 87.0 | 38.8 | 17.1 | 7.0 | 2.6 | 1.4 | 0.7 | 0.3 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 |
| 2005 | 44.0 | 68.7 | 30.7 | 13.5 | 4.7 | 1.7 | 0.9 | 0.5 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 |
| 2006 | 56.2 | 35.9 | 57.3 | 25.7 | 9.5 | 2.9 | 1.0 | 0.6 | 0.3 | 0.2 | 0.1 | 0.1 | 0.1 |
| 2007 | 73.3 | 45.2 | 29.6 | 47.3 | 18.3 | 5.3 | 1.5 | 0.6 | 0.4 | 0.2 | 0.1 | 0.1 | 0.0 |
| 2008 | 76.9 | 54.8 | 34.6 | 22.5 | 30.1 | 10.2 | 2.8 | 0.8 | 0.3 | 0.2 | 0.1 | 0.1 | 0.0 |
| 2009 | 90.1 | 49.7 | 35.6 | 21.6 | 11.3 | 13.3 | 5.1 | 1.4 | 0.4 | 0.2 | 0.1 | 0.1 | 0.0 |
| 2010 | 84.1 | 56.6 | 31.3 | 21.6 | 11.5 | 6.0 | 7.8 | 2.8 | 0.8 | 0.2 | 0.1 | 0.1 | 0.0 |
| 2011 | 92.2 | 49.9 | 33.5 | 17.1 | 10.3 | 6.3 | 3.7 | 4.4 | 1.6 | 0.4 | 0.1 | 0.1 | 0.0 |
| 2012 | 52.4 | 68.0 | 37.8 | 24.7 | 11.5 | 6.9 | 4.3 | 2.4 | 2.8 | 1.0 | 0.3 | 0.1 | 0.0 |
| 2013 | 101.1 | 42.9 | 57.6 | 32.1 | 19.9 | 9.0 | 5.3 | 3.1 | 1.7 | 2.1 | 0.7 | 0.2 | 0.1 |
| 2014 | 164.1 | 85.3 | 37.3 | 50.2 | 26.6 | 15.8 | 6.9 | 3.8 | 2.2 | 1.2 | 1.5 | 0.5 | 0.1 |

*Table A4. Northern cod biomass-at-age estimates (Kt) from the **C15+** NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 122.9 | 145.2 | 179.3 | 220.3 | 104.8 | 96.0 | 152.3 | 117.1 | 76.1 | 20.5 | 8.9 | 4.3 | 4.5 |
| 1984 | 102.7 | 208.1 | 222.9 | 247.3 | 236.0 | 95.6 | 78.7 | 115.1 | 77.2 | 48.9 | 14.3 | 6.7 | 3.3 |
| 1985 | 51.2 | 161.6 | 299.0 | 295.7 | 265.4 | 204.0 | 68.2 | 54.1 | 70.3 | 50.1 | 29.9 | 9.3 | 4.6 |
| 1986 | 50.3 | 82.0 | 237.9 | 404.8 | 302.6 | 221.0 | 133.5 | 44.4 | 34.8 | 41.3 | 28.0 | 14.8 | 5.5 |
| 1987 | 78.8 | 80.6 | 121.8 | 326.8 | 434.4 | 245.1 | 156.2 | 83.3 | 28.8 | 19.2 | 24.3 | 15.3 | 8.7 |
| 1988 | 89.2 | 103.6 | 101.6 | 152.2 | 320.1 | 288.0 | 140.6 | 86.2 | 42.1 | 14.2 | 10.6 | 11.2 | 7.6 |
| 1989 | 103.8 | 153.6 | 154.1 | 134.1 | 161.3 | 250.2 | 203.8 | 89.1 | 52.6 | 27.7 | 9.6 | 7.1 | 7.2 |
| 1990 | 74.2 | 193.7 | 239.8 | 213.6 | 150.5 | 134.7 | 174.1 | 129.7 | 57.5 | 30.6 | 17.1 | 5.8 | 4.6 |
| 1991 | 77.9 | 83.7 | 205.0 | 255.8 | 172.4 | 86.7 | 66.9 | 66.0 | 46.9 | 21.5 | 11.7 | 5.7 | 2.2 |
| 1992 | 45.6 | 79.1 | 76.7 | 186.9 | 145.0 | 58.3 | 20.8 | 9.9 | 8.3 | 6.6 | 2.9 | 1.4 | 0.5 |
| 1993 | 9.5 | 21.9 | 34.8 | 36.7 | 37.9 | 14.3 | 3.2 | 1.2 | 0.6 | 0.6 | 0.4 | 0.2 | 0.1 |
| 1994 | 6.6 | 6.9 | 12.4 | 17.5 | 5.4 | 2.9 | 0.8 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 1995 | 3.0 | 4.2 | 3.8 | 8.3 | 4.4 | 1.1 | 0.6 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1996 | 5.0 | 4.4 | 5.8 | 5.4 | 9.0 | 4.2 | 0.9 | 0.5 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1997 | 5.0 | 5.2 | 4.8 | 7.7 | 5.4 | 8.7 | 3.7 | 0.7 | 0.4 | 0.1 | 0.1 | 0.0 | 0.0 |
| 1998 | 4.9 | 6.7 | 6.3 | 6.5 | 8.8 | 6.0 | 8.9 | 3.5 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 |
| 1999 | 6.7 | 6.7 | 7.8 | 7.7 | 5.7 | 8.1 | 5.3 | 8.1 | 3.0 | 0.6 | 0.3 | 0.1 | 0.0 |
| 2000 | 8.0 | 11.0 | 8.7 | 9.9 | 6.3 | 4.1 | 5.8 | 4.1 | 6.5 | 2.4 | 0.4 | 0.2 | 0.1 |
| 2001 | 7.4 | 9.0 | 8.2 | 7.4 | 4.5 | 3.1 | 2.4 | 4.3 | 3.0 | 4.9 | 1.8 | 0.3 | 0.1 |
| 2002 | 7.1 | 8.7 | 7.5 | 6.9 | 4.0 | 2.5 | 1.8 | 1.8 | 3.3 | 2.4 | 3.6 | 1.3 | 0.2 |
| 2003 | 6.9 | 9.5 | 8.0 | 7.2 | 5.1 | 2.9 | 1.6 | 1.3 | 1.2 | 2.5 | 1.8 | 2.8 | 1.0 |
| 2004 | 8.1 | 10.2 | 9.2 | 6.8 | 4.2 | 3.3 | 2.1 | 1.2 | 0.9 | 0.8 | 1.6 | 1.2 | 1.8 |
| 2005 | 4.1 | 18.2 | 17.0 | 12.7 | 7.2 | 4.0 | 2.9 | 2.0 | 1.1 | 0.8 | 0.7 | 1.4 | 1.0 |
| 2006 | 5.2 | 9.5 | 32.0 | 25.1 | 14.2 | 6.5 | 3.4 | 2.6 | 1.7 | 1.0 | 0.7 | 0.6 | 1.2 |
| 2007 | 6.8 | 11.9 | 16.4 | 46.8 | 28.1 | 11.6 | 4.6 | 2.4 | 1.9 | 1.3 | 0.7 | 0.5 | 0.4 |
| 2008 | 7.3 | 14.4 | 19.2 | 22.0 | 46.9 | 22.8 | 8.3 | 3.3 | 1.7 | 1.4 | 0.9 | 0.5 | 0.3 |
| 2009 | 8.8 | 13.5 | 19.8 | 21.1 | 17.4 | 30.2 | 15.6 | 5.4 | 2.1 | 1.1 | 0.8 | 0.6 | 0.3 |
| 2010 | 8.4 | 16.0 | 17.9 | 21.2 | 17.8 | 13.6 | 24.4 | 11.1 | 3.7 | 1.4 | 0.7 | 0.6 | 0.4 |
| 2011 | 9.4 | 14.4 | 20.1 | 17.4 | 15.9 | 14.2 | 11.4 | 18.0 | 7.9 | 2.5 | 0.9 | 0.5 | 0.4 |
| 2012 | 5.3 | 20.4 | 23.4 | 26.6 | 18.5 | 15.6 | 13.3 | 9.6 | 14.7 | 6.3 | 2.0 | 0.7 | 0.4 |
| 2013 | 10.2 | 12.6 | 37.2 | 35.6 | 34.1 | 21.2 | 16.5 | 12.6 | 8.8 | 13.3 | 5.5 | 1.7 | 0.7 |
| 2014 | 16.4 | 25.0 | 23.4 | 58.7 | 47.2 | 39.7 | 22.4 | 15.5 | 11.3 | 7.7 | 11.4 | 4.6 | 1.4 |

*Table A5. Northern cod mature biomass-at-age estimates (Kt) from the **C15+** NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 0.0 | 0.7 | 3.3 | 13.0 | 41.7 | 83.5 | 149.2 | 116.3 | 76.1 | 20.5 | 8.9 | 4.3 | 4.5 |
| 1984 | 0.0 | 0.1 | 5.4 | 35.0 | 113.4 | 86.6 | 77.1 | 114.7 | 77.1 | 48.9 | 14.3 | 6.7 | 3.3 |
| 1985 | 0.0 | 0.0 | 1.4 | 32.9 | 156.6 | 190.1 | 67.7 | 54.0 | 70.3 | 50.1 | 29.9 | 9.3 | 4.6 |
| 1986 | 0.0 | 0.1 | 0.6 | 21.6 | 117.6 | 204.7 | 132.9 | 44.3 | 34.8 | 41.3 | 28.0 | 14.8 | 5.5 |
| 1987 | 0.0 | 0.1 | 1.7 | 12.9 | 178.7 | 187.0 | 154.8 | 83.2 | 28.8 | 19.2 | 24.3 | 15.3 | 8.7 |
| 1988 | 0.0 | 0.2 | 1.3 | 18.6 | 121.6 | 258.2 | 132.5 | 86.1 | 42.1 | 14.2 | 10.6 | 11.2 | 7.6 |
| 1989 | 0.0 | 0.3 | 2.3 | 15.4 | 93.5 | 225.6 | 202.0 | 88.0 | 52.6 | 27.7 | 9.6 | 7.1 | 7.2 |
| 1990 | 0.0 | 0.2 | 4.0 | 20.9 | 85.6 | 125.5 | 172.8 | 129.6 | 57.3 | 30.6 | 17.1 | 5.8 | 4.6 |
| 1991 | 0.0 | 0.0 | 3.7 | 33.3 | 74.8 | 80.7 | 66.4 | 66.0 | 46.9 | 21.5 | 11.7 | 5.7 | 2.2 |
| 1992 | 0.1 | 0.1 | 1.0 | 46.7 | 82.3 | 49.3 | 20.6 | 9.9 | 8.3 | 6.6 | 2.9 | 1.4 | 0.5 |
| 1993 | 0.1 | 0.2 | 1.3 | 10.1 | 32.6 | 13.1 | 3.1 | 1.2 | 0.6 | 0.6 | 0.4 | 0.2 | 0.1 |
| 1994 | 0.0 | 0.2 | 0.9 | 9.0 | 5.0 | 2.8 | 0.8 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 1995 | 0.0 | 0.0 | 0.4 | 3.4 | 4.3 | 1.1 | 0.6 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1996 | 0.0 | 0.0 | 0.2 | 1.5 | 7.7 | 4.2 | 0.9 | 0.5 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1997 | 0.0 | 0.0 | 0.1 | 2.3 | 3.2 | 8.5 | 3.7 | 0.7 | 0.4 | 0.1 | 0.1 | 0.0 | 0.0 |
| 1998 | 0.0 | 0.2 | 0.5 | 2.0 | 7.3 | 5.0 | 8.9 | 3.5 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 |
| 1999 | 0.0 | 0.1 | 0.9 | 3.6 | 5.0 | 8.0 | 5.1 | 8.1 | 3.0 | 0.6 | 0.3 | 0.1 | 0.0 |
| 2000 | 0.0 | 0.0 | 0.6 | 3.2 | 5.6 | 4.0 | 5.8 | 4.0 | 6.5 | 2.4 | 0.4 | 0.2 | 0.1 |
| 2001 | 0.0 | 0.0 | 0.3 | 2.0 | 2.9 | 3.1 | 2.4 | 4.3 | 3.0 | 4.9 | 1.8 | 0.3 | 0.1 |
| 2002 | 0.0 | 0.1 | 0.2 | 2.2 | 2.5 | 2.2 | 1.8 | 1.8 | 3.3 | 2.4 | 3.6 | 1.3 | 0.2 |
| 2003 | 0.0 | 0.2 | 0.6 | 2.7 | 4.3 | 2.6 | 1.6 | 1.3 | 1.2 | 2.5 | 1.8 | 2.8 | 1.0 |
| 2004 | 0.0 | 0.1 | 1.0 | 2.9 | 3.9 | 3.2 | 2.1 | 1.2 | 0.9 | 0.8 | 1.6 | 1.2 | 1.8 |
| 2005 | 0.0 | 0.1 | 1.0 | 4.8 | 6.2 | 4.0 | 2.9 | 2.0 | 1.1 | 0.8 | 0.7 | 1.4 | 1.0 |
| 2006 | 0.0 | 0.2 | 2.8 | 7.9 | 10.6 | 6.4 | 3.4 | 2.6 | 1.7 | 1.0 | 0.7 | 0.6 | 1.2 |
| 2007 | 0.0 | 0.3 | 1.9 | 26.2 | 22.0 | 10.8 | 4.6 | 2.4 | 1.9 | 1.3 | 0.7 | 0.5 | 0.4 |
| 2008 | 0.0 | 0.1 | 2.1 | 10.7 | 44.2 | 22.0 | 8.2 | 3.3 | 1.7 | 1.4 | 0.9 | 0.5 | 0.3 |
| 2009 | 0.0 | 0.2 | 0.9 | 8.2 | 15.1 | 30.1 | 15.5 | 5.4 | 2.1 | 1.1 | 0.8 | 0.6 | 0.3 |
| 2010 | 0.0 | 0.2 | 1.4 | 5.7 | 13.7 | 13.3 | 24.4 | 11.1 | 3.7 | 1.4 | 0.7 | 0.6 | 0.4 |
| 2011 | 0.1 | 0.2 | 1.7 | 5.5 | 11.8 | 13.4 | 11.4 | 18.0 | 7.9 | 2.5 | 0.9 | 0.5 | 0.4 |
| 2012 | 0.0 | 0.7 | 2.1 | 10.7 | 13.2 | 14.9 | 13.1 | 9.5 | 14.7 | 6.3 | 2.0 | 0.7 | 0.4 |
| 2013 | 0.0 | 0.3 | 7.0 | 15.2 | 28.3 | 19.8 | 16.4 | 12.5 | 8.8 | 13.3 | 5.5 | 1.7 | 0.7 |
| 2014 | 0.1 | 0.5 | 2.9 | 34.4 | 40.0 | 38.6 | 22.1 | 15.4 | 11.3 | 7.7 | 11.4 | 4.6 | 1.4 |

*Table A6. Northern cod F-at-age estimates from the **C15+** NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 0.00 | 0.00 | 0.04 | 0.18 | 0.27 | 0.32 | 0.35 | 0.46 | 0.45 | 0.35 | 0.24 | 0.22 | 0.13 |
| 1984 | 0.00 | 0.00 | 0.04 | 0.13 | 0.24 | 0.38 | 0.38 | 0.46 | 0.37 | 0.40 | 0.33 | 0.25 | 0.18 |
| 1985 | 0.00 | 0.00 | 0.04 | 0.20 | 0.29 | 0.48 | 0.48 | 0.45 | 0.51 | 0.54 | 0.64 | 0.43 | 0.32 |
| 1986 | 0.00 | 0.00 | 0.04 | 0.15 | 0.29 | 0.40 | 0.54 | 0.47 | 0.60 | 0.51 | 0.56 | 0.47 | 0.28 |
| 1987 | 0.00 | 0.01 | 0.05 | 0.12 | 0.25 | 0.39 | 0.53 | 0.58 | 0.58 | 0.44 | 0.60 | 0.51 | 0.36 |
| 1988 | 0.00 | 0.02 | 0.10 | 0.18 | 0.30 | 0.34 | 0.48 | 0.48 | 0.38 | 0.33 | 0.32 | 0.34 | 0.32 |
| 1989 | 0.00 | 0.01 | 0.07 | 0.14 | 0.28 | 0.40 | 0.46 | 0.41 | 0.48 | 0.40 | 0.41 | 0.30 | 0.25 |
| 1990 | 0.00 | 0.02 | 0.10 | 0.19 | 0.26 | 0.30 | 0.42 | 0.43 | 0.37 | 0.33 | 0.44 | 0.30 | 0.32 |
| 1991 | 0.00 | 0.04 | 0.14 | 0.32 | 0.47 | 0.54 | 0.71 | 0.83 | 0.69 | 0.70 | 0.82 | 1.03 | 1.24 |
| 1992 | 0.00 | 0.01 | 0.07 | 0.17 | 0.32 | 0.49 | 0.61 | 0.52 | 0.38 | 0.44 | 0.37 | 0.61 | 1.12 |
| 1993 | 0.00 | 0.01 | 0.10 | 0.18 | 0.22 | 0.35 | 0.47 | 0.22 | 0.05 | 0.05 | 0.07 | 0.17 | 0.52 |
| 1994 | 0.00 | 0.01 | 0.04 | 0.10 | 0.17 | 0.21 | 0.28 | 0.11 | 0.05 | 0.08 | 0.13 | 0.26 | 0.76 |
| 1995 | 0.00 | 0.00 | 0.01 | 0.03 | 0.06 | 0.11 | 0.12 | 0.09 | 0.07 | 0.11 | 0.22 | 0.43 | 1.01 |
| 1996 | 0.00 | 0.00 | 0.02 | 0.06 | 0.09 | 0.11 | 0.13 | 0.11 | 0.10 | 0.08 | 0.18 | 0.40 | 1.02 |
| 1997 | 0.00 | 0.00 | 0.01 | 0.02 | 0.04 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.11 | 0.30 | 0.98 |
| 1998 | 0.00 | 0.00 | 0.02 | 0.07 | 0.12 | 0.17 | 0.14 | 0.17 | 0.16 | 0.16 | 0.22 | 0.30 | 0.73 |
| 1999 | 0.00 | 0.00 | 0.02 | 0.10 | 0.26 | 0.34 | 0.30 | 0.23 | 0.21 | 0.27 | 0.22 | 0.18 | 0.41 |
| 2000 | 0.00 | 0.01 | 0.03 | 0.10 | 0.18 | 0.24 | 0.21 | 0.19 | 0.14 | 0.11 | 0.09 | 0.10 | 0.14 |
| 2001 | 0.00 | 0.01 | 0.09 | 0.19 | 0.32 | 0.39 | 0.28 | 0.22 | 0.16 | 0.20 | 0.19 | 0.12 | 0.10 |
| 2002 | 0.00 | 0.00 | 0.03 | 0.10 | 0.23 | 0.35 | 0.30 | 0.29 | 0.18 | 0.15 | 0.11 | 0.09 | 0.10 |
| 2003 | 0.00 | 0.00 | 0.00 | 0.01 | 0.05 | 0.09 | 0.12 | 0.16 | 0.14 | 0.17 | 0.15 | 0.13 | 0.11 |
| 2004 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.09 | 0.09 | 0.08 | 0.06 | 0.05 | 0.04 | 0.04 | 0.02 |
| 2005 | 0.00 | 0.00 | 0.00 | 0.01 | 0.06 | 0.08 | 0.08 | 0.05 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| 2006 | 0.00 | 0.00 | 0.01 | 0.03 | 0.11 | 0.16 | 0.18 | 0.12 | 0.11 | 0.08 | 0.05 | 0.06 | 0.07 |
| 2007 | 0.00 | 0.00 | 0.00 | 0.02 | 0.06 | 0.09 | 0.11 | 0.08 | 0.07 | 0.06 | 0.04 | 0.04 | 0.06 |
| 2008 | 0.00 | 0.00 | 0.01 | 0.02 | 0.05 | 0.09 | 0.12 | 0.12 | 0.10 | 0.08 | 0.05 | 0.04 | 0.05 |
| 2009 | 0.00 | 0.00 | 0.01 | 0.01 | 0.04 | 0.06 | 0.09 | 0.10 | 0.08 | 0.08 | 0.06 | 0.06 | 0.05 |
| 2010 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 | 0.04 | 0.04 | 0.04 |
| 2011 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.08 | 0.08 | 0.07 | 0.06 | 0.06 | 0.03 | 0.02 | 0.03 |
| 2012 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.05 | 0.07 | 0.05 | 0.05 | 0.05 | 0.04 | 0.02 | 0.02 |
| 2013 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.04 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.04 | 0.01 |
| 2014 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.04 | 0.03 | 0.01 |

*Table A7. Northern cod M-at-age estimates from the* ***C15+*** *NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
|---|---|---|---|---|---|---|---|
| 1983 | 0.50 | 0.30 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| 1984 | 0.57 | 0.37 | 0.24 | 0.25 | 0.27 | 0.27 | 0.27 |
| 1985 | 0.56 | 0.34 | 0.21 | 0.23 | 0.26 | 0.26 | 0.23 |
| 1986 | 0.56 | 0.33 | 0.20 | 0.23 | 0.30 | 0.26 | 0.20 |
| 1987 | 0.76 | 0.49 | 0.29 | 0.35 | 0.53 | 0.47 | 0.33 |
| 1988 | 0.49 | 0.32 | 0.19 | 0.21 | 0.32 | 0.32 | 0.25 |
| 1989 | 0.42 | 0.28 | 0.17 | 0.19 | 0.27 | 0.28 | 0.26 |
| 1990 | 0.93 | 0.67 | 0.40 | 0.47 | 0.66 | 0.72 | 0.82 |
| 1991 | 1.06 | 0.81 | 0.53 | 0.70 | 0.99 | 1.21 | 1.47 |
| 1992 | 1.81 | 1.58 | 1.25 | 1.88 | 2.37 | 2.75 | 2.51 |
| 1993 | 1.39 | 1.33 | 1.18 | 2.20 | 2.75 | 2.88 | 2.19 |
| 1994 | 1.51 | 1.34 | 0.96 | 1.76 | 1.79 | 1.70 | 1.26 |
| 1995 | 0.66 | 0.42 | 0.24 | 0.37 | 0.38 | 0.41 | 0.39 |
| 1996 | 1.01 | 0.67 | 0.28 | 0.40 | 0.34 | 0.37 | 0.41 |
| 1997 | 0.77 | 0.55 | 0.26 | 0.32 | 0.26 | 0.25 | 0.27 |
| 1998 | 0.74 | 0.58 | 0.35 | 0.51 | 0.34 | 0.28 | 0.24 |
| 1999 | 0.56 | 0.48 | 0.32 | 0.56 | 0.47 | 0.33 | 0.24 |
| 2000 | 0.94 | 1.03 | 0.71 | 1.15 | 0.89 | 0.63 | 0.36 |
| 2001 | 0.89 | 0.93 | 0.67 | 0.89 | 0.64 | 0.46 | 0.29 |
| 2002 | 0.75 | 0.83 | 0.59 | 0.67 | 0.48 | 0.39 | 0.32 |
| 2003 | 0.65 | 0.78 | 0.73 | 0.99 | 0.77 | 0.54 | 0.44 |
| 2004 | 0.24 | 0.23 | 0.24 | 0.39 | 0.40 | 0.35 | 0.26 |
| 2005 | 0.20 | 0.18 | 0.18 | 0.33 | 0.42 | 0.41 | 0.31 |
| 2006 | 0.22 | 0.19 | 0.19 | 0.31 | 0.46 | 0.51 | 0.43 |
| 2007 | 0.29 | 0.27 | 0.27 | 0.44 | 0.53 | 0.56 | 0.48 |
| 2008 | 0.44 | 0.43 | 0.47 | 0.67 | 0.76 | 0.61 | 0.58 |
| 2009 | 0.47 | 0.46 | 0.50 | 0.61 | 0.59 | 0.47 | 0.52 |
| 2010 | 0.52 | 0.52 | 0.60 | 0.73 | 0.58 | 0.44 | 0.51 |
| 2011 | 0.30 | 0.28 | 0.30 | 0.39 | 0.36 | 0.30 | 0.37 |
| 2012 | 0.20 | 0.17 | 0.16 | 0.21 | 0.22 | 0.21 | 0.26 |
| 2013 | 0.17 | 0.14 | 0.13 | 0.18 | 0.21 | 0.22 | 0.29 |
| 2014 | 0.19 | 0.15 | 0.15 | 0.20 | 0.26 | 0.30 | 0.41 |

*Table A8. Northern cod Z-at-age estimates from the **C15+** NCAM.*

| Year\Age | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 0.50 | 0.30 | 0.24 | 0.38 | 0.47 | 0.52 | 0.55 | 0.66 | 0.65 | 0.55 | 0.44 | 0.42 | 0.33 |
| 1984 | 0.57 | 0.37 | 0.28 | 0.38 | 0.52 | 0.65 | 0.65 | 0.73 | 0.64 | 0.68 | 0.60 | 0.52 | 0.46 |
| 1985 | 0.56 | 0.34 | 0.26 | 0.43 | 0.55 | 0.74 | 0.70 | 0.68 | 0.74 | 0.77 | 0.86 | 0.66 | 0.54 |
| 1986 | 0.56 | 0.34 | 0.24 | 0.38 | 0.58 | 0.66 | 0.74 | 0.67 | 0.80 | 0.71 | 0.76 | 0.67 | 0.49 |
| 1987 | 0.76 | 0.50 | 0.34 | 0.47 | 0.78 | 0.87 | 0.86 | 0.92 | 0.91 | 0.78 | 0.94 | 0.84 | 0.69 |
| 1988 | 0.49 | 0.34 | 0.29 | 0.39 | 0.62 | 0.66 | 0.72 | 0.73 | 0.62 | 0.57 | 0.57 | 0.59 | 0.56 |
| 1989 | 0.42 | 0.29 | 0.24 | 0.34 | 0.55 | 0.68 | 0.72 | 0.67 | 0.74 | 0.66 | 0.68 | 0.57 | 0.51 |
| 1990 | 0.93 | 0.69 | 0.50 | 0.67 | 0.92 | 1.01 | 1.24 | 1.25 | 1.19 | 1.15 | 1.26 | 1.12 | 1.14 |
| 1991 | 1.06 | 0.84 | 0.66 | 1.02 | 1.46 | 1.74 | 2.18 | 2.30 | 2.16 | 2.17 | 2.29 | 2.50 | 2.70 |
| 1992 | 1.81 | 1.59 | 1.32 | 2.05 | 2.69 | 3.23 | 3.12 | 3.03 | 2.89 | 2.95 | 2.88 | 3.12 | 3.63 |
| 1993 | 1.39 | 1.34 | 1.28 | 2.38 | 2.97 | 3.23 | 2.67 | 2.41 | 2.25 | 2.25 | 2.27 | 2.36 | 2.72 |
| 1994 | 1.51 | 1.35 | 1.00 | 1.86 | 1.96 | 1.91 | 1.54 | 1.38 | 1.32 | 1.35 | 1.40 | 1.52 | 2.02 |
| 1995 | 0.66 | 0.42 | 0.25 | 0.40 | 0.44 | 0.51 | 0.51 | 0.48 | 0.46 | 0.50 | 0.61 | 0.82 | 1.40 |
| 1996 | 1.01 | 0.68 | 0.30 | 0.46 | 0.43 | 0.48 | 0.53 | 0.52 | 0.50 | 0.49 | 0.58 | 0.80 | 1.42 |
| 1997 | 0.77 | 0.55 | 0.27 | 0.34 | 0.30 | 0.31 | 0.34 | 0.33 | 0.32 | 0.32 | 0.39 | 0.58 | 1.26 |
| 1998 | 0.74 | 0.58 | 0.37 | 0.58 | 0.46 | 0.45 | 0.38 | 0.41 | 0.40 | 0.40 | 0.46 | 0.54 | 0.97 |
| 1999 | 0.56 | 0.48 | 0.35 | 0.66 | 0.72 | 0.67 | 0.55 | 0.48 | 0.45 | 0.51 | 0.46 | 0.42 | 0.66 |
| 2000 | 0.94 | 1.04 | 0.74 | 1.25 | 1.07 | 0.87 | 0.57 | 0.55 | 0.50 | 0.48 | 0.46 | 0.47 | 0.50 |
| 2001 | 0.89 | 0.94 | 0.76 | 1.09 | 0.97 | 0.85 | 0.57 | 0.52 | 0.45 | 0.49 | 0.48 | 0.42 | 0.40 |
| 2002 | 0.75 | 0.83 | 0.62 | 0.78 | 0.71 | 0.74 | 0.62 | 0.61 | 0.50 | 0.47 | 0.43 | 0.40 | 0.42 |
| 2003 | 0.65 | 0.78 | 0.74 | 1.00 | 0.82 | 0.63 | 0.57 | 0.60 | 0.58 | 0.62 | 0.59 | 0.57 | 0.55 |
| 2004 | 0.24 | 0.23 | 0.24 | 0.40 | 0.44 | 0.44 | 0.35 | 0.34 | 0.32 | 0.31 | 0.30 | 0.30 | 0.29 |
| 2005 | 0.20 | 0.18 | 0.18 | 0.35 | 0.48 | 0.49 | 0.39 | 0.36 | 0.35 | 0.35 | 0.34 | 0.34 | 0.34 |
| 2006 | 0.22 | 0.19 | 0.19 | 0.34 | 0.58 | 0.67 | 0.61 | 0.54 | 0.53 | 0.51 | 0.48 | 0.49 | 0.50 |
| 2007 | 0.29 | 0.27 | 0.28 | 0.45 | 0.59 | 0.65 | 0.60 | 0.57 | 0.56 | 0.54 | 0.52 | 0.52 | 0.54 |
| 2008 | 0.44 | 0.43 | 0.47 | 0.69 | 0.82 | 0.70 | 0.70 | 0.70 | 0.69 | 0.66 | 0.63 | 0.62 | 0.63 |
| 2009 | 0.47 | 0.46 | 0.50 | 0.63 | 0.62 | 0.53 | 0.61 | 0.62 | 0.60 | 0.60 | 0.58 | 0.57 | 0.57 |
| 2010 | 0.52 | 0.53 | 0.60 | 0.74 | 0.60 | 0.49 | 0.57 | 0.57 | 0.58 | 0.58 | 0.55 | 0.55 | 0.55 |
| 2011 | 0.30 | 0.28 | 0.30 | 0.40 | 0.40 | 0.38 | 0.45 | 0.44 | 0.43 | 0.43 | 0.39 | 0.39 | 0.40 |
| 2012 | 0.20 | 0.17 | 0.16 | 0.22 | 0.24 | 0.26 | 0.32 | 0.31 | 0.30 | 0.31 | 0.29 | 0.28 | 0.28 |
| 2013 | 0.17 | 0.14 | 0.14 | 0.19 | 0.23 | 0.26 | 0.34 | 0.34 | 0.34 | 0.33 | 0.34 | 0.33 | 0.30 |
| 2014 | 0.19 | 0.15 | 0.15 | 0.21 | 0.28 | 0.34 | 0.46 | 0.46 | 0.46 | 0.44 | 0.45 | 0.44 | 0.42 |

## APPENDIX III – FIGURES

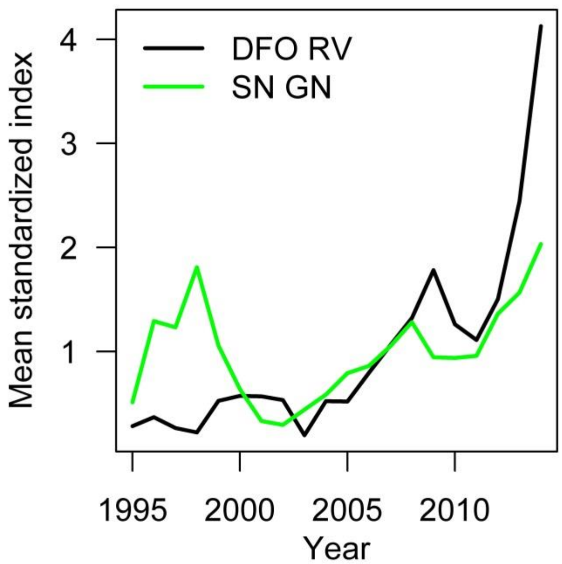


*Figure 1. Mean standardized DFO autumn bottom trawl total abundance index (DFO RV) and the Sentinel gillnet (5.5 in. mesh) total abundance index for NAFO Divisions 3K and 3L (SN GN).*

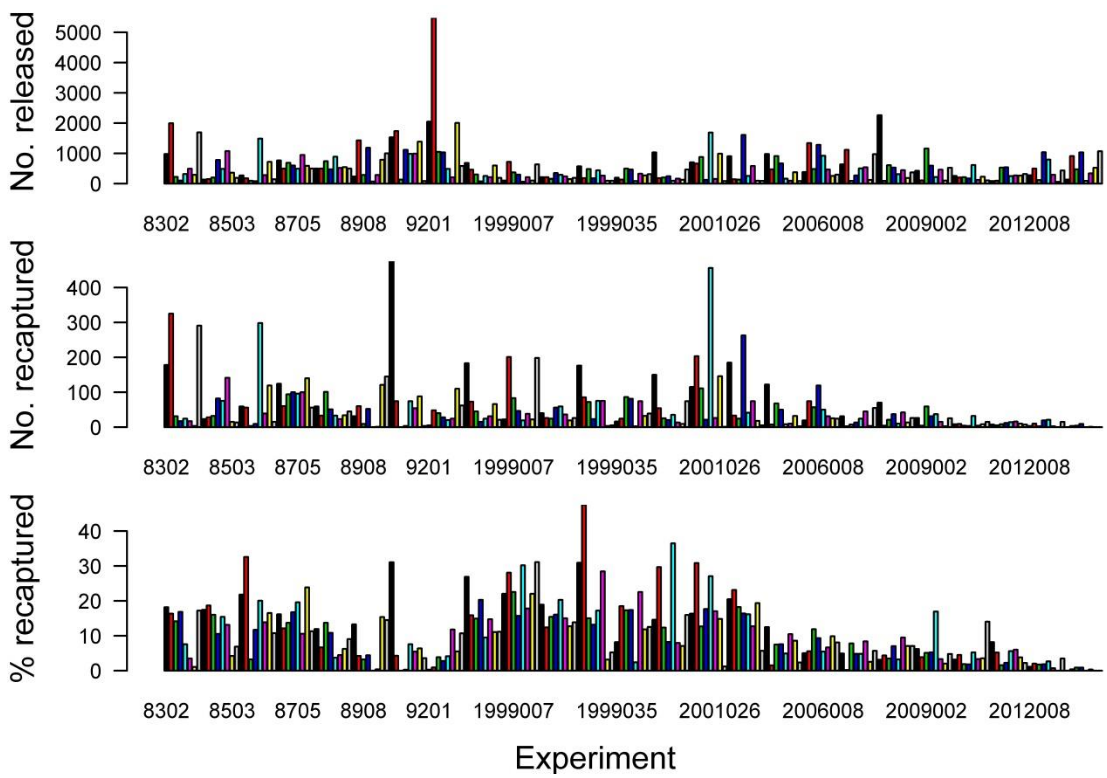


*Figure 2a. Total number of fish tagged (top panel), recaptured (middle panel), and percent recaptured (bottom panel). Each bar represents an experiment; these are ordered by year of release.*

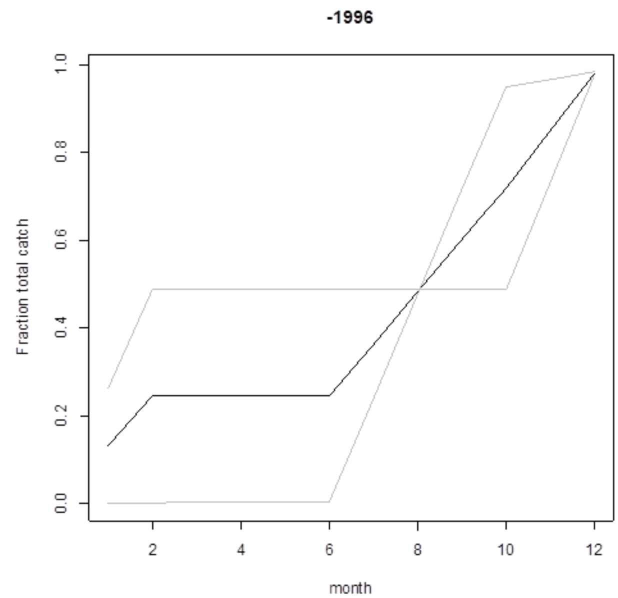


*Figure 2b. Illustrative approximation of the fraction of catch taken by month (black lines) during 1983-1996. Grey lines indicate the fractions taken in the inshore and offshore.*

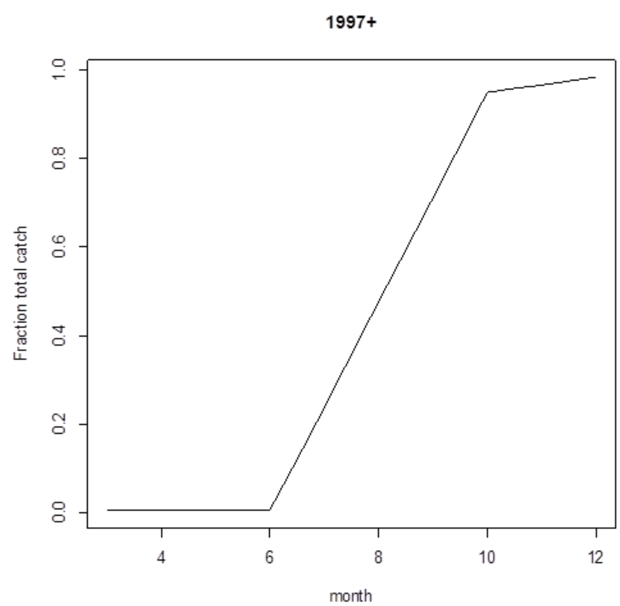


*Figure 2c. Illustrative approximation of the fraction of inshore catch taken by month (black lines) during 1997-2014.*

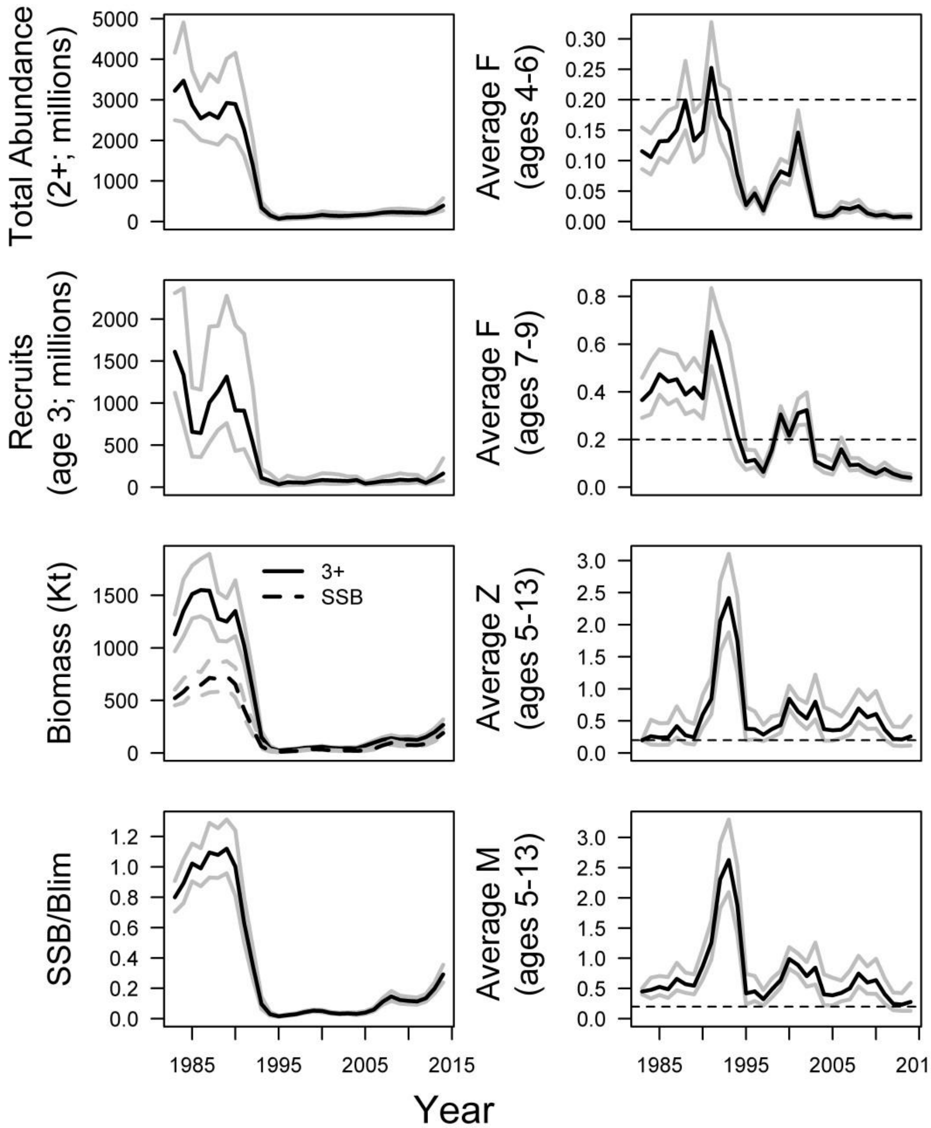


*Figure 3a. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) from the **C15+** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

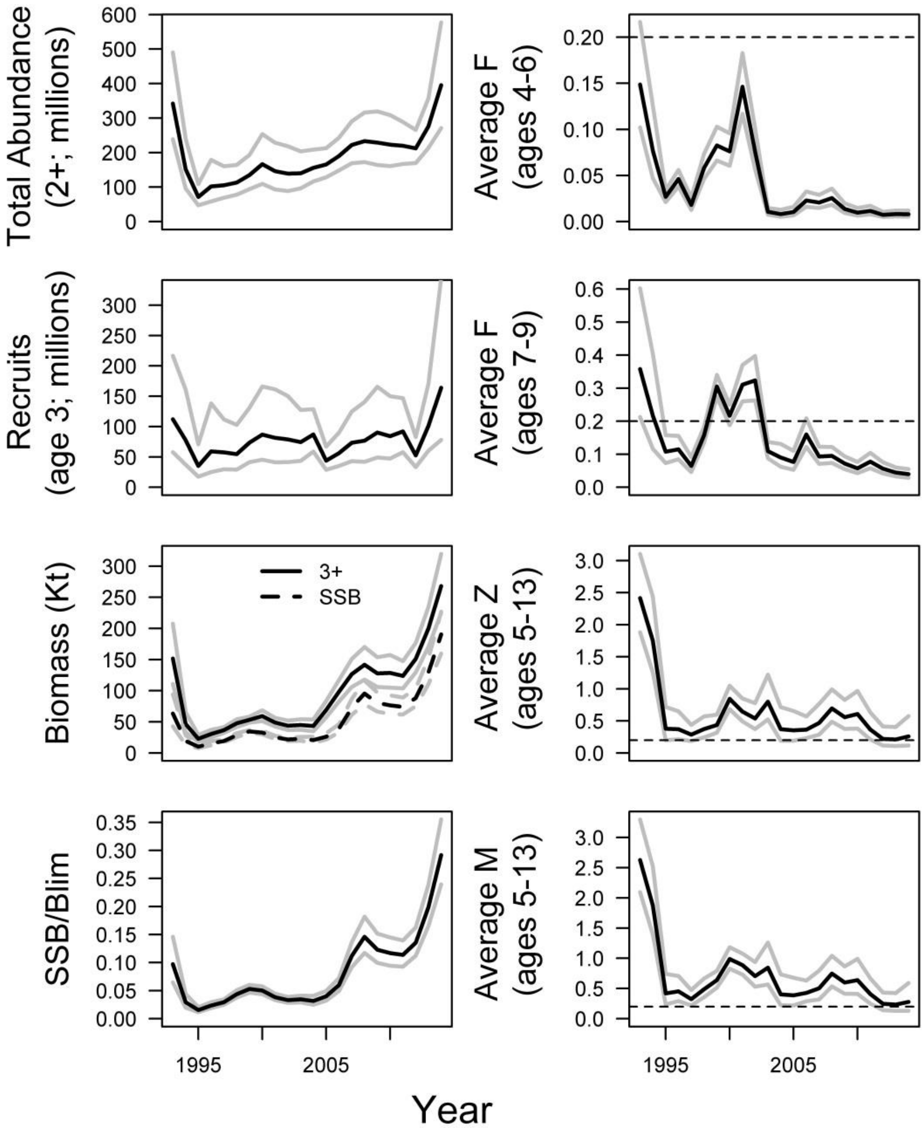


*Figure 3b. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) for 1993-2014 from the **C15+** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

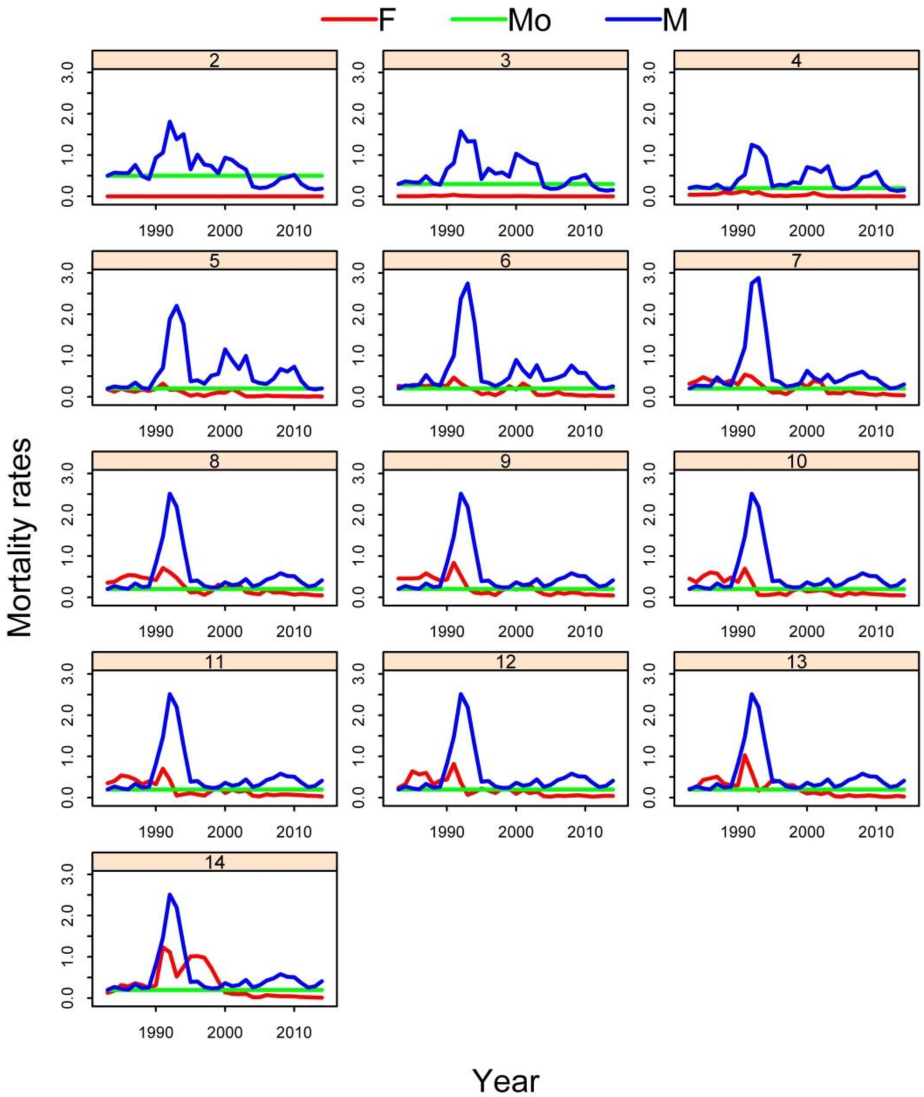


*Figure 4. Mortality rate at age estimates from the **C15+** NCAM formulation. Green lines indicate the fixed mean values of M.*

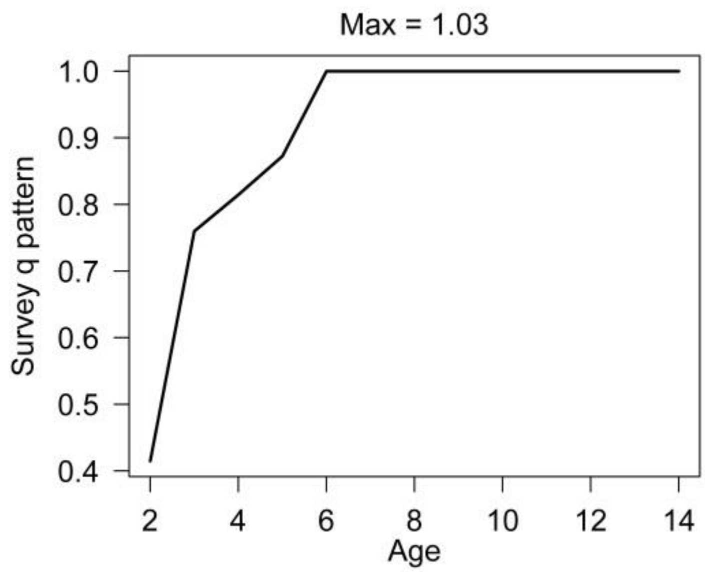


*Figure 5a. **C15+** NCAM estimates of survey catchability (q), scaled to a maximum of one, for the DFO RV survey. The maximum value of q is indicated at the top of the panel.*

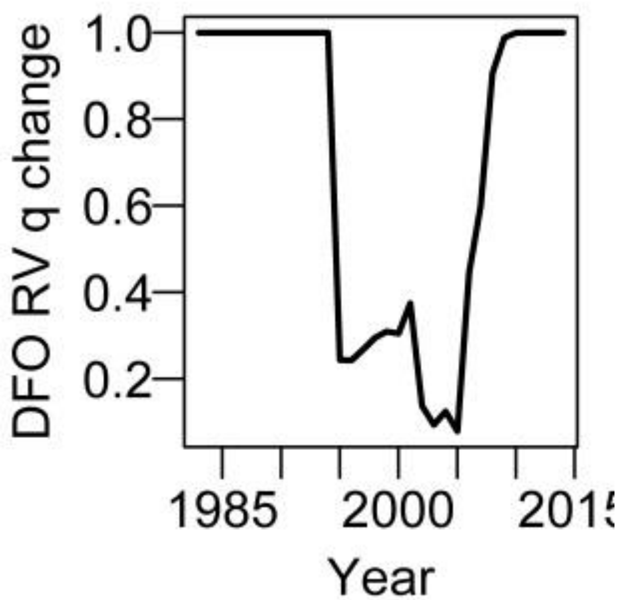


*Figure 5b. Multiplicative change in **C15+** NCAM catchability (q) for the DFO RV survey, averaged for ages 5+.*


*Figure 5c. **C15+** NCAM estimates of survey catchability (q), scaled to a maximum of one, for the Sentinel gillnet (5.5 in mesh) catch rate index for NAFO Divisions 3K and 3L. The maximum value of q is indicated at the top of the panel.*

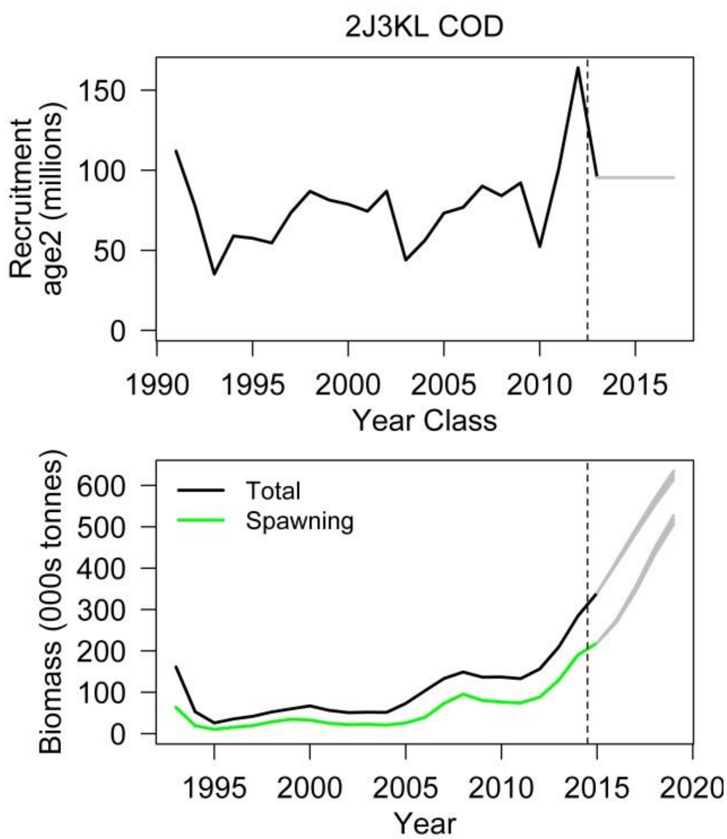


*Figure 6a. **C15+** NCAM estimates of recruitment (age 2; top panel), total biomass (age 2+) and mature biomass (bottom panel). Five year projections are indicated by grey lines. Three constant catch projections scenarios are shown in the bottom panel, for 2014 catch multipliers of 0.5, 1.0, and 1.5.*

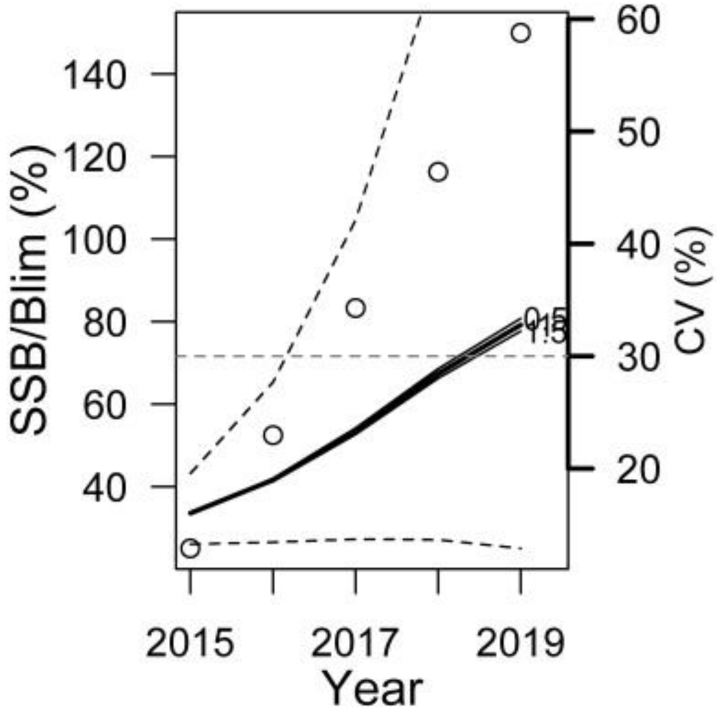


*Figure 6b. **C15+** NCAM projected mature biomass relative to Blim for constant catch scenarios based on 2014 catch multipliers of 0.5, 1.0, and 1.5. Dashed lines indicate 95% confidence intervals for projections based on status-quo catch. Circles indicate projection coefficients of variations (CV's) and the horizontal dashed line indicate a CV of 30%.*

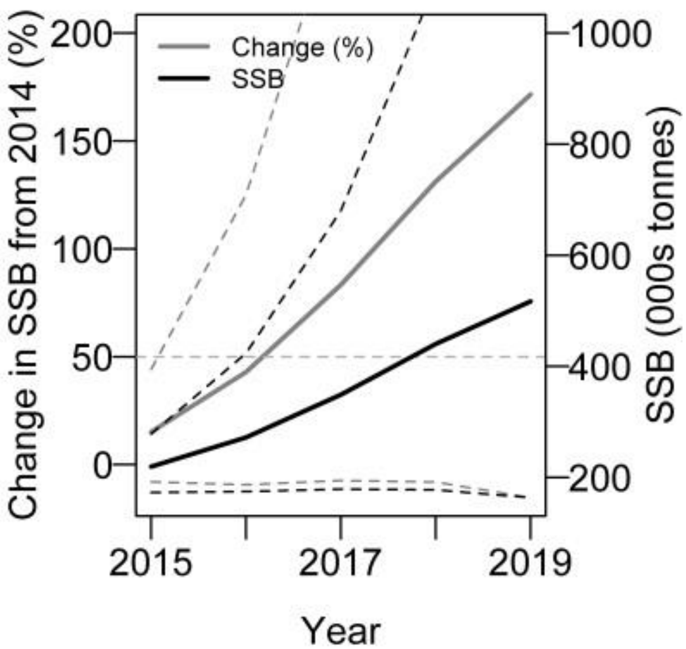


*Figure 6c. **C15+** NCAM projected mature biomass and change in mature biomass from 2014, for projections based on status-quo catch. Dashed lines indicate 95% confidence intervals The horizontal dashed line indicates a 50% increase in mature biomass relative to the 2014 level.*

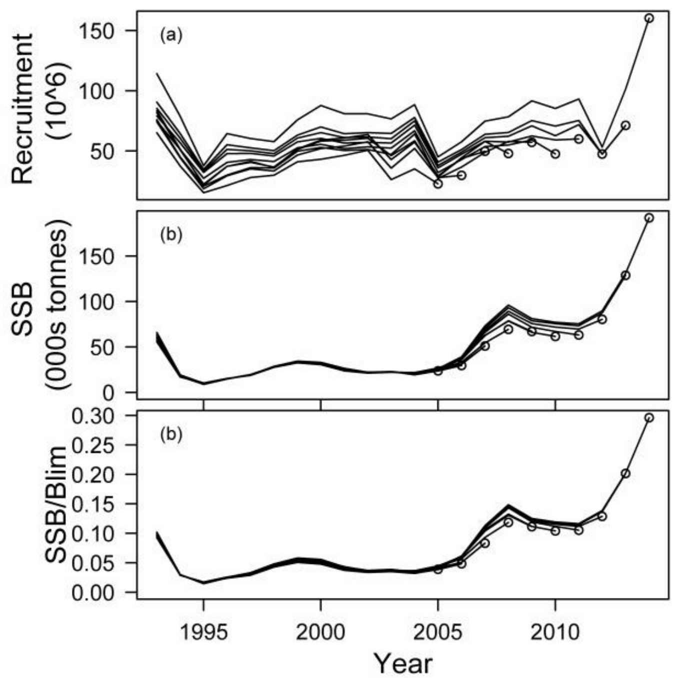


*Figure 7a. **C15+** NCAM retrospective estimates of (a) recruitment (age 3), (b) SSB, (c) SSB relative to Blim. Circles indicate the most recent estimate for each retrospective year.*

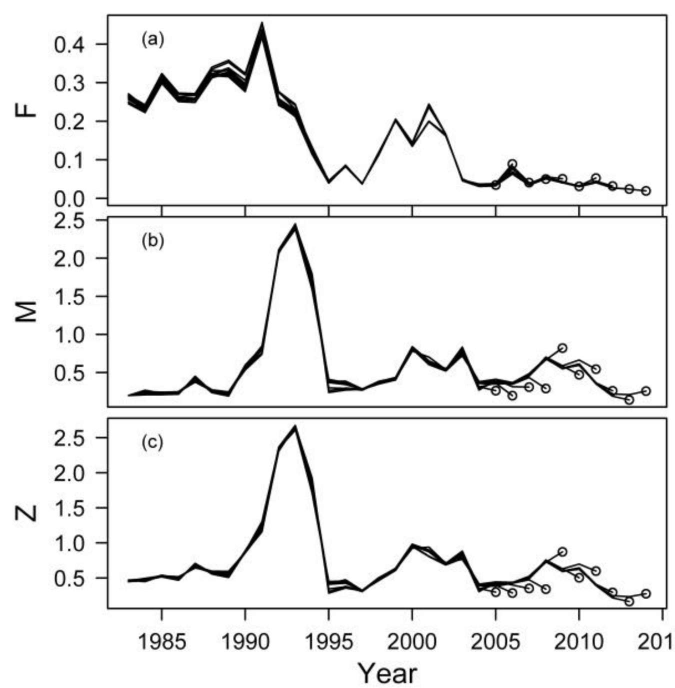


*Figure7b. **C15+** NCAM retrospective estimates of average (ages 5+) (a) F , (b) M, (c) Z. Circles indicate the most recent estimate for each retrospective year.*

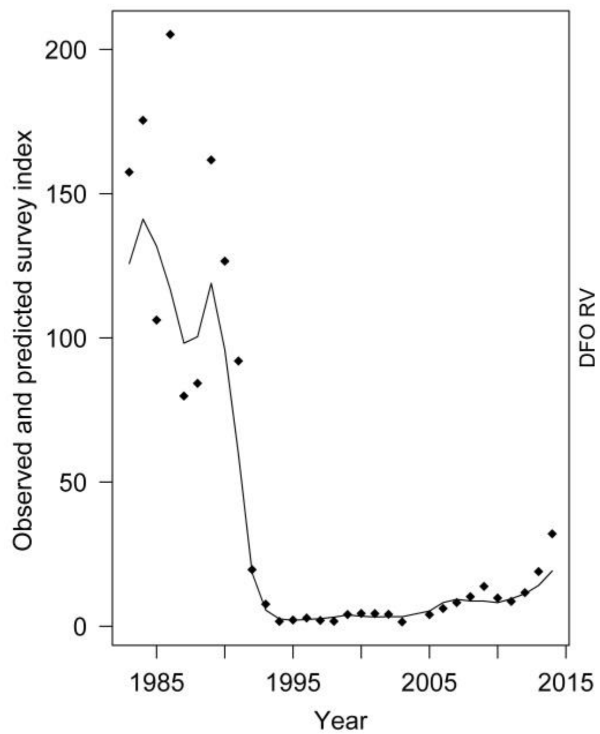


*Figure 8a. Total observed (points) and **C15+** NCAM predicted (lines) DFO RV survey index.*

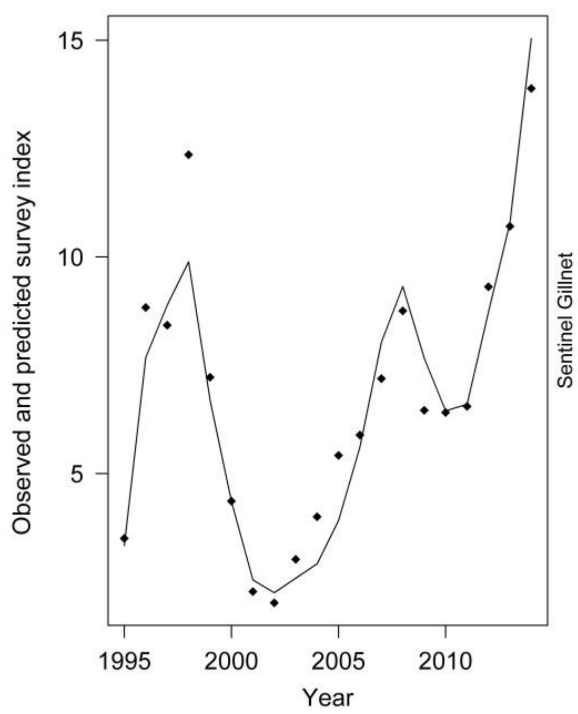


*Figure 8b. Total observed (points) and **C15+** NCAM predicted (lines) Sentinel gillnet (5.5 in mesh) catch rate index for NAFO Divisions 3K and 3L.*

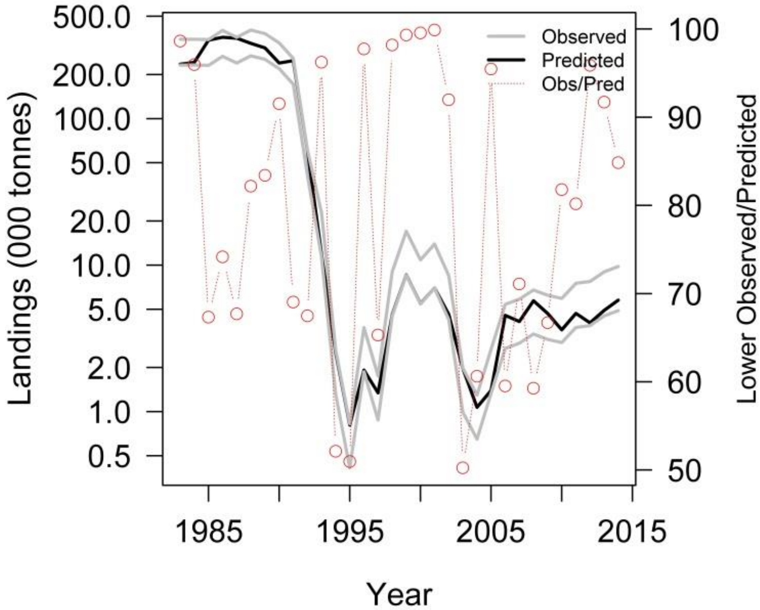


*Figure 8c. **C15+** NCAM estimated total catch weight (black lines) and assumed catch bounds (grey lines). The left-hand y-axis is in log scale. Superimposed is the reported/estimated catch (circles) with y-axis scale on the right-hand side.*

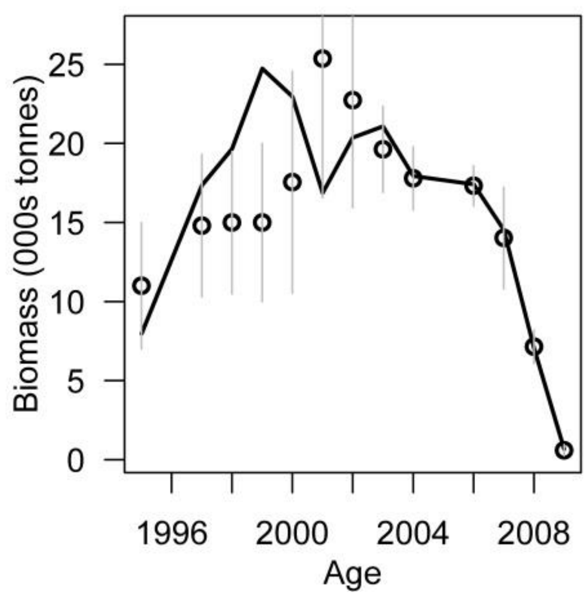


*Figure 8d. Observed (circles) versus **C15+** NCAM predicted (lines) Smith Sound acoustic biomass estimates. Vertical grey line segments indicate 95% confidence intervals based on survey standard errors.*

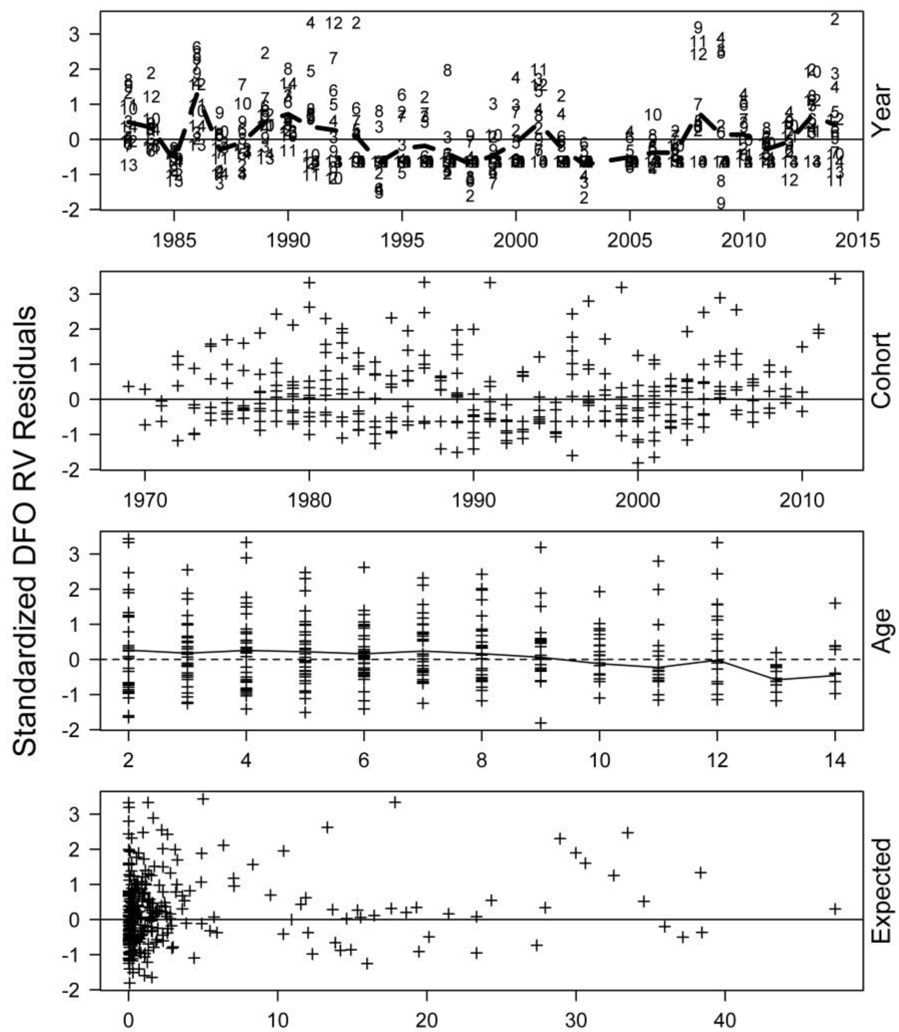


*Figure 9a. DFO RV survey standardized residuals from **C15+** NCAM. These residuals are the log observed survey catch minus the estimate and divided by the survey estimated standard deviation. From top to bottom the panels show residuals versus year, cohort, age, and predicted value. The dashed line in the top panel indicates the average residual each year and the plotting symbols indicate age.*

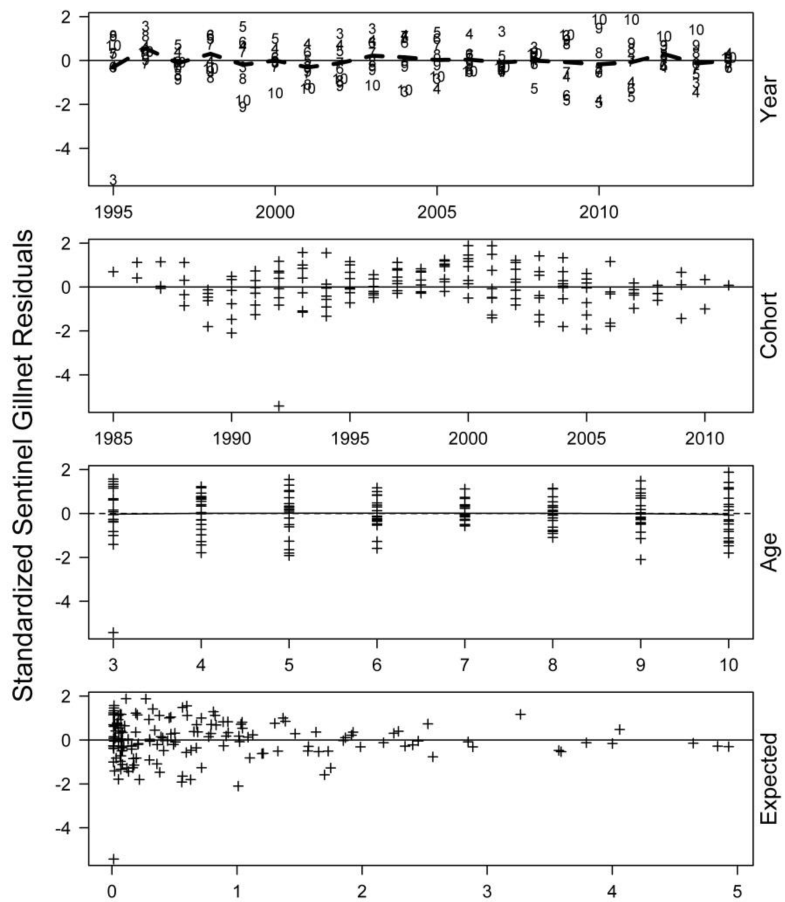


*Figure 9b. Sentinel gillnet (5.5 in mesh) catch rate standardized residuals from* ***C15+*** *NCAM. These residuals are the log observed survey catch minus the estimate and divided by the survey estimated standard deviation. From top to bottom the panels show residuals versus year, cohort, age, and predicted value. The dashed line in the top panel indicates the average residual each year and the plotting symbols indicate age.*

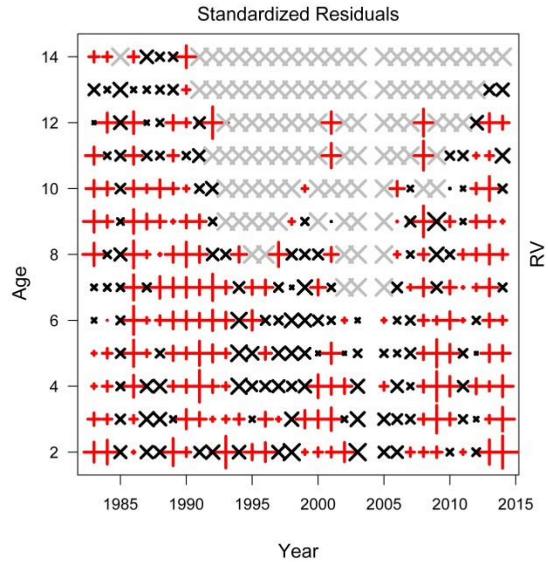


*Figure 9c. Matrix plot of base model DFO RV standardized residuals from **C15+** NCAM. Red +'s are positive, black ×'s are negative, and grey ×'s are residuals when indices are zero. The sizes of plotting symbols are proportional to the absolute value of the residuals. Blanks indicate missing values.*

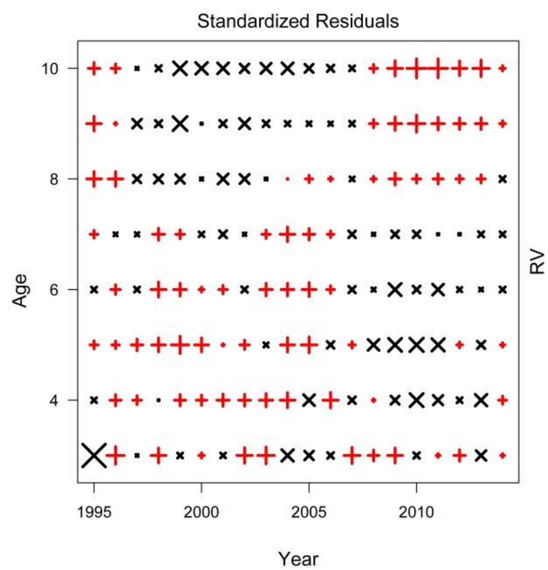


*Figure 9d. Matrix plot of base model Sentinel gillnet (5.5 in mesh) catch rate standardized log residuals from **C15+** NCAM. Red +'s are positive, black ×'s are negative. The sizes of plotting symbols are proportional to the absolute value of the residuals.*

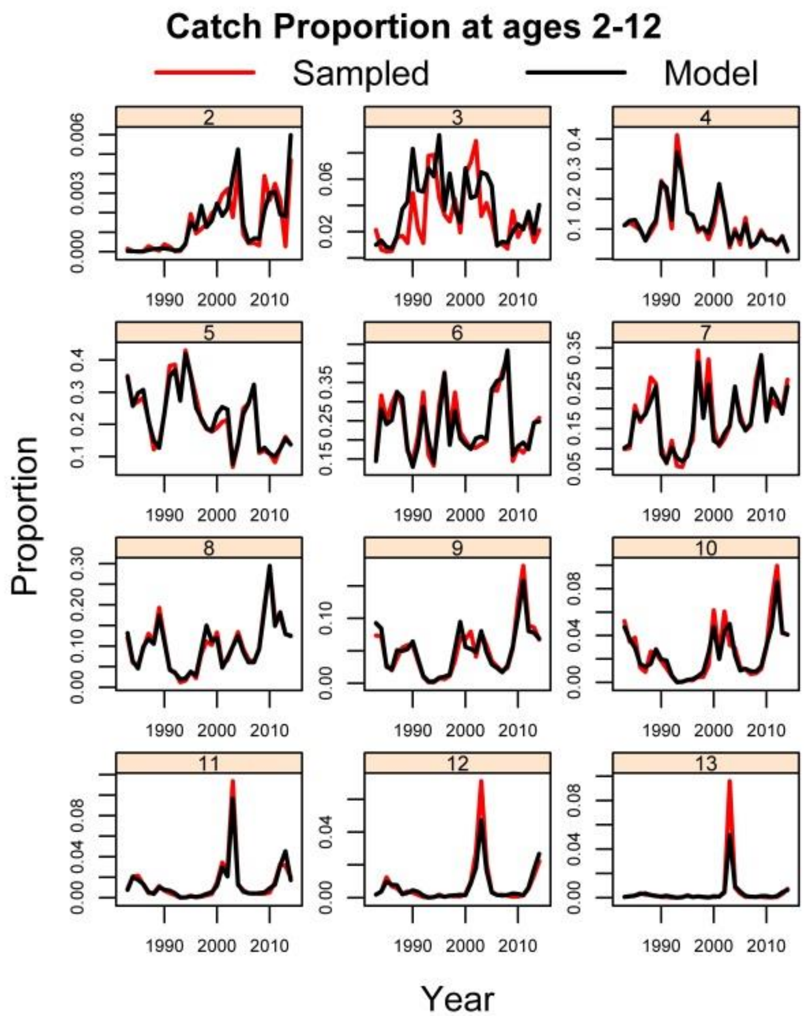


*Figure 9e. Observed (red lines) and* ***C15+*** *NCAM predicted (black lines) catch proportions at age. Each panel shows results for an age which is listed in the top strip. The y-axis scale varies for each panel.*

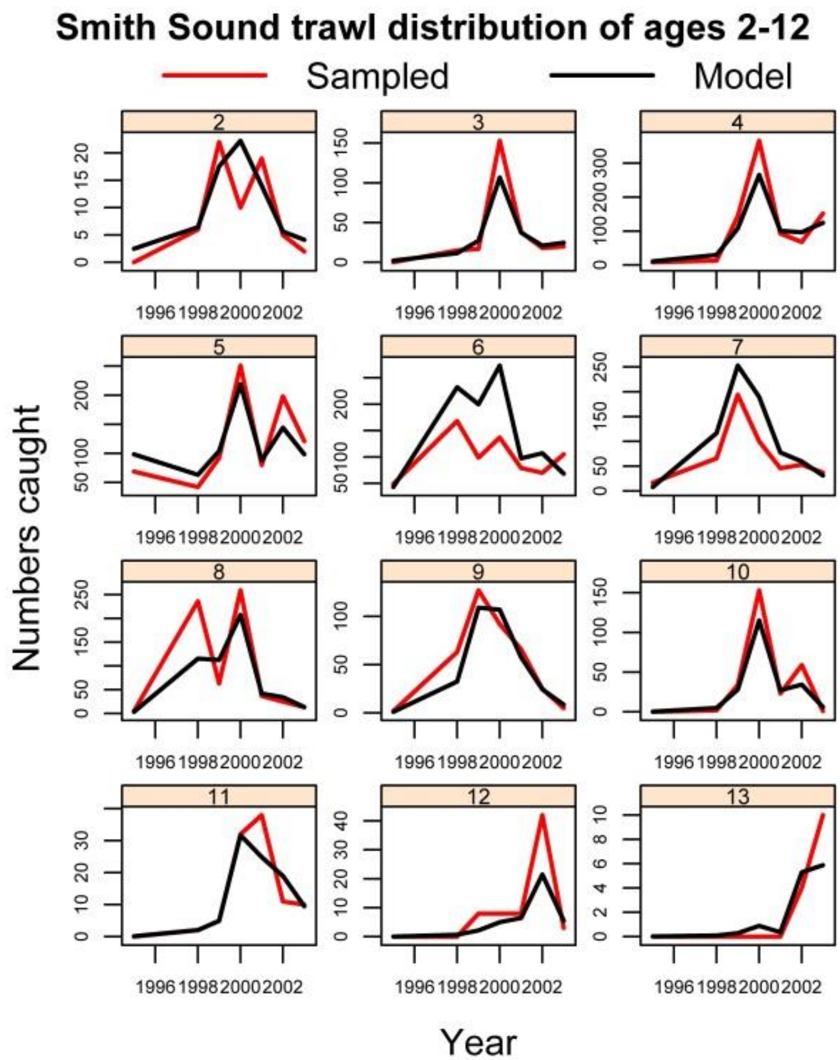


*Figure 9f. Observed (red lines) and **C15+** NCAM predicted (black lines) Smith Sound trawl catches for age compositions. Each panel shows results for an age which is listed in the top strip. The y-axis scale varies for each panel*

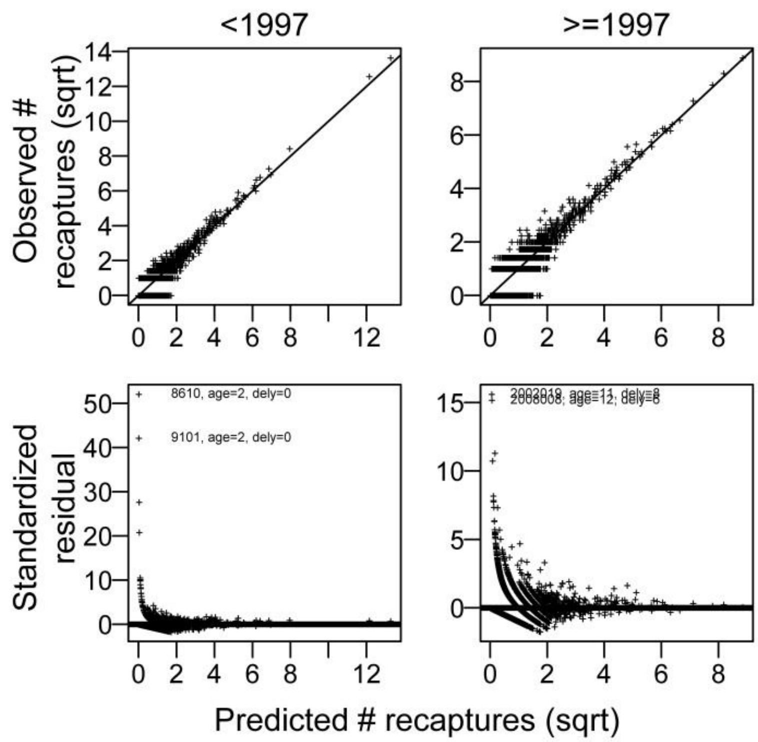


*Figure 10a. Observed versus **C15+** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014. Conditional Poisson standardized residuals are shown in the bottom panels.*

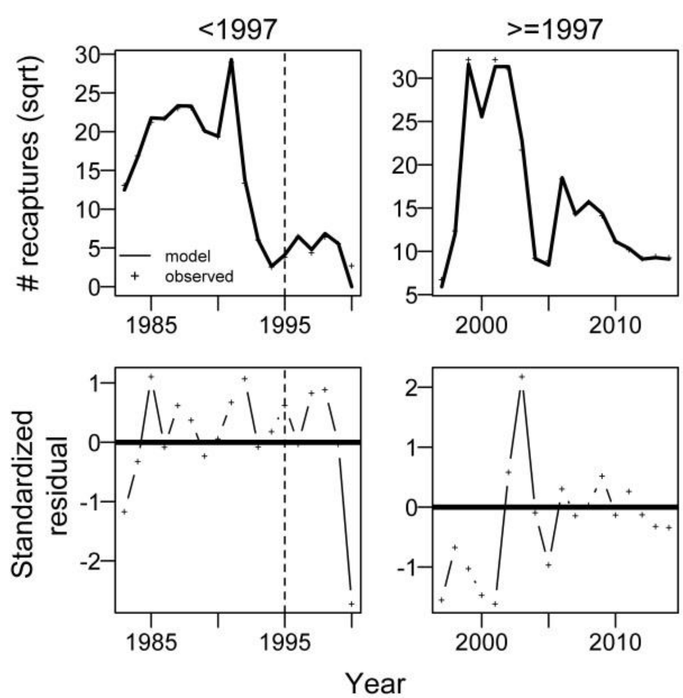


*Figure 10b. Aggregate observed versus **C15+** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014. Conditional Poisson aggregate standardized residuals are shown in the bottom panels.*

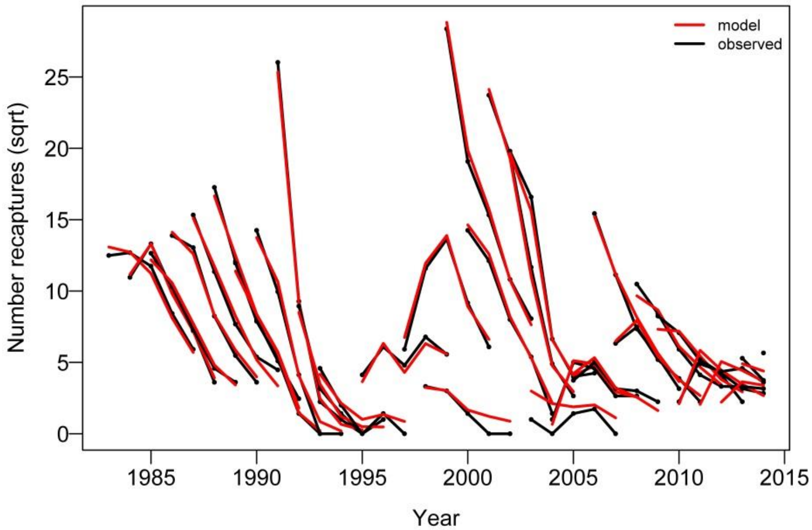


*Figure 10c. Aggregate observed versus **C15+** NCAM predicted reported catches of tagged cod for experiments conducted during 1983-2014. Each line represents total reported catches for up to 5 years-at-liberty. The start of each line segment indicates the release year.*

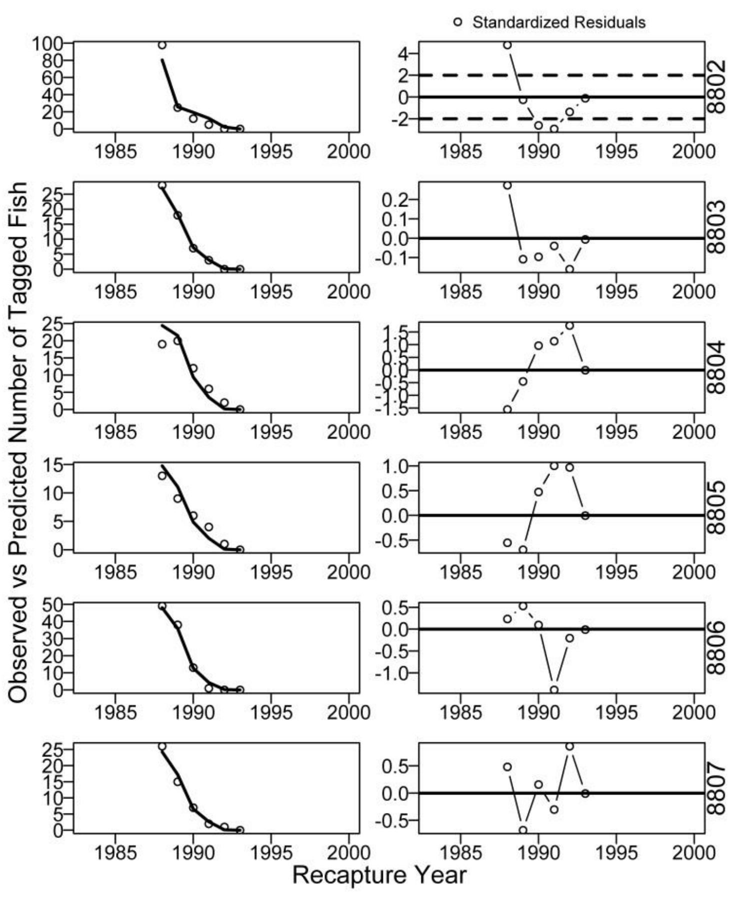


*Figure 11a. Aggregate (all ages) observed versus **C15+** NCAM predicted reported catches of tagged cod (left column) and conditional Poisson aggregate standardized residuals (right column). Tagging experiment is indicated at the right-hand side of each row. Selected experiments are illustrative of the 66 experiments during 1983-1996 used to estimate NCAM.*

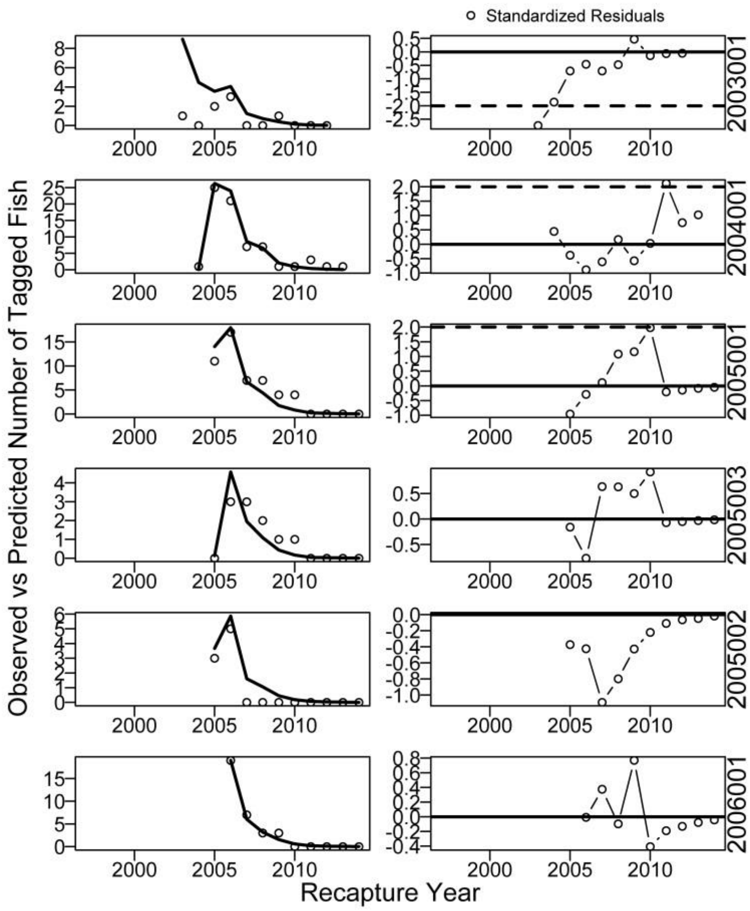


*Figure 11b. Aggregate (all ages) observed versus* ***C15+*** *NCAM predicted reported catches of tagged cod (left column) and conditional Poisson aggregate standardized residuals (right column). Tagging experiment is indicated at the right-hand side of each row. Selected experiments are illustrative of the 137 experiments during 1997-2014 used to estimate NCAM.*

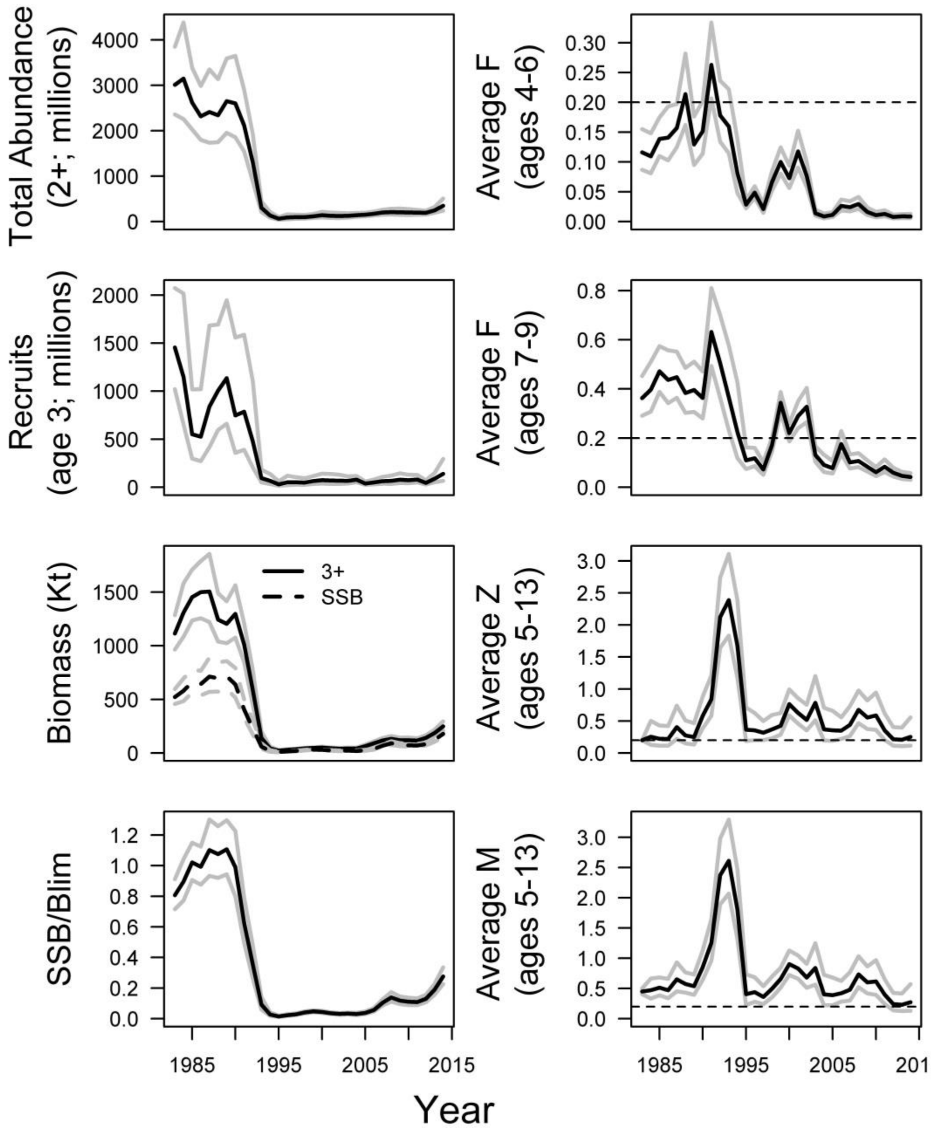


*Figure 12. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) from the **NB** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

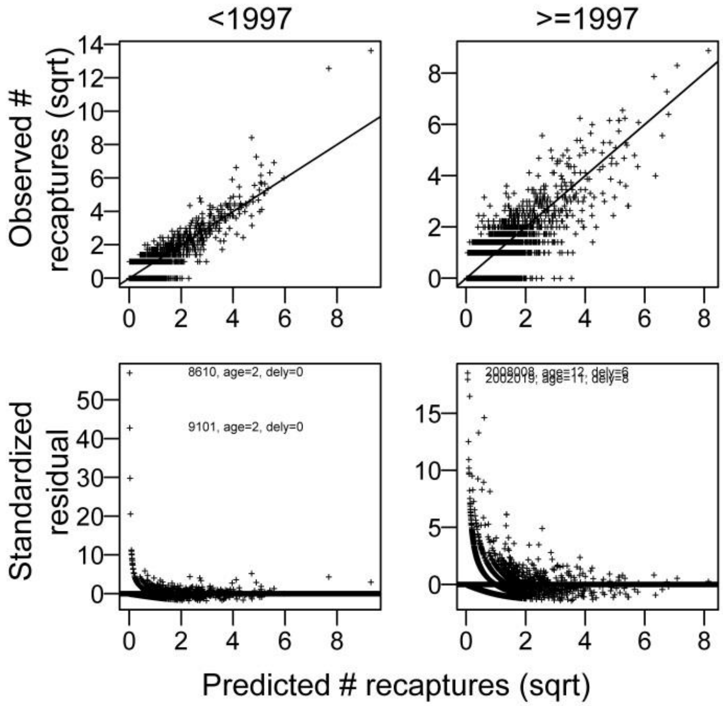


*Figure 13a. Observed versus **NB** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014.Marginal NB standardized residuals are shown in the bottom panels*

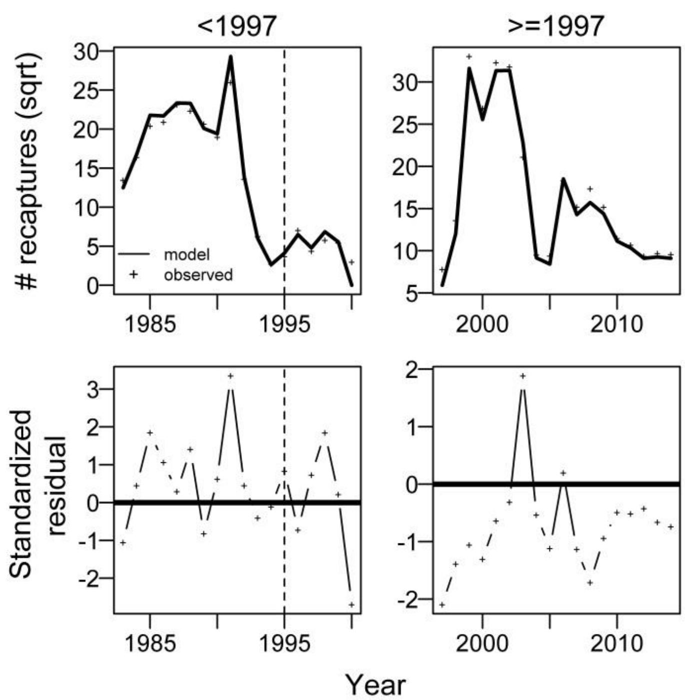


*Figure 13b. Aggregate observed versus **NB** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014. Marginal NB aggregate standardized residuals are shown in the bottom panels*

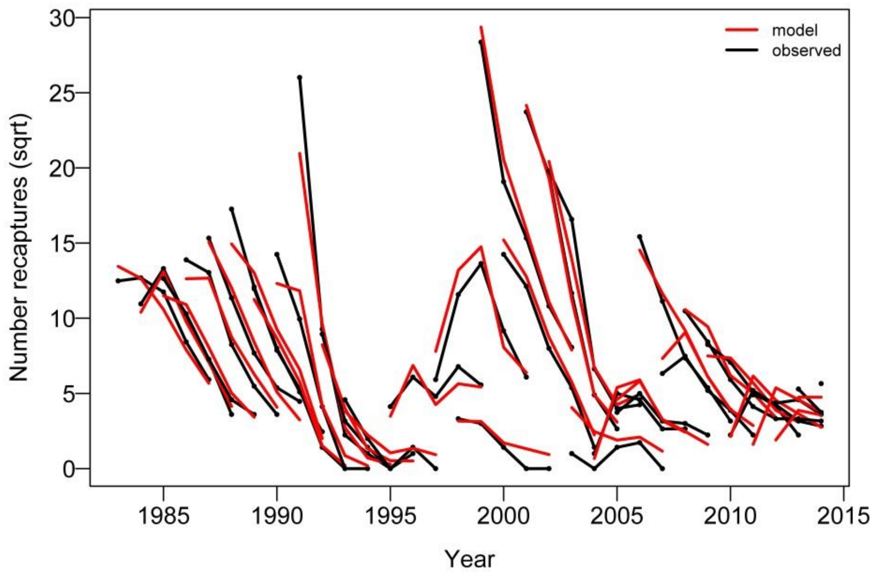


*Figure 13c. Aggregate observed versus **NB** NCAM predicted reported catches of tagged cod for experiments conducted during 1983-2014. Each line represents total reported catches for up to 5 years-at-liberty. The start of each line segment indicates the release year.*

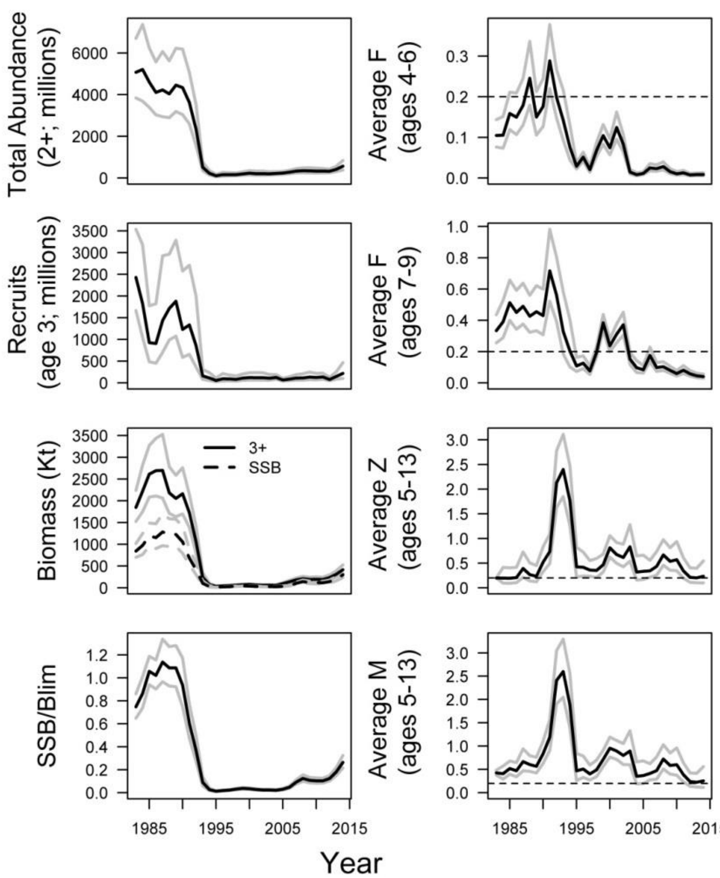


*Figure 14a. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) from the **NB_LC** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3$^{rd}$ panel, 1$^{st}$ column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

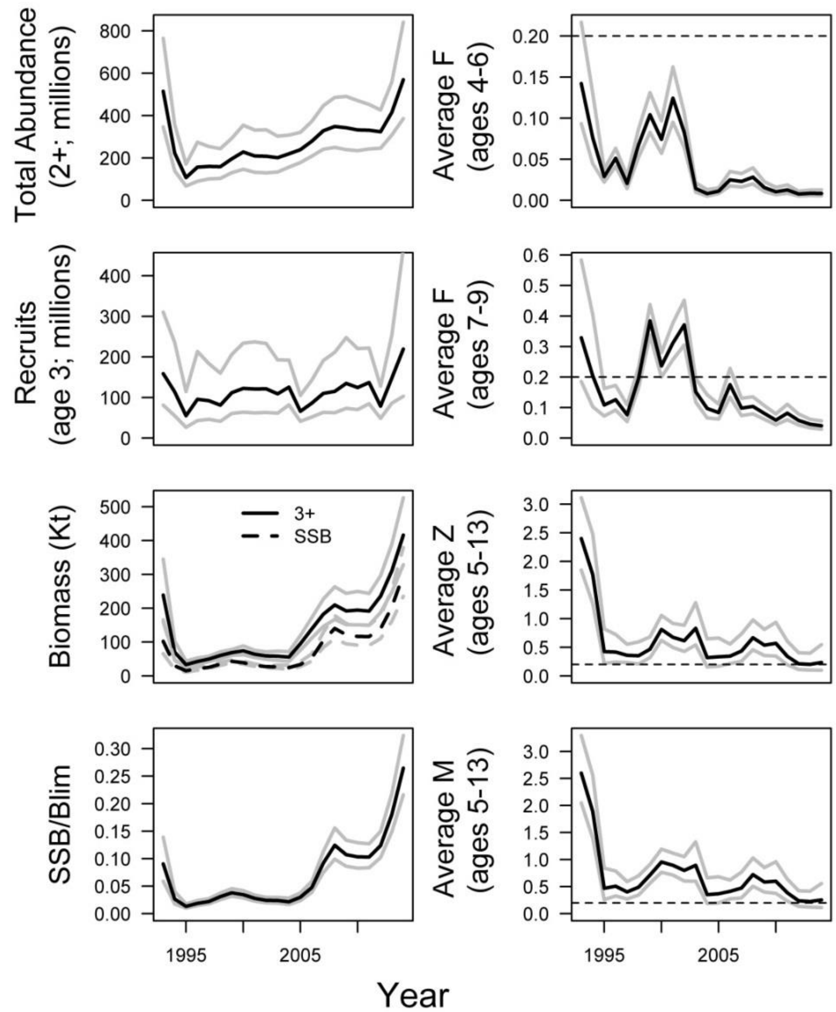


*Figure 14b. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) for 1993-2014 from the **NB_LC** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

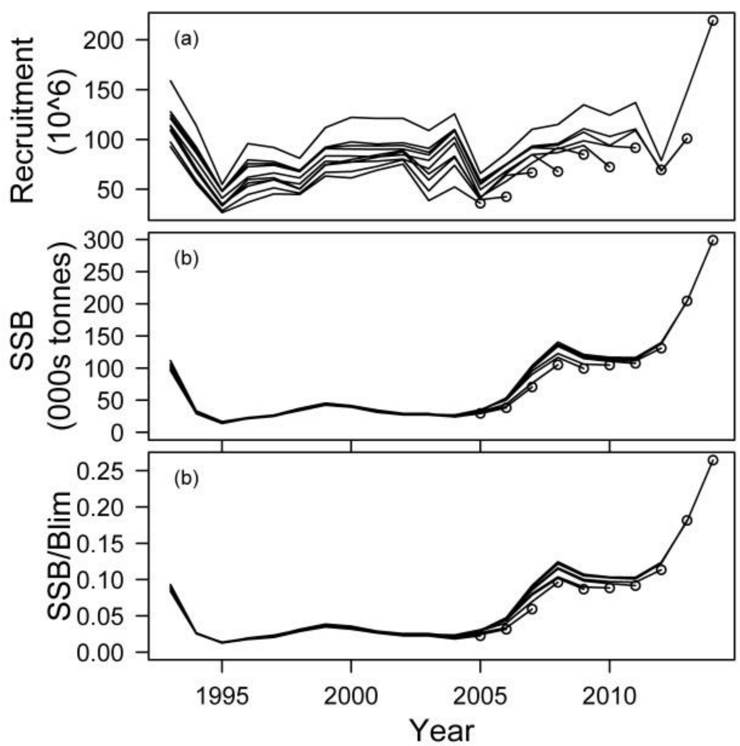


*Figure 15a. **NB_LC** NCAM retrospective estimates of (a) recruitment (age 3), (b) SSB, (c) SSB relative to Blim. Circles indicate the most recent estimate for each retrospective year.*

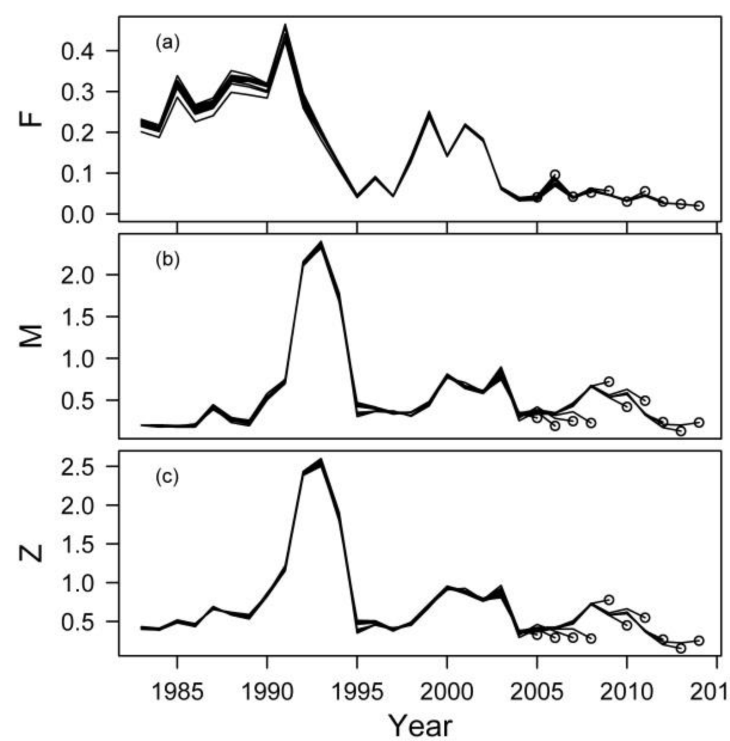


*Figure 15b. **NB_LC** NCAM retrospective estimates of average (ages 5+) (a) F , (b) M, (c) Z. Circles indicate the most recent estimate for each retrospective year.*

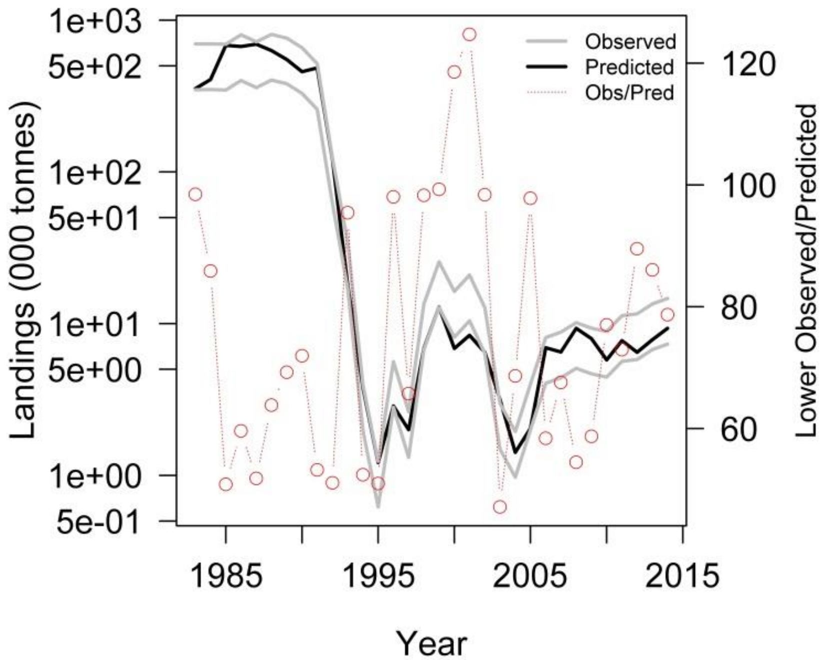


*Figure 16. **NB_LC** NCAM estimated total catch weight (black lines) and assumed catch bounds (grey lines). The left-hand y-axis is in log scale. Superimposed is the reported/estimated catch (circles) with y-axis scale on the right-hand side*

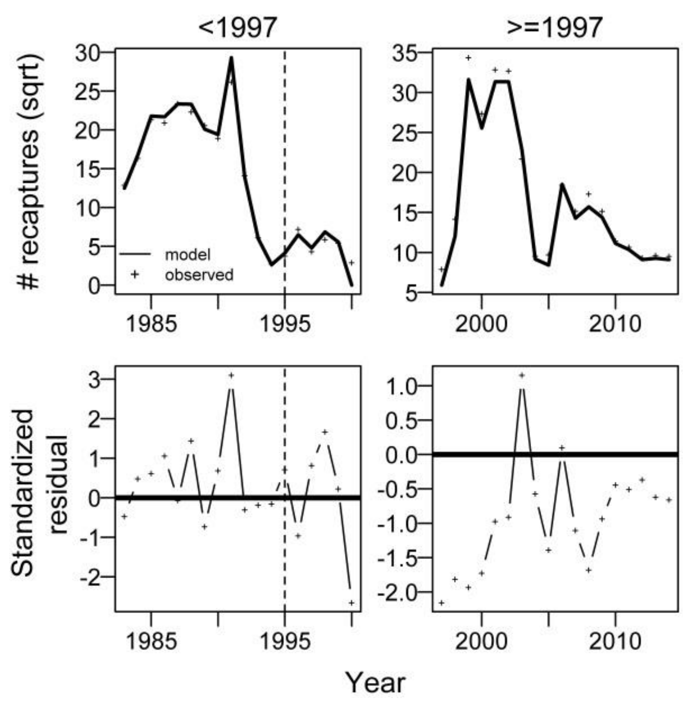


*Figure 17. Aggregate observed versus **NB_LC** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014. Conditional Poisson aggregate standardized residuals are shown in the bottom panels.*

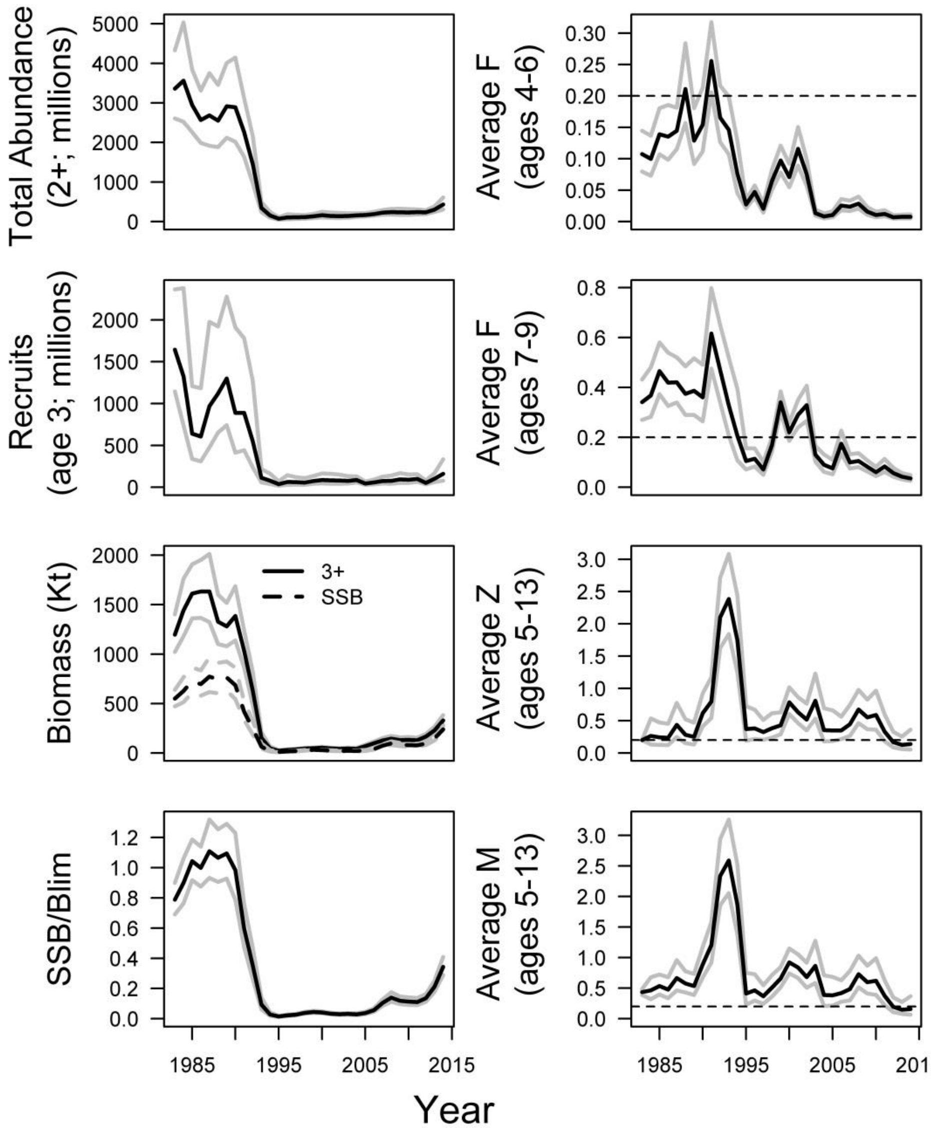


*Figure 18a. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) from the **NB_ACO** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

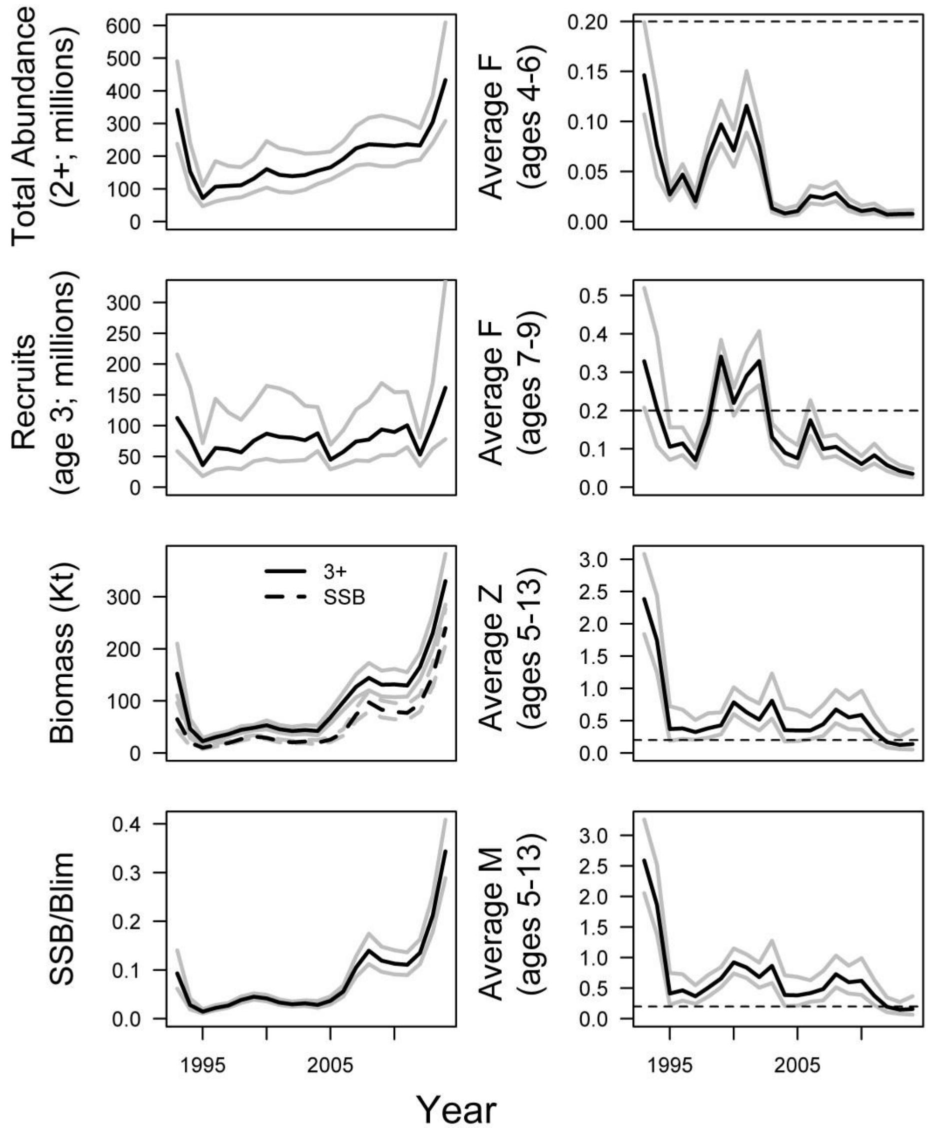


*Figure 18b. Stock size and mortality rate estimates and 95% confidence intervals (grey lines) for 1993-2014 from the **NB_ACO** NCAM formulation. Quantities are indicate to the left of each panel. In the biomass panel (3rd panel, 1st column), solid lines are for age 3+ biomass and dashed lines are for mature biomass (SSB).*

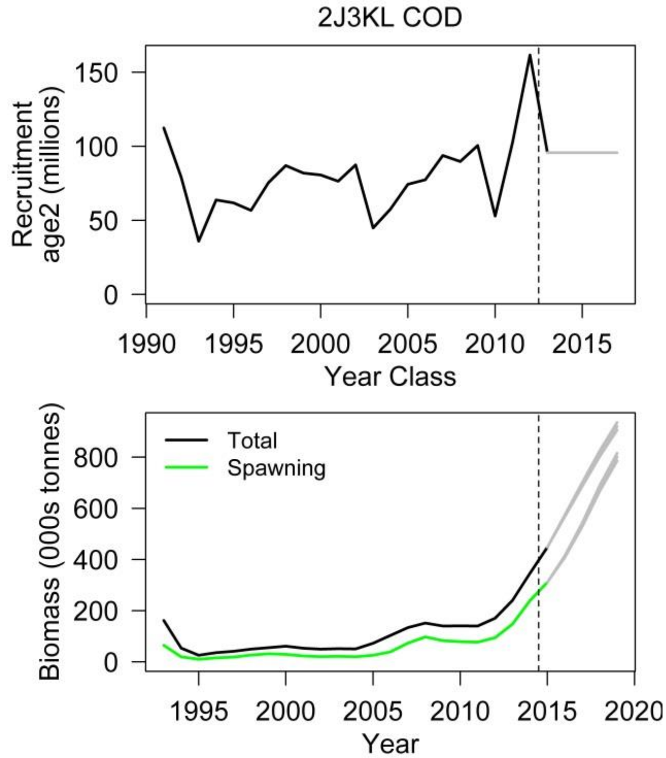


*Figure 19a. **NB_ACO** NCAM estimates of recruitment (age 2; top panel), total biomass (age 2+) and mature biomass (bottom panel). Five year projections are indicated by grey lines. Three constant catch projections scenarios are shown in the bottom panel, for 2014 catch multipliers of 0.5, 1.0, and 1.5.*

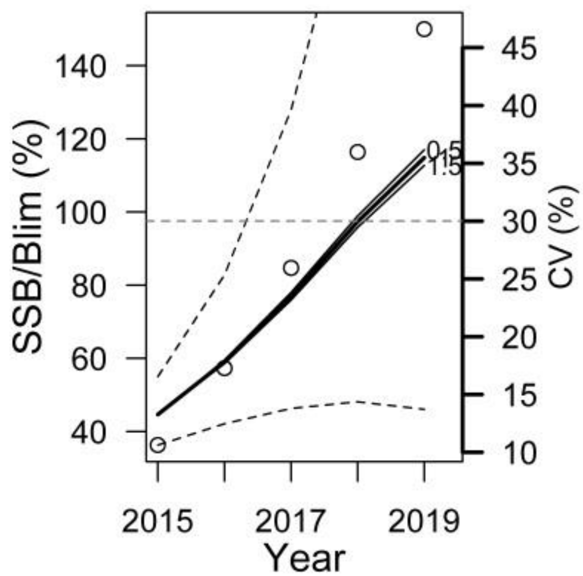


*Figure 19b. **NB_ACO** NCAM projected mature biomass relative to Blim for constant catch scenarios based on 2014 catch multipliers of 0.5, 1.0, and 1.5. Dashed lines indicate 95% confidence intervals for projections based on status-quo catch. Circles indicate projection coefficients of variations (CV's) and the horizontal dashed line indicate a CV of 30%.*

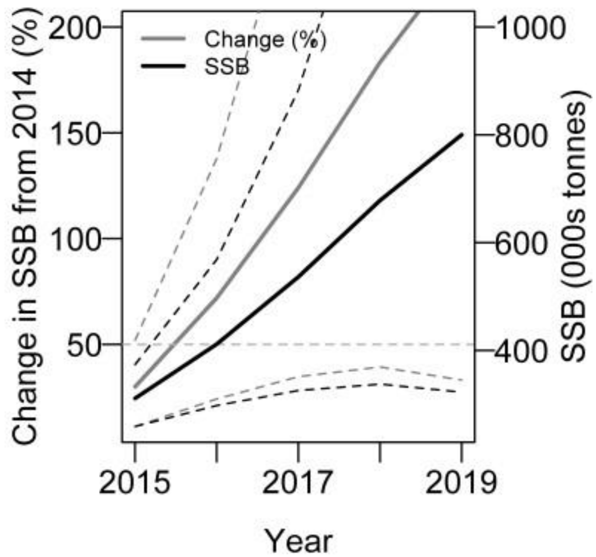


*Figure 19c. **NB_ACO** NCAM projected mature biomass and change in mature biomass from 2014, for projections based on status-quo catch. Dashed lines indicate 95% confidence intervals The horizontal dashed line indicates a 50% increase in mature biomass relative to the 2014 level.*

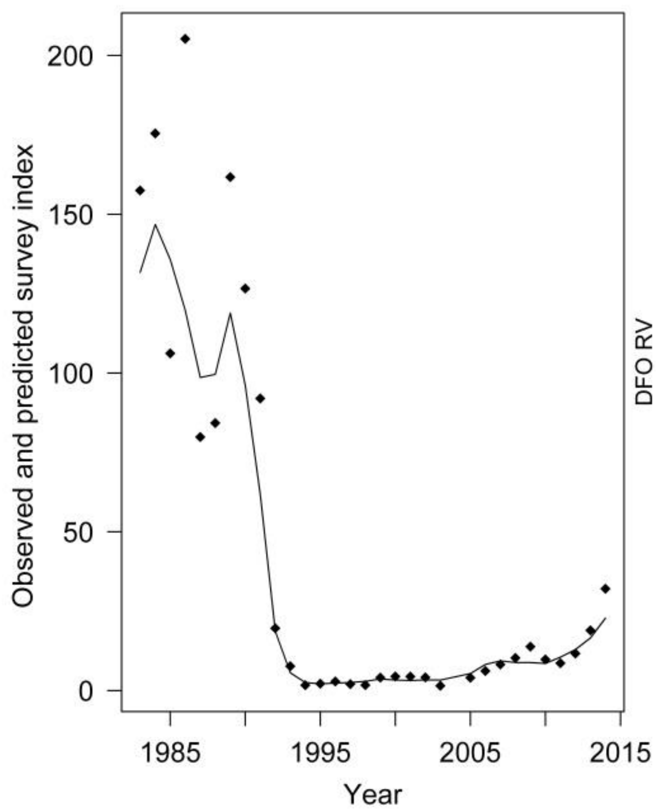


*Figure 20a. Total observed (points) and **NB_ACO** NCAM predicted (lines) DFO RV survey index*

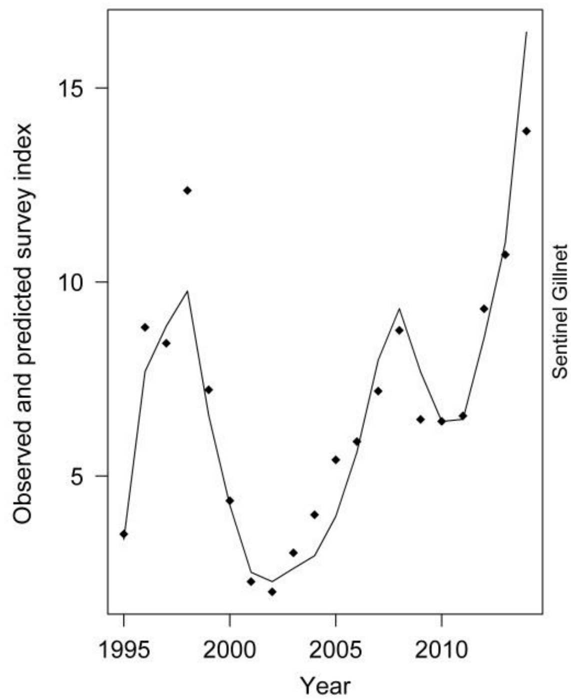


*Figure 20b. Total observed (points) and **NB_ACO** NCAM predicted (lines) Sentinel gillnet (5.5 in mesh) catch rate index for NAFO Divisions 3K and 3L.*

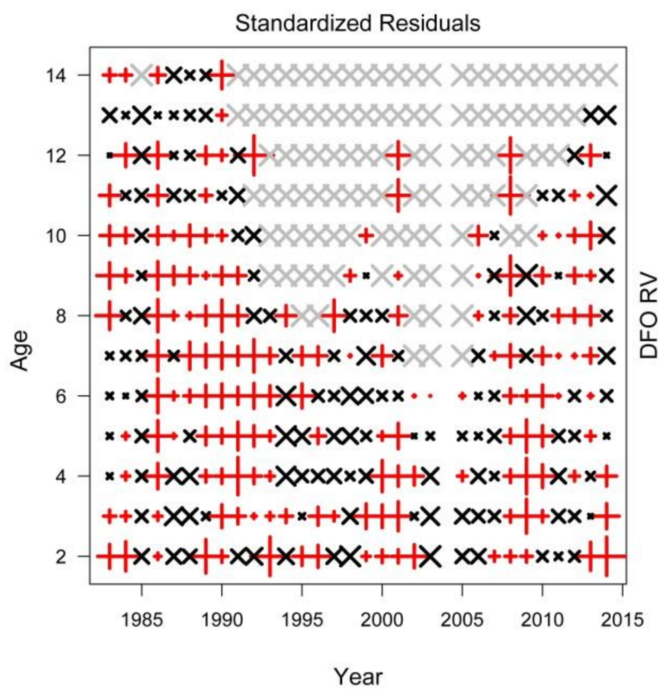


*Figure 21. Matrix plot of base model DFO RV standardized residuals from **NB_ACO** NCAM. Red +'s are positive, black ×'s are negative, and grey ×'s are residuals when indices are zero. The sizes of plotting symbols are proportional to the absolute value of the residuals. Blanks indicate missing values.*

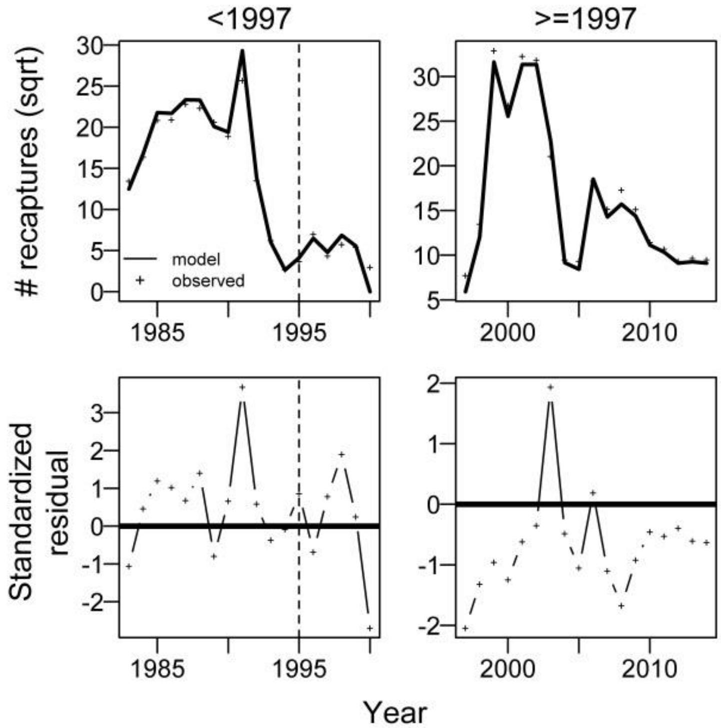


*Figure 22. Aggregate observed versus **NB_ACO** NCAM predicted reported catches of tagged cod (top panels) for tagging experiments conducted during 1983-1996 and 1997-2014. Marginal NB aggregate standardized residuals are shown in the bottom panels.*

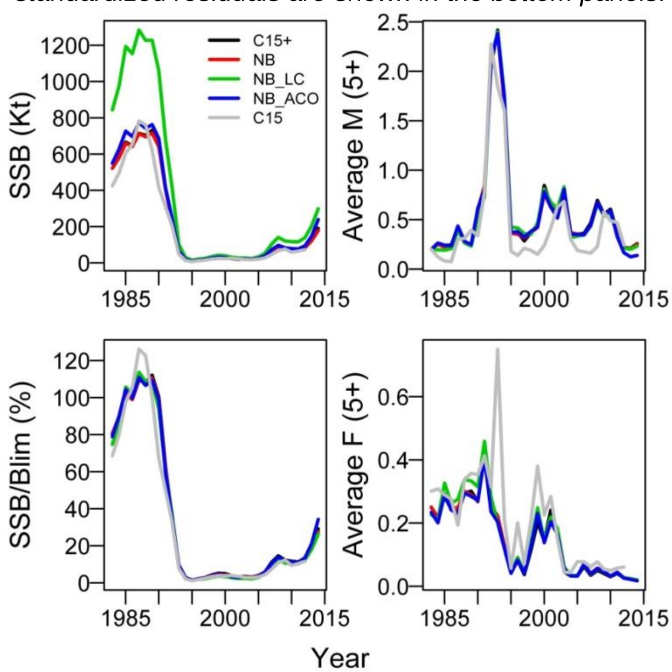


*Figure 23a. A comparison of mature biomass (top-left panel), stock status relative to Blim (bottom-left panel), average M (top-right panel), and average F (bottom-right panel) for the four NCAM formulations: 1) C15+: Updated formulation of Cadigan (2015); 2) NB: C15+ but with NB approach to tag-returns; 3) NB_LC: NB but with higher bounds on total catch weight; 4) NB_ACO: NB and hypothetical offshore acoustic survey. C15 are results from Cadigan (2015).*

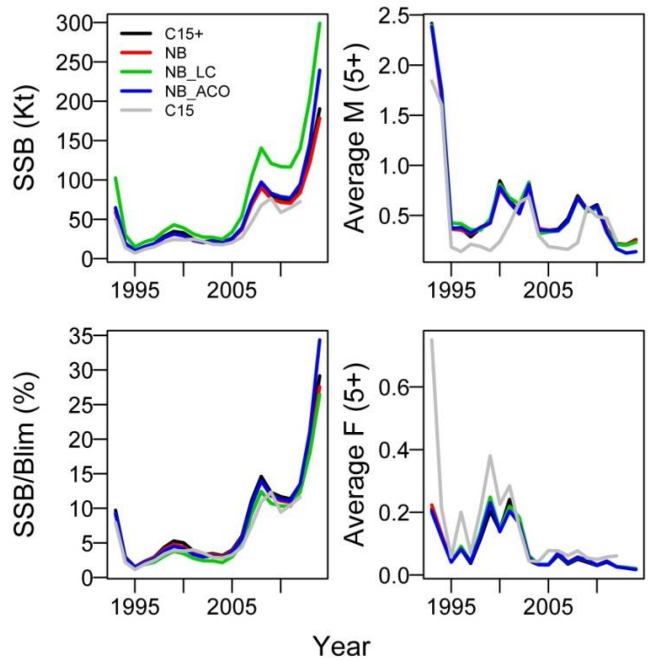


*Figure 23b. A comparison of mature biomass (top-left panel), stock status relative to Blim (bottom-left panel), average M (top-right panel), and average F (bottom-right panel) during 1993-2014 for the four NCAM formulations: 1) C15+: Updated formulation of Cadigan (2015); 2) NB: C15+ but with NB approach to tag-returns; 3) NB_LC: NB but with higher bounds on total catch weight; 4) NB_ACO: NB and hypothetical offshore acoustic survey. C15 are results from Cadigan (2015).*

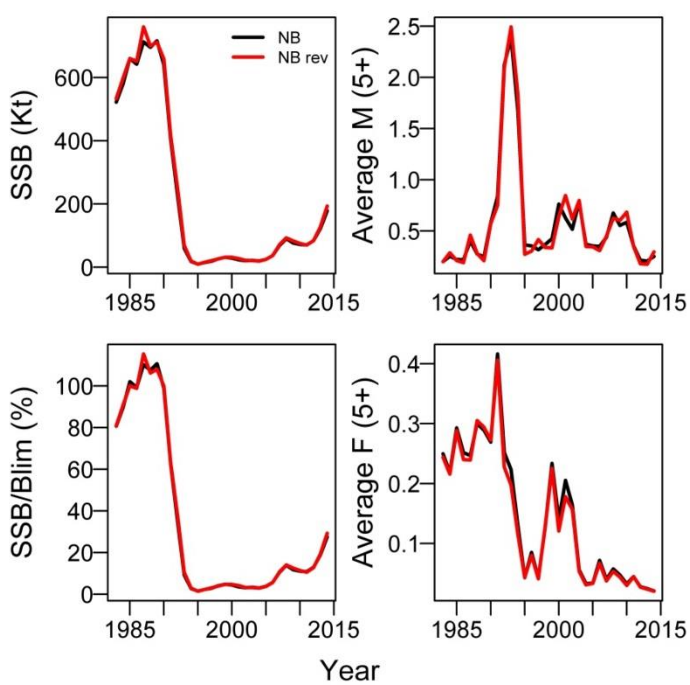


*Figure 24. A comparison of mature biomass (top-left panel), stock status relative to Blim (bottom-left panel), average M (top-right panel), and average F (bottom-right panel) during 1993-2014 for the NB NCAM formulation and the revision (rev) with a change in how M was modelled for tagged fish in their year of release.*

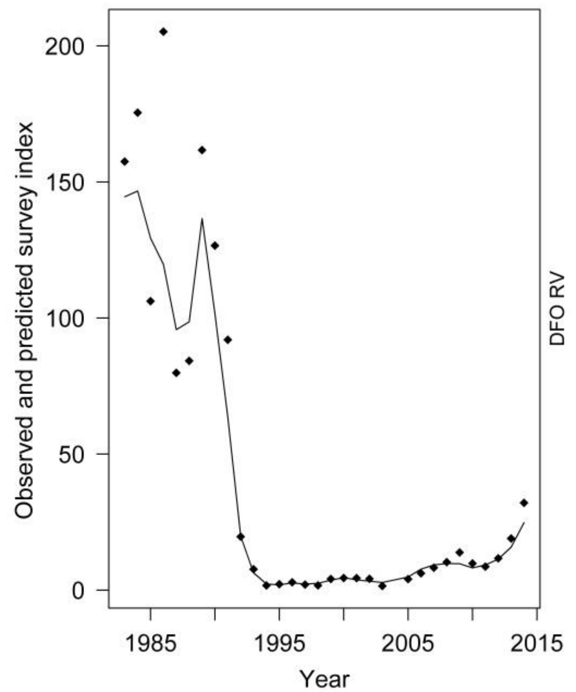


*Figure 25a. Total observed (points) and NB sensitivity NCAM predicted (lines) DFO RV survey index.*

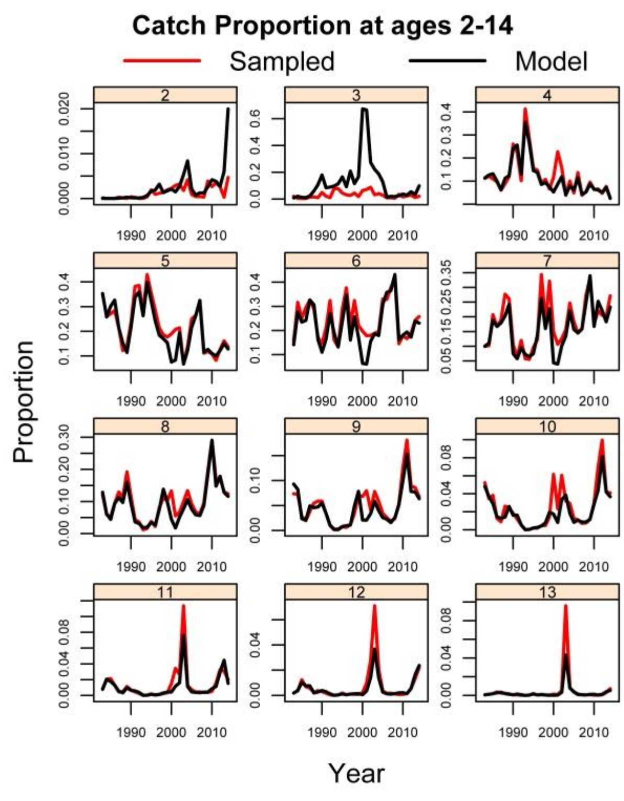


*Figure 25b. Observed (red lines) and NB sensitivity NCAM predicted (black lines) catch proportions at age. Each panel shows results for an age which is listed in the top strip. The y-axis scale varies for each panel.*