A framework for closed-loop simulation of fishery harvest strategies: operating model specifications and example evaluation of F0.1 policies for 2J3KL northern cod (*gadus morhua*)

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Review some of the features that should be added to this, e.g., SR depensation, biomass-dependent M, prior-M from tagging. Could estimate the value of tagging information on M.

Foreword (do not change the information on this page)

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Abstract

Recent assessments for Canada's 2J3KL northern cod stock indicate that brief periods of extremely high natural mortality rates for adult cod can lead to stock collapse even in the presence of theoretically conservative fishing mortality rates (e.g., *F*0.1). Future non-stationarity in demographic rates of cod, as well as potential errors in assessment of stock abundance, should therefore be taken into account when evaluating future rebuilding strategies. This paper develops a closed-loop simulation framework for evaluating possible harvest strategies for Canada's 2J3KL northern cod fishery. Key components of the framework include: (1) operating models that reflect a range of potential future changes in natural mortality, growth rate, and productivity of cod, as well as changes in fishery age-selectivity, (2) candidate management procedures (MP) comprised of data, stock assessment, and harvest control rules (HCR) for determining annual catch limits; and (3) biological limit (*B*lim = 840,000 t) and upper stock (2*B*lim = 1,680,000 t) reference points used to derive harvest strategy performance metrics. We demonstrate the properties of the simulation framework in an example performance evaluation for an F0.1 harvest strategy. A statistical catch-at-age (SCA) stock assessment model is simulated within the MP to mimic realistic errors and time lags in assessing cod abundance and natural mortality estimates. The operating model history (1983-2014) is populated with historical estimates for recruitment, natural mortality, and growth rates of cod based on the most recent 2J3KL stock assessments. This singular history was combined with 4 scenarios for future natural mortality patterns and three scenarios for recruitment. The first *M* scenario assumes that future *M* fluctuates in a random walk pattern around the present (*M*2014) value, while the remaining three scenarios assume that future natural mortality patterns exhibit short-term pulses of extreme mortality (6.5*M*2014) occurring at either 20 or 40 year intervals, or at 20-year intervals only while the stock is below Blim. The three recruitment scenarios include (i) constant at the recent average recruitment from 2005 - 2014, (ii) 50% of 1980s mean recruitment, or (iii) an increasing trend from the recent average to half the 1980s average.

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Résumé

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# introduction

Recent stock assessments suggest that the 2J3KL cod stock may be rebuilding from a severely depleted historical state. The original collapse of this stock in the early 1990s was initially attributed to fishing; however, in hindsight, it appears that elevated natural mortality could have been a key contributing factor to the rapid decline in stock biomass over a short time (Cadigan 2016; CSAP 2016 proceedings). A return of natural mortality to levels observed prior to the collapse, combined with relatively strong recruitment, have led to sustained biomass growth to near 30% of BLim. Continued biomass growth at this pace could potentially re-establish directed commercial cod fisheries in the near future.

Renewing the fishery for northern cod requires a harvest strategy designed to take into account uncertainties in cod stock abundance and dynamics as well as fishery economic preferences. Current stock assessment models, regardless of complexity, are not capable of providing the information needed to design such harvest strategies because they do not adequately account for feedbacks between future management procedures (i.e., combinations of data, assessment, and harvest control rule) and performance measures related to stock biomass and fishery outcomes (e.g., yield, variability in yield, and risk). Closed-loop computer simulations are currently the only practical way to test whether harvest strategy designs that appear precautionary *in theory* are actually likely to be precautionary *in practice*.

Stock assessment model errors and target fishing mortality rates are the main factors that interact to create both short-term and long-term weaknesses in fishery harvest strategies. The limitations of fishery stock assessment models are reasonably well-understood – models that are based on high-quality data are generally good at estimating relative changes in abundance over time and sometimes abundance relative to reference points such as the unfished biomass; however, the models are also not always capable of providing unbiased estimates of the absolute fish stock biomass, mortality rates, or productivity. For output quota fisheries, including the northern cod fishery, biomass estimation biases from stock assessment models are translated directly into biases in short-term harvest quotas; that is, over-estimating biomass causes the actual fishing mortality rate on the stock to be greater than intended. If the fishery is managed using standard fishing mortality targets such as F0.1 or FMSY, then biomass estimation errors can propagate to substantially higher quotas than intended. Persistent biomass over-estimation during a stock decline may lead to a positive feedback because stock assessment model biases are usually worst when stock biomass is changing rapidly. Thus, stock assessment biases and relatively high target Fs can lead to long-term declines and, in some cases, collapses of important fish stocks despite considerable efforts put into data collection, stock assessment modelling, and theoretically conservative harvest control rules.

This paper develops a closed-loop computer simulation framework for evaluating proposed future harvest strategies for 2J3KL cod. The key elements of the framework attempt to closely mimic northern cod stock dynamics, stock assessment model performance, and management decision rules that aim to promote simultaneous rebuilding of both the stock and the fishery. Our intent is to demonstrate some of the key features and properties of closed-loop simulation as it could be applied to support future evaluation of harvest strategies for this fishery. Practical evaluation of harvest strategies for 2J3KL northern cod would necessarily involve substantial contributions from a broader range of policy-makers and fishery stakeholders.

# METHODS and study design

Management strategy simulations for output quota fisheries require three main components: (*i*) an operating model to represent population dynamics of the stock, the mechanisms generating survey and age-composition data, and relationships between harvest decisions and fishing mortality on the stock; (*ii*) a management procedure consisting of (at least) monitoring data, stock assessment analyses, and harvest control rules for setting target fishing mortality and catch limits; and (*iii*) performance indicators for comparing simulated outcomes against fishery objectives. The following sections describe the models used for each of these components. Our model notation attempts to maintain consistent conventions for state variables and parameters across both the operating model and stock assessment model, while also making clear the differences between operating model variables, equilibrium solutions, parameters estimated in stock assessment models, and variables derived from these parameter estimates. As a general rule, any parameter or variable (e.g., *B*0) that does not show a "^" or "~" symbol is part of the operating model. Variables without subscripts for time (e.g., ) are considered constant and usually represent equilibrium quantities. The symbol "^" over a variable indicates a parameter (e.g., ) or variable estimated by the stock assessment model. The combination of "^" and "~" symbols and time subscripts (e.g., ) indicates a quantity that is a function of estimated stock assessment model parameters while time subscripts (e.g., "*T*") on parameters such as the one shown above indicate an estimate of that quantity given data up to the time step indicated. Vector objects are denoted using R-like notation such as 1:*T* in subscripts (e.g., ).



Some model features, such as the shape of the selectivity functions, time varying catchability, etc., are not included in this section, but instead are presented in the Appendix.

## Age-structured operating model

### Equilibrium characteristics and biological reference points

Abundance dynamics were simulated via an age-structured model with *A = 14* age classes, where the index *A* represents a plus-group. Notation, parameter settings, and equations for the operating model are given in Tables 1, 2, and 3, respectively. If required, equilibrium biomass and fishing mortality reference points for the age-structured model (Table 4) can be derived from either the yield-per-recruit (EQ3.4) and spawning biomass-per-recruit functions (EQ3.5), which involve only life history and selectivity parameters, or the total recruitment (EQ3.6), biomass (EQ3.7), and yield (EQ3.8) relationships, which involve all life history, selectivity, and stock-recruitment parameters. Operating model biological reference points *B*MSY and *F*MSY, and harvest control points (defined below) derived from age-structured stock assessment model parameters are also computed using these functions if necessary. Reference and control point proxies derived from yield-per-recruit (e.g., *F*0.1) or spawning potential ratios (e.g., *F*40%) are also computed using these equilibrium relationships, although none of these are implemented here for 23JKL cod.



### Population dynamics

The total simulation time frame (1983-2035) is divided into an historical period, , corresponding to 1983-2014, and a projection period, , corresponding to 2015-2035. The operating model population is initialized in the deterministic, unfished equilibrium state at time *t* = 1 (corresponding to actual year 1983). For 23JKL Cod, these initial equilibrium abundances are then modified by age-specific multipliers to re-scale abundances to non-equilibrium numbers-at-age taken from the 2016 NCAM stock assessment (Cadigan 2015). State dynamics are then driven by stochastic growth, recruitment, and natural mortality processes.



### Growth, recruitment, natural and fishing mortality, and maturity

We modelled size-at-age of cod by cohort using cohort-specific Walford growth parameters  estimated from the historical size-at-age data. These were estimated via ordinary linear regression of length-at-age *a* on length-at-age *a*-1. The values were highly correlated, so we modelled  as a linear function of  (OM2.10) to ensure that simulated future growth parameter maintained a similar correlation as in the empirical data. Equations OM2.11-2.13 show the sequence of calculations used to derive the annual weights-at-age. Length-weight conversion parameters and were obtained from Froese et al. 2014.

Recruitment to the population is assumed to occur in a single pulse at the beginning of the year. Annual age-1 recruitment values in the historical period are derived from the NCAM annual values of age-2 recruitment and the age-2 natural mortality rate estimated for 1983, assuming age-1 mortality for the historical period is identical to age-2 mortality. Similarly, natural mortality rates for the historical period were fixed at age-/year-specific estimates from NCAM.

Projections of the Walford growth parameter , recruitment and natural mortality are modelled as AR(1) processes in the operating model. Equation OM2.14, where the generic variable X represents one of these processes, gives the general formula. Autocorrelated deviations in the Walford growth intercept alphat have a standard deviation of sigma.alpha=0.1 and an autocorrelation coefficient of gamma.alpha=0.2. Recruitment deviations have a standard deviation , to maintain consistency with variability in NCAM, and an autocorrelation coefficient of gammaR=0.8. Finally, natural deviations have a standard deviation of sigmaM = 0.255 and autocorrelation coefficient of gammaM=0.534, consistent with NCAM estimates. Simulated natural mortality and growth rates for the projection period were scaled such that values of the historical and projection periods match exactly at the end of the historical period ().

Equations OM2.17-2.20 gives the abundance-at-age, spawning biomass, and exploitable biomasses implied by the parameters and fishing mortality rates. The operating model assumes a single fishery with  values derived via annual fully-selected F values in the historical period (from NCAM) and, in the projection period, via solutions to the catch equation (OM2.21) given annual quotas output from the management procedures (described below). Fishing selectivity-at-age is time varying, which in the historical period is solved from NCAM fishing mortality-at-age estimates by scaling the maximum values to 1. Projected selectivity-at-age is resampled with replacement from the historical values using a time series bootstrap, which is similar to a traditional bootstrap with one important difference. Where a traditional bootstrap will sample single points of data with replaced, the time series bootstrap samples random length segments from the history in order to preserve any auto-correlation that may exist in those segments.

Maturity-at-age is modeled by parametrically by cohort using logistic functions (equation OM 2.2). In the historical period, cohort-specific age-at-maturity ogives for 50% and 95% mature are estimated from observations of the proportion mature at age in the RV survey. When projecting forward, ogives are resampled from the historical data using the time series bootstrap.

### Data generation from the operating model

At each time step, the operating model generates a log-normally distributed exploitable biomass estimate or index with catchability coefficient  (OM2.23) and vectors of observed age-proportions in the fishery catch and survey, respectively. The survey index standard error is assumed constant at . Age-composition is modelled using multivariate logistic distributions with independent errors (OM2.24-2.26; Schnute and Richards 1995). Standard errors for simulated assessment age-composition data were .



### Operating model projection scenarios

Cod production is highly sensitive to adult natural mortality rates (M) and age-1 recruitment. We defined 12 operating model scenarios based on combinations of natural mortality (4) and recruitment (3) assumptions in the projection period.

The first natural mortality scenario (conM) is a stationary, zero-trend random walk  around the historical mean M value. This scenario provides a best-case benchmark. Other natural mortality scenarios each assume that historical natural mortality patterns resulted from the above random walk plus short-term pulses of extreme mortality, occurring at random with frequencies once every 40 years (pM40), once every 20 years (pM20), and once every 20 years while spawning stock biomass is below (pM20lim). A pulse magnitude of 650% of average was chosen to mimic the highest observed M event in the historical period.

The three recruitment scenarios assume that future average  is (i) constant at the recent average recruitment from 2005 – 2014, which is 16% of the 1980s mean recruitment (), (ii) 50% of 1980s mean recruitment (), or (iii) an increasing trend from the recent average to half the 1980s average ().

While this limited suite of scenarios is far from exhaustive, it suffices to demonstrate some of the challenges in developing management procedures in the presence of non-stationary population dynamics and in judging performance with respect to LRPs and fishery objectives.

## Management procedures

Simulated management procedures (MPs) in the projection period consist of three components: (1) a fishery data set involving time-series (t = 1, 2,…,*T*) of total catch, an exploitable biomass index time-series, and proportions-at-age in the fishery catch and RV survey; (2) a stock assessment model that uses the simulated data to estimate historical biomass, recruitment, natural mortality, selectivity, and stock-recruitment parameters up to time step *t* (AM.1), as well as any values required by harvest control rules (Cox et al. 2013); and (3) a harvest control rule for computing a catch limit based on stock assessment results. The sections below describe how each of these components is implemented in the simulations.

### Simulated stock assessment data

Although the operating model simulates the data used in fishery stock assessments, the MP controls the types, frequency, and precision of the simulated data because these are typically under management control. Annual estimates of cod spawning biomass are required by all management procedures. For this study, we generated unbiased, absolute values of spawning biomass as the biomass index data (OM2.23). The coefficients of variation (CVs) of these estimates were constant over time and set to values estimated in the 2015 stock assessment (see above for standard errors). Fishery and survey age-composition data required for the simulated SCA stock assessments (defined below) are generated annually from OM2.24-2.26.

### Catch-at-age stock assessment models

The statistical catch-at-age assessment model (AM; Table 4) used in the simulated management procedures differs slightly from the age-structured operating model. The four main differences are that (*i*) recruitment in the AM is based on a Beverton-Holt stock-recruit relationship with uncorrelated process errors (AM.6 and Table 6 eq L.4), (*ii*) catch in the AM is taken assuming a discrete fishery (i.e. a single fleet) occurring at the beginning of the year (AM.7) instead of continuously as it is in the operating model, (*iii*) weight-at-age is assumed constant in the AM, and (*iv*) the AM assumes only a single time-varying *Mt* value that applies to all ages. Equations AM.1-AM.8 show how the relevant calculations in the AM are affected by these differences. The AM estimator uses all potential data sources generated by the operating model, including catch, biomass survey indices, and proportions-at-age in the catch and survey. Operating model schedules of maturity-at-age are assumed constant and known in theAM and are therefore part of the assessment input data. Recruitment deviations are only estimated for years because there is little information in age-composition data about more recent recruitment. We use age-at-50% maturity instead of age-at-50% selectivity to bound the size of the recruitment deviation vector because the former is a known input whereas the latter is based on estimated model parameters and therefore violates AD Model Builder rules of differentiation (i.e., the length of a parameter vector cannot be a function of an estimated parameter). Natural mortality rate is estimated in the AM as a random walk to allow for non-stationary natural mortality. In all cases, we use a somewhat informative prior on the initial *Mt* value at *t* = 1.



Maximum likelihood estimates of error variances are computed analytically in the AM by conditioning on the leading parameters. For this study, we assumed that RV survey catchability  in the AM because (i) preliminary tests of the AM estimator assuming  closely matched actual stock assessments that estimated q (which was close to 1 anyway) and (ii) assuming  gives a more stable AM estimator in closed-loop simulations.

Table 6 provides the likelihood components and calculations involved in the negative-log-posterior distribution function (*G*; L.10). The AM uses an errors-in-variables (EIV) maximum likelihood formulation for modeling the combined biomass index and process error likelihood (; L.1-L.6). The EIV approach reduces the number of estimated parameters by assuming a total error variance () that comprises observation error () and age-1 recruitment process error () components, i.e., . Assuming that the observation error proportion of this total is known (), the individual variance estimates are and , where the estimate of the total variance is given by L.5. Our justification for the EIV likelihood is similar to our q=1 assumption; that is, it is generally faster to simulate and produces results similar to more complex and time-consuming estimation methods.



We use a robust normal likelihood (Fournier et al. 1998) for the age-proportion data (L.7) assuming sample sizes are all equal to an effective size . The total negative log-posterior distribution function includes an informative Beta prior distribution on the stock-recruitment steepness parameter (*h*; L.8) and an informative prior distribution on the natural mortality rate at *t*=1. The shape parameters () of the Beta distribution (L.8) for steepness are derived via moment matching to a prior mean (), standard deviation () given the constraint . These informative prior distributions improve stability of the AM parameter estimation procedure, but otherwise have little impacts because simulated harvest control rules do not use MSY and *F*MSY estimates.



The AM outputs include predicted values for all the input data sources given above as well as derived equilibrium quantities (which may or may not be used), and time-series of exploitable biomass (), spawning biomass (), fishing mortality rates (), and age-1 recruitment ().



### Harvest control rule

We examined a single harvest control rule with a constant target F0.1 = 0.18/yr fishing mortality rate of to demonstrate the simulation framework. This rule uses the estimated present state of the stock (i.e., ) from the AM and a projected expected biomass to determine a catch limit for the upcoming year () by solving the Baranov catch equation,



where is a 1-year-ahead stock assessment model projection of the exploitable biomass for the coming year and is the current estimate of natural mortality from the assessment model. This projection is based on deterministic age-1 recruitments from the estimated spawner-recruit relationship for years to because recruitment is not well-estimated in more recent years (see above).



Finally, annual catch taken from the operating model population is set equal to the TAC obtained from the target fishing mortality; that is, we assume that all the TAC is landed (no unreported or at-sea discarding) and the fisheries close when the TAC is reached. Some of these assumptions are not realistic for 2J3KL cod, but the model could be easily modified if required.

### Performance measures

We use five common metrics to summarise conservation and yield performance of simulated management procedures.

Conservation performance was measured using the median proportion of simulations in which the spawning biomass drops below the operating model , i.e.,

1. the probability (*)* of spawning stock biomass being within Critical zone () at the end of year ().

Yield performance of each MP is summarized via:

1. the median average annual catch () during the period ();
2. average annual variability of yield (AAV);

,



where *Qt* is the simulated quota obtained from applying a given MP in year .

The final 2 metrics provide information about stock rebuilding during the projection period:

1. first year in which is reached with probability *p*: ();
2. first year in which USR = with probability *p*: ().

These are estimated as the first time that the th percentile of all projected trajectories passes or the USR = .

# Results

## Simulation model dynamics

The operating model (OM) agreed reasonably well with the historical spawning biomass estimates from NCAM (Figure 3), which is not surprising given that the OM is initialized with NCAM abundances, natural-mortality-at-age, fishing mortality-at-age, as well as changes in weight and maturity at age over time. Figure 3 also shows the alternative assessment estimates of biomass, F, and M from applying the management procedure assessment model (i.e., AM, Tables 5 and 6) to the actual 2J3KL northern cod data. Biomass estimates from this model also agree reasonably well with NCAM in the 1980s and in the period following the collapse. Although the AM also estimates high M leading up to the collapse, it also estimates much higher F and lower M during the collapse compared to NCAM. This probably occurs because of the AM assumption that survey catchability q = 1, while NCAM allows temporal variation in survey q.

Figure 4 shows the simulated natural mortality patterns arising from the 4 natural mortality scenarios, with two versions of pm20lim shown for contrast. The conM scenario M values occur in a tight envelope centered on the historical mean (Figure 4 – conM), while the two pulse M scenarios show either one period of pulse M events for the 40-year frequency (pM40) or 4 periods (one sustained for 3 years) for the 20-year frequency (pM20). The biomass-dependent natural mortality pulses (pM20lim) behave differently under the different recruitment scenarios. In the low recruitment scenarios (, ) the biomass stays below Blim more often, leading aggregate behaviour similar to the 20-year frequency scenario (pM20). In the high recruitment scenario (.5R) pulses occur in the short term because biomass is currently below Blim, and but less often near the end of the time series, resulting in a final pulse that is sustained for only one year.

Figure 5 shows the simulated recruitment patterns arising from the 3 recruitment scenarios. The scenario R values occur in a tight envelope around the recent (2005 – 2014) average age-1 recruitment for the projection period. The scenario envelope widens as average age-1 recruitment trends towards 50% of the 1980s mean. The scenario values occur in a wide, uniform envelope the same width as the final year of the scenario. Recruitment values are generated by modifying the average R value with log normal deviations, which act proportionally and result in wider envelopes for larger average recruitments.

Figures 6-9 demonstrate example simulation and management behaviour of the simulation framework under the F0.1 management procedure (MP) for each of the four natural mortality scenarios combined with the recruitment scenario. The behaviour of and are qualitatively similar to the scenarios, however there is more contrast between pM20 and pM20lim scenarios when there is higher recruitment.

Performance of the F0.1 MP under the conM scenarios is the most optimistic (Figure 6), showing the stock and fishery catch recovering rapidly over approximately 10 years to pre-collapse levels. Due to the on-average upward trajectory of biomass, the stock assessment underestimates biomass, and unreported or discarded catch does not have a significant impact, with fishing mortality maintained near the reference F0.1 = 0.18/yr. A low recruitment event approximately halfway through the projection period resulted in a realised F approximately twice the maximum reference value; however, the over-fishing impact was minor because the stock was generally in good health.

Dynamics of 2J3KL cod under the pulse M scenarios (Figures 7, 8 and 9) showed similar initial biomass growth to pre-collapse levels, but the unpredictable high natural mortality events caused dramatic collapse behaviour similar to that observed in the 1990s. During collapses fishing mortality spiked, realising values of F > 1.0/yr as the stock assessment could not detect biomass declines fast enough during pulse M events. In all of these cases recruitment is independent of biomass, so that the stock recovers once the TACs are reduced to nearly zero. In the particular simulation replicate we show, the low (pM40, Figure 7) frequency pulse M events are followed by a quick recovery to historically high biomass levels. Unfortunately, the high (pM20, Figure 8) frequency and biomass dependent (pM20Lim, Figure 9) pulse M events do not experience the same swift recovery, with high spikes in fishing mortality followed by slower growth. In both cases, the slow growth can be attributed to low recruitment leading up to and following the collapse, delaying recovery. Outside of the unpredictable M events, the realised fishing mortality is maintained near the target reference.

## Performance of the f0.1 procedure

Performance metrics for the F0.1 management procedure on each scenario are presented in Table 8.

As expected, in more optimistic scenarios, when average recruitment was higher and average mortality lower, the F0.1 MP showed high catches and relatively strong stock recovery to above . However, there was no  scenario where the limit reference point was reached with 50% probability (Table 8). In fact, there was effectively 100% probability that biomass remained below Blim in all .16R scenarios (Figure 10).

There were no scenarios in which the stock reached the upper stock reference point (2Blim) with at least 50% probability. Some replicates in .5R scenarios achieve this level (Figure 12), but far fewer than 50%. Slower biomass growth may be due in part to assessment errors that lead to realized F values much higher than F0.1 following high M events (Figure 13).

# Discussion

In this paper, we presented a closed-loop simulation framework for evaluating candidate harvest strategies for future management of 2J3KL (northern) cod. This simulation framework uses operating and assessment models that differ in complexity from the recent assessment of northern cod (Cadigan 2015) because of the intensive and repetitive nature of closed-loop simulation. Nevertheless, the simulations effectively demonstrate some of the key challenges in designing rebuilding strategies for stock that experience non-stationary in demographic parameters related to natural mortality and recruitment. Even conservative fishery policies derived under equilibrium assumptions fail to actually achieve conservative outcomes.

Recent stock assessments (Cadigan 2015) estimate large variability in recruitment and natural mortality processes in 2J3KL cod, although the models are largely descriptive and do not offer hypotheses to explain such behaviour. As a result, our operating model projections of recruitment and natural mortality dynamics mainly involve density-independent random processes. The exception, p20Lim, represented the hypothesis that small spawning stocks are more vulnerable to stochastic events affecting mortality.

The simulation framework presented herein provides a potential basis for evaluation of candidate 2J3KL cod harvest strategies. The operating model is flexible enough to include alternative hypotheses for cod dynamics either via alternative parameterizations of the current model or via addition of more structural population dynamics hypotheses.

## Limitations

The suite of operating models examined here is not exhaustive with respect to potential future natural mortality, recruitment, and fishing scenarios (for other critiques and responses see Appendix A). Clearly, we lack mechanistic understanding of the relationships among natural mortality, fishing mortality, and stock biomass. All of our scenarios, except the biomass-dependent 20-year pulse M, assume that recruitment and natural mortality are density-independent processes. While it is possible that recruitment and M may be density-independent over the short-term, such as our 20-year projection period, this is probably not true over multi-decadal time scales.

Although we included a diverse set of operating model scenarios and incorporated realistic assessment model errors in the simulated management procedures, there are some places where the model implementation could be adjusted. We did not account for random implementation uncertainty – or stochastic deviations between the intended TAC and the actual catch, and instead we assumed that the TAC was the entire amount of removals from the stock. However, there is potential in the fishery for unreported catch. For instance, subsistence fishing and at-sea-discarding of smaller pieces (high-grading) may combine in some years to increase fishing mortality to high levels, and the associated risks should be considered.

Parametric fishery selectivity can take both asymptotic and domed shapes (see Appendix A), but it is currently time-invariant. This has the effect of averaging over the historical variation that is observed in the fishing-mortality-at-age estimates from NCAM. Including an option for modeling time-varying parametric selectivity similar to maturity in the historical period, and projection either by time series bootstrap or random walk would reduce the smoothing effect of a constant selectivity and allow for modelling changing behaviours of harvesters or reactions of fish to gear.

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**APPENDIX A: Alternative Model Features**

This appendix outlines the extra features we added to the operating and assessment models following a DFO Science Response Review.

**A.1 OPERATING MODEL**

The operating model has alternative options for the shape of the selectivity function, the modeling of life-history parameters in both the historical and projection periods, and adding unreported catch to the yearly removals.

**A.1.1 Selectivity:**

There are three options for simulating fishery selectivity in the operating model. The first, implemented in the analysis above, reads in a selectivity-at-age/time matrix (here supplied by NCAM), which has explicit selectivity values for each age during each time period. Then, the future selectivity patterns are projected forward using the time series bootstrap method to sample the history, as described in section 2.1.3. The range of this historical period that the time series bootstrap may sample from can be set in advance. For instance, this can be used to sample from years where a single, inshore gillnet fishery has been operating to better reflect more recent selectivity patterns.

The other two options we included use parametric selectivity functions for dome-shaped or asymptotic selectivity curves. In each case, the operating model calculates the selectivity curve from a two-parameter model, and sets this as the constant OM fishery selectivity for the historical and projection periods. The parametric asymptotic selectivity model uses the logistic equation in OM2.3, with age-at-50% and -95% selectivity values supplied as parameters.

For dome-shaped selectivity-at-age, we use an unnormalised gamma distribution

 (a)

where  is the shape parameter and  is the inverse scale parameter.

We chose the gamma model for dome-shaped selectivity because of how it fit the historical period’s selectivity patterns. We fit three 2-parameter dome shaped models to the historical data using least squares, with residuals calculated as the difference between the model selectivity and the observed selectivity from NCAM. The three models were the gamma model, a normal model, and a log-normal model. We calculated the AIC of the resulting fits of each model and found the gamma model had the best fit (Figure 14), with  and .

**A.1.2 Life History**

Modelling life history has different options, depending on the particular life history trait.

**A.1.2.1 Maturity**

We have included two options for simulating maturity at age in the operating model. These options are similar to selectivity: there is a time varying option and a constant option. The time-varying option is implemented in the main analysis and described in section 2.1.3. Again, a historical period can be nominated for sampling with the time series bootstrap when projecting maturity forward. The constant option uses an asymptotic model of maturity-at-age (Eq. OM2.2), which has parameters supplied to the operating model, fixing maturity the same for all cohorts across time.

**A.1.2.2 Natural Mortality**

When applying a pulse of high natural mortality in the analysis presented in this report, we assume that the pulses last only for a single year, after which the mortality rate returns to normal. We included in the operating model an option to nominate a pulse period, during which the stock experiences a sustained high natural mortality event.

**A.1.2.3 Joint Time Series Bootstrap**

The usage of the time series bootstrap is not restricted to only a few LH parameters, and it can be applied to produce joint bootstraps of all life history parameters. We have included a switch in the operating model that, when activated, will jointly resample Walford growth parameters, maturity-at-age ogives and natural mortality-at-age rates for the projection. Maturity-at-age ogives are sampled from past cohorts instead of years. Again, the historical period sampled by the time series bootstrap can be restricted.

**A.1.3 Unreported Catch**

We have modeled unreported catch as an option to add a constant fraction *u* of the TAC to total removals. That is, the fishing mortality experienced by the stock is calculated from the true removals , with operating model selectivity applied. This leads to higher spikes in fishing mortality due to assessment error and decreased biomass under otherwise identical conditions (Figure 15).

**A.2 ASSESSMENT MODEL**

**A.2.1 Selectivity**

We now have 2 options for modeling selectivity in the assessment model. When activated, the assessment model will estimate a gamma model of domed selectivity (as shown above) instead of a logistic model. We chose a gamma model as it matches the dome-shaped model used in the operating model.

Table 1. Notation used in the operating model.

| Symbol | Description |
| --- | --- |
| *T*0 | Starting year of initialisation period |
| *T*1 | Year in which the management procedure begins (*T1* = 33, Year = 2016) |
| *T*2 | Year in which the simulation ends (*T2* = 53, Year = 2036) |
| *A* | Number of age-classes |
| *t* | Time step |
| *a* | Age-class in years |
| *B*0 | Unfished spawning biomass (units determined by units of weight-at-age) |
| *h* | Recruitment function steepness |
| *Mt* | Instantaneous natural mortality rate in year *t* |
| *L∞* | Asymptotic length (cm) |
| *L*1 | Mean length-at-age-1 (cm) |
| *k* | von Bertalanffy growth constant (/yr) |
|  | Age-at-50% maturity |
|  | Age-at-95% maturity |
|  | Age-at-50% selectivity by survey (X=S) and fishery (X=F) |
|  | Age-at-95% selectivity by survey (X=S) and fishery (X=F) |
|  | Dome-shaped selectivity shape parameter |
|  | Dome-shaped selectivity scale parameter |
| *q* | Spawn survey scaling parameter |
| *R*0 | Unfished recruitment |
| *ma* | Proportion mature-at-age |
|  | Proportion selected-at-age by survey (X=S) and fishery (X=F) |
| *wa* | Individual weight-at-age |
| x | Equilibrium yield (x=y) or spawning biomass (x=ssb) per recruit |
| *Na,t* | Number of age *a* fish in year *t* |
| *Ba,t* | Biomass of age *a* fish in year *t* |
|  | Spawning biomass in year *t* |
|  | Exploitable biomass in year *t* |
| *Ca,t* | Number of age *a* fish in year *t* catch |
| *Ct* | Fishery catch numbers |
|  | True proportion-at-age *a* in time *t* catch |
| *Qt* | Fishery catch biomass |
| *It* | Survey biomass estimate |
|  | Standard error of the random walk in recruitment |
|  | Standard error of the random walk in natural mortality rate |
|  | Standard error of the random walk in Walford intercept (growth rate) |
|  | Lag-1 autocorrelation in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter (). |
|  | Auto-correlated error in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter ( ) |
|  | *Normal*(0,1) error component in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter ( |
|  | Survey coefficient of variation in year *t* |
|  | Standard error of proportions-at-age in fishery catch (*X = F*) and surveys (*X = S*) |
|  | Uncorrelated *Normal*(0,1) error in log-survey |
|  | Uncorrelated *Normal*(0,1) error in logistic-transformed proportions-at-age |
|  | Zero-centred log-residual of proportion-at-age |
|  | Observed proportion-at-age *a* in year *t* catch |

Table 2. Operating model parameter values used to specify simulation scenarios. Equilibrium values in the final three columns are computed using M1983 and the historical values for . Biomass columns B0, BMSY and MSY are in units of Kt.



|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | B0 | avgR | M1983 | M2016 | M2036 |  |  |  | q |  |  |  |
| ConM\_.16R | 1388.07 | 254.3 | 0.39 | 0.36 | 0.28 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM40\_.16R | 1388.07 | 254.3 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20\_.16R | 1388.07 | 254.3 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20lim\_.16R | 1388.07 | 254.3 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| ConM\_.incR | 1388.07 | Trending | 0.39 | 0.36 | 0.28 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM40\_.incR | 1388.07 | Trending | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20\_.incR | 1388.07 | Trending | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20lim\_.incR | 1388.07 | Trending | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| ConM\_.5R | 1388.07 | 794.8 | 0.39 | 0.36 | 0.28 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM40\_.5R | 1388.07 | 794.8 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20\_.5R | 1388.07 | 794.8 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |
| pM20lim\_.5R | 1388.07 | 794.8 | 0.39 | 0.36 | 0.31 | 0.255 | 0.534 | 0.428 | 0.817 | 0.36 | 0.247 | 0.247 |

Table 3. General age-structured, continuous fishery operating model used in closed loop simulations of 23JKL Cod. The generic superscript "X" is used wherever a function is identical for the fishery (X=F) and survey (X=S).

|  |  |
| --- | --- |
| **Parameters** | |
| OM2.1 |  |
| **Maturity and selectivity schedules** | |
| OM2.2 |  |
| OM2.3 |  |
| **Stock-recruitment parameters and equilibrium population** | |
| OM2.4 |  |
| OM2.5 |  |
| OM2.6 |  |
| OM2.7 |  |
| OM2.8 |  |
| OM2.9 |  |
| **State dynamics** | |
| OM2.10 |  |
| OM2.11 |  |
| OM2.12 |  |
| OM2.13 |  |
| OM2.14 |  |
| OM2.15 |  |
| OM2.16 |  |
| OM2.17 |  |
| OM2.18 |  |
| OM2.19 |  |
| OM2.20 |  |
| OM2.21 |  |
| OM2.22 |  |
| **Survey and proportion-at-age observations** | |
| OM2.23 |  |
| OM2.24 |  |
| OM2.25 |  |
| OM2.26 |  |

Table 4. Equilibrium solutions for spawning biomass, , exploitable biomass, , and yield, , given a fishing mortality rate,. Top set of parameters, , is used to calculate operating model reference points. Elements of the parameter set, are estimates updated to time T by the assessment model – these are substituted for their operating model counterparts to compute equilibrium quantities B0 and FMSY as required by the harvest control rules. Values for FMSY are obtained by numerically maximizing with respect to .



|  |  |
| --- | --- |
| Eq. | Formula |
| EQ3.1 |  |
| EQ3.2 |  |
| EQ3.3 |  |
| EQ3.4 |  |
| EQ3.5 |  |
| EQ3.6 |  |
| EQ3.7 |  |
| EQ3.8 |  |
|  |  |

Table 5. Catch-at-age assessment model (AM) quantities that differ from operating model values. The generic superscript "X" is used for selectivity because fishery F and survey S selectivity functions only differ in the parameters given in AM.1.

|  |  |
| --- | --- |
| AM.1 |  |
| AM.2 |  |
| AM.3 |  |
| AM.4 |  |
| AM.5 |  |
| AM.6 |  |
| AM.7 |  |
| AM.8 |  |

Table 6. Components of the total negative log-posterior density function (G) given data up to time T. Negative log-likelihood functions for biomass index and recruitment () and age-proportion data (), prior distributions for stock-recruitment steepness () and natural mortality ( including M1 and deviations in the random walk).



|  |  |
| --- | --- |
| L.1 |  |
| L.2 |  |
| L.3 |  |
| L.4 |  |
| L.5 |  |
| L.6 |  |
| L.7 |  |
| L.8 |  |
| L.9 |  |
| L.10 |  |

Table 7. Estimates of important parameters from the 2016 stock assessment model NCAM (Cadigan, 2016), the assessment model (section 2.2.2) fit to the data for 23JKL cod and the operating model (section 2.1) initialized on NCAM outputs. Estimates are shown of Blim (average SSB for ), SSB2015, SSB2015/Blim, average M2015.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Blim | SSB2015 | SSB2015/Blim | M2015 |
| NCAM | 839 | 294 | 0.35 | 0.289 |
| AMdata | 833 | 190 | 0.23 | 0.186 |
| OM | 840 | 312 | 0.37 | 0.342 |

Table 8. Performance of the F0.1 management procedure under the 12 recruitment and mortality operating model scenarios. Performance metrics from left to right are: average catch (Kt) for 3, 5 and 10 year time periods, median probabilities of being in the critical zone for 3, 5 and 10 year time periods; the first time that Blim is reached with 50%, 75% and 90% probability; the first time that the upper stoc reference is reached with 50%, 75% and 90% probability; and average annual variation for the 10 year period. Taking median probabilities leads to probabilities that do not sum to 1 in some scenarios. Times marked NA in the and columns show that the operating model SSB did not reach those levels with probability *p* in the projection period (20 years). Bold entries indicate the best performance in each metric for each scenario combination.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **F0.1 Harvest Control Rule** |  |  |  | **Simulation outcome** | | |  |  | **Performance Metrics** | | |  |  |  |
| **Operating Model Scenario** | **Recruitment** |  |  |  |  |  |  |  |  |  |  |  |  | **AAV** |
| Constant M | *0.16R* | 56.92 | 61.71 | 54.88 | 0.97 | 0.99 | 0.98 | NA | NA | NA | NA | NA | NA | 26.34 |
|  | *incR* | 55.54 | 81.50 | 102.78 | 0.97 | 0.74 | 0.24 | 2030 | 2033 | NA | NA | NA | NA | 25.39 |
|  | *0.5R* | 63.30 | 169.91 | 161.00 | 0.61 | 0.02 | 0.03 | 2019 | 2020 | 2021 | NA | NA | NA | 26.26 |
| Pulse M every 40 years | *0.16R* | 55.58 | 54.52 | 50.74 | 0.97 | 0.98 | 0.98 | NA | NA | NA | NA | NA | NA | 28.37 |
|  | *incR* | 54.10 | 72.10 | 95.14 | 0.96 | 0.76 | 0.39 | 2030 | NA | NA | NA | NA | NA | 27.95 |
|  | *0.5R* | 64.37 | 150.22 | 146.03 | 0.68 | 0.20 | 0.19 | 2019 | 2020 | NA | NA | NA | NA | 27.69 |
| Pulse M every 20 years | *0.16R* | 54.20 | 49.19 | 42.07 | 0.97 | 0.99 | 0.99 | NA | NA | NA | NA | NA | NA | 27.03 |
|  | *incR* | 52.70 | 66.58 | 78.69 | 0.96 | 0.79 | 0.49 | 2032 | NA | NA | NA | NA | NA | 27.13 |
|  | *0.5R* | 61.98 | 146.08 | 123.37 | 0.71 | 0.29 | 0.28 | 2019 | 2030 | NA | NA | NA | NA | 28.76 |
| Pulse M 20 when | *0.16R* | 54.20 | 49.19 | 42.07 | 0.97 | 0.99 | 0.99 | NA | NA | NA | NA | NA | NA | 27.03 |
|  | *incR* | 52.70 | 66.58 | 79.57 | 0.96 | 0.79 | 0.48 | 2032 | NA | NA | NA | NA | NA | 27.13 |
|  | *0.5R* | 61.98 | 155.45 | 141.39 | 0.71 | 0.22 | 0.13 | 2019 | 2025 | NA | NA | NA | NA | 26.67 |



Figure 1. The harvest control rule (HCR) defined in section 2.2.3, with a constant target fishing mortality F = 0.18.



Figure 2. Total Allowable Catch estimated by using the HCR defined in section 2.2.3 and shown in Figure 1. The thin blue line shows the TAC as given by the noMaxTAC management procedure, and the thin black stepped lines show the TAC ceilings defined by the maxTAC rule.



Figure 3. Time series plots of outputs from the three models NCAM, AMdata and OM comparing (a) spawning stock biomass, (b) fully selected (maximum) fishing mortality and (c) mean natural mortality across all age classes. The OM is not shown in (b) or (c) as the NCAM values are identical for the years shown.



Figure 4. Natural mortality rate (M) envelopes by scenario. The vertical line represents the first year of the projection period. Simulation envelopes include the median (thick black dashed line) and central 90% of M trajectories over 100 simulations (grey shaded region).



Figure 5. Recruitment (R) envelopes by scenario. The vertical line represents the first year of the projection period. Simulation envelopes include the median (thick black dashed line) and central 90% of R trajectories over 100 simulations (grey shaded region).



Figure 6. A single simulation replicate from the scenario with constant average mortality and half of 1980’s average recruitment (conM\_.5R). Plots show a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of exploitable biomass, b) landed and actual catch, c) realized fishing mortality and d) recruitment numbers. Dashed lines represent actual catch (b), and target fishing mortality (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass.



Figure 7. A single simulation replicate from the scenario with a pulse of high mortality every 40 years and half of average recruitment in the 1980s (pM40\_.5R). Plots show a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of exploitable biomass, b) landed and actual catch, c) realized fishing mortality and d) recruitment numbers. Dashed lines represent catch including discards (b), and target fishing mortality (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass.



Figure 8. A single simulation replicate from the scenario with a pulse of high mortality every 20 years while with half of average recruitment in the 1980s (pM20Lim\_.5R). Plots show a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of exploitable biomass, b) landed and actual catch, c) realized fishing mortality and d) recruitment numbers. Dashed lines represent actual catch (b), and target fishing mortality (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass.



Figure 9. A single simulation replicate from the scenario with a pulse of high mortality every 20 years and half of average recruitment in the 1980s (pM20\_.5R). Plots show a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of exploitable biomass, b) landed and actual catch, c) realized fishing mortality and d) recruitment numbers. Dashed lines represent catch including discards (b), and target fishing mortality (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass.



Figure 10. Simulated spawning biomass (top) and catch (bottom) performance envelope plots for the all scenarios with16% of average 1980s recruitmentduring the projection period. Each pair of Biomass/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading). The dashed line in the biomass plots represents .



Figure 11. Simulated spawning biomass (top) and catch (bottom) performance envelope plots for the constant all scenarios withincreasing recruitmentduring the projection period. Each pair of Biomass/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading). The dashed line in the biomass plots represents .



Figure 12. Simulated spawning biomass (top) and catch (bottom) performance envelope plots for the all scenarios with50% of average 1980s recruitmentduring the projection period. Each pair of Biomass/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading). The dashed line in the biomass plots represents .



Figure 13. Fishing mortality envelope plots for the F0.1 management procedure under 4 combinations of the most and least optimistic mortality and recruitment scenarios. Large spikes in realised fishing mortality in the pM20 scenarios are the result of increased natural mortality, driving biomass down and increasing assessment error.



Figure 14. A comparison of parametric dome shaped fishing selectivity and the observed fishing selectivity (from NCAM). The thin grey lines are each a different selectivity-at-age line from the historical period, and the thick black line is the least-squares fit of the gamma model to the historical period.



Figure 15. A comparison of projected simulation dynamics with unreported catch (left) and no unreported catch (right). In this scenario, the unreported catch increased removals by 30% of the TAC, shown as the blue dashed line. As expected, with higher removals the fishing mortality rate spikes increases in times of decline due to assessment error.