A candidate harvest strategy for Canada's northern cod 2J3KL fishery: performance evaluation in the presence of time-varying natural mortality

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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 low fishing mortality rates. It is therefore critical to examine how potential harvest strategies might deal with such risks in the future. This paper develops a closed-loop simulation framework for evaluating candidate harvest strategies for Canada's northern cod fishery in area 2J3KL. The model simulates both the annual statistical catch-at-age (SCA) stock assessment and precautionary harvest control rules to mimic more realistic future information states. In particular, the simulated SCA model attempts to track changes in natural mortality so that potential consequences can be incorporated into the harvest control rule used to provide TAC advice.

The simulation 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. Key components of the framework are: (1) operating models that reflect a range of potential future changes in natural mortality, (2) candidate management procedures (MP) comprised of data, stock assessment, and harvest control rules (HCR) for determining annual TACs; and (3) biological limit reference points (LRP) and harvest strategy performance metrics derived from DFO policy and stakeholder input.

Cod production is highly sensitive to adult natural mortality rates (M), so we develop 5 scenarios for future natural mortality patterns. Our first scenario uses a time-series bootstrap of the historical natural mortality time-series. This approach has the advantage of matching the historical mean, variance, and auto-correlation in M over time. The disadvantage is that the mean of future M will be nearly identical to the historical mean. Thus, if current M (i.e., 2015) is below the historical mean, then, in the future, natural mortality rates increase and harvest strategy performance will look poor overall. The opposite occurs if M is currently greater than the historical mean – future M will be lower, on average, and therefore harvest strategy performance will look good. We used a set of three scenarios that assume historical natural mortality patterns resulted from short-term pulses of extreme mortality, and therefore that future natural mortality pulses occur at random every 10, 20, or 40 years. The final scenario projects M as a random walk around the historical average value to provide a baseline best-case scenario benchmark.

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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 was likely a contributing factor to the rapid changes in stock biomass over a short time (Cadigan 2016; CSAP 2016 proceedings). A return of natural mortality to levels observed prior to the collapse and relatively strong recruitment have combined to put the stock on a clear increasing trajectory such that the stock is currently estimated to be near 30% of BLim. Continued spawning stock biomass growth at this pace would potentially re-establish directed commercial cod fisheries in the relatively 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. Standard best assessment 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 harvesting decisions and the future state of the stock. 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 and mortality rates. 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 and stock assessment modelling.

This paper develops a closed-loop computer simulation framework to 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. The objective of the study is to evaluate the performance of model-based harvest strategies given uncertainty in future productivity of northern cod.

# 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 how each of these components are modelled for the northern cod fishery. 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., ).

## Age-structured operating model

### Equilibrium characteristics and biological reference points

Abundance dynamics were simulated via an age-structured model with *A* 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. Equilibrium biomass and fishing mortality reference points for the age-structured model (Table 4) are 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 computed using these functions. 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 is divided into historical () and projection () periods. 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 values of numbers at age from the 2016 stock assessment, NCAM (Cadigan 2015). State dynamics are then driven by stochastic recruitment (OM2.12 and OM2.15), natural mortality (OM2.13-2.14), growth, and fishing mortality processes (OM2.16-2.17).

Recruitment in the operating model is modeled as white noise around mean age-1 recruitment to mimic the process of NCAM as closely as possible (Cadigan, 2016). Expected age-1 recruitment to the population is estimated from the NCAM values of age-2 recruitment and age-2 mortality in 1983. Recruitment to the population is assumed to occur in a single pulse at the beginning of the year.

During the projection period , values for recruitment deviations  are drawn from  distribution and combined with the previous year’s deviation in an auto-correlated red-noise process with auto-correlation coefficient of 0.8. Values for fishing mortality  were computed by solving the catch equation (OM2.21) given annual quotas output from the management procedures described below.

### Natural mortality and growth

Natural mortality and the Walford growth intercept (hereafter referred to as growth rate) were modelled as trending AR(1) processes (OM2.10-2.11). For the historical period (1983-2015), natural mortality values were fixed at mortality-at-age estimates from NCAM, and growth rates were estimated from weight-at-age data using a length-weight transformation with and (Froese et al., 2014).

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 (). Future trends in natural mortality and growth rates simulated by random walk were linearly interpolated between the last historical value and a scenario-specific target (defined below) for the final time step  while preserving the random walk process defined in OM2.10.

### Data generation from the operating model

At each time step, the operating model generates a log-normally distributed exploitable biomass estimate or index (OM2.23) and vectors of observed age-proportions in the fishery catch and survey, respectively. Age-composition is modelled using multivariate logistic distributions with independent errors (OM2.24-2.26; Schnute and Richards 1995). Standard errors for simulated assessment data are all determined as part of the management procedure (described below).

### Parameterization from historical data

We parameterized the operating model from the NCAM age structured assessment of 23JKL cod data (Cadigan, 2016). NCAM provided natural mortality trajectories for ages 2, 3, 4, 5, 6, 7, and 8+, fishing mortality and numbers-at-age for ages 2 and up in 1983. Numbers-at-age-1 are estimated from numbers-at-age-2 by assuming age-1 mortality for the historical period is identical to age-2 mortality.

Specifically, we first initialized the operating model age-composition for each stock at the estimated unfished equilibrium values for the first time step using 1983 mortality at age. Then, we modified the values at each age to match the abundances-at-age in 1983 estimated from the numberis provided by NCAM. For the historical period, , we informed the population dynamics using assessment estimates of recruitment deviations (), natural mortality (), fully-selected fishing mortality ( ), estimated cohort-specific Walford growth parameters (), and time varying maturity-at-age. A comparison of the NCAM model and OM SSB trajectories is shown in Figure 11(a).

### Operating model projection scenarios

Cod production is highly sensitive to adult natural mortality rates (M) and cod abundance is highly sensitive to the age-1 recruitment. Therefore, 12 operating model scenarios were developed to capture combinations of 4 future natural mortality scenarios and 3 recruitment scenarios.

The first natural mortality scenario (conM) is a random walk around the historical mean value with a coefficient of variation of 0.25, providing a best-case benchmark scenario. The last 3 natural mortality scenarios assume historical natural mortality patterns resulted from short-term pulses of extreme mortality, and therefore that future natural mortality pulses occur at random. A pulse magnitude of 650% of average was chosen to simulate historical increases in natural mortality similar to the observed highest M event, but preserve a lower baseline average M by removing the autocorrelation seen in the history. The frequency of the high M pulses is set to once every 40 years (pM40), once every 20 years (pM20), and once every 20 years while spawning stock biomass is below (pM20lim).

The two recruitment scenarios reflect different levels of optimism about future recruitment dynamics. The first assumes that future recruitment events will deviate around an average R that is 50% of the 1980s mean age-1recruitment (.5R) and the second around an average that’s 150% of 1980s mean recruitment (1.5R).

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. These scenarios were expected to have the strongest impact on future fishery development. Making more optimistic scenarios (i.e. decreasing natural mortality) is less useful for testing fishery management because it would lead to more optimistic responses to management procedures.

## Management procedures

Simulated management procedures (MPs) consist of three components: (1) a fishery data set involving time-series (t = 1, 2,…,*T*) of total catch, a time-series of exploitable biomass indices, and proportions-at-age in the fishery catch and survey; (2) a stock assessment model that estimates historical biomass, recruitment, natural mortality, selectivity, and stock-recruitment parameters up to time step *t* (AM.1) as well as operational control points derived from these parameters as 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.

### Fishery 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.

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 is based on a Beverton-Holt stock-recruit relationship with uncorrelated process errors in the AM (AM.6 and Table 5 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, spawning biomass survey indices, and proportions-at-age in the catch. 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 both the OM and the AM because (i) preliminary tests of the AM estimator assuming q=1 closely matched actual stock assessments that estimated q (which was close to 1 anyway) and (ii) assuming q=1 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 maximum likelihood formulation for modeling the combined biomass index and process error likelihood (; L.1-L.6) in which the total error variance () is assumed to be comprised of 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 that our q=1 assumption – 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 , and time-series of exploitable biomass (), spawning biomass (), fishing mortality rates (), and age-1 recruitment ().

### Harvest control rule

There are two variable F and two constant F management procedures tested. The feedback harvest control rule we examine for the variable F management procedures uses data on the present (i.e., ) state of the stock to determine a catch limit for the upcoming year (). We examined two options for implementation of the harvest control rule that have been proposed as sustainable approaches to managing the Northern cod stock: the basic rule (noMaxTAC), and the same rule modified by a TAC ceiling applied at certain spawning stock abundances (maxTAC). Examples of both implementations are shown in Figures 1 and 2.

The harvest control rule computes the target fishing mortality rate  via a piece-wise linear function of the stock status estimated from the assessment, reference biomass level , two reference fishing mortality rates and, and control points *C*1 and *C*2, i.e.,

The rule uses the limit reference point estimated by NCAM as the reference biomass level (i.e., ). The two reference fishing mortality rates are and . The rule is designed to gradually increase fishing mortality to in a 2 stage process. First, while in the Critical Zone, the rule increases target fishing mortality to the conservative level . Then, once has increased above and entered a productive state, the rule ramps up with increased speed to approach the reference mortality at .

Once the target fishing mortality rate is determined, the harvest control rule computes the annual quota using the Baranov catch equation,



where  is a 1-year-ahead stock assessment model projection of the exploitable biomass for the coming year. These projections use estimated recruitments off the spawner-recruit relationship for age-1 abundances in years  to . Under the TAC ceiling (maxTAC), the annual quota is fixed to a TAC given by the following rules:

a-1. 5,000t when SSB is 0-25% of ,

a. 10,000t when SSB is 26-50% of ,

b. 15,000t when SSB is 51-75% of ,

c. 20,000t when SSB is 76-100% of .

Finally, we describe the two constant F management procedures. The first, conF, uses the lower reference fishing mortality rate . The second, F\_SAR, uses a fishing mortality rate estimated from the recent TAC of 35Kt set by the recent SAR document, with reference exploitable biomass assumed to be 538Kt.

### Performance measures

Five commonly accepted fishery performance metrics are used to provide a general indication of the conservation and yield performance of simulated management procedures.

Conservation performance was measured using

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

The above probability is calculated as the median across simulation trials of the proportion of years that the operating model spawning biomass is at or below .

Yield performance of each MP is summarized via:

1. the median average annual yield () 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 the stock performance over the full projection period. They are:

1. time to with probability p: ();
2. time to USR = with probability p: ().

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

# Results

## Simulation model dynamics

We selected four example replicates to illustrate the simulated dynamics of the conM 3 different pM operating model scenarios for average R recruitment in Figures 4 through 7. Only replicates for the .5R recruitment scenario are shown, as the behaviour of 1.5R scenarios is the same but with numbers inflated by a factor of 3. Results are summarized using retrospective patterns of AM performance, the realized spawning biomass, catch, and fishing mortality outcomes from the closed-loop simulations. Results are presented only for the noMaxTAC management procedure, as the behaviour of the other MPs all had similar dynamics in each replicate.

The conM operating model scenario is the most optimistic natural mortality scenario. Simulated spawning stock biomass (SSB) increases slowly on average during the projection period (Figure 4a), with occasional spikes followed by declines occurring 3 years after low recruitment events due to the maturity lag (Figure 4d). The AM shows an interesting retrospective pattern, often underestimating SSB while the stock is increasing, but overestimating SSB during years of steep decline corresponding to those low R events (Figure 4a, blue spaghetti lines). Overestimates of biomass during years of steep decline causes spikes in realized fishing mortality resembling fishing mortality in 2003, much lower than peak historic levels.

The ‘pulse’ simulation scenarios represent the case of periodic (every 40 or 20 years) extreme 1-year natural mortality events, after which M returns to the historical average. In these scenarios, the frequency of high M events determines their relative impact – more frequent extreme events (e.g. pM20, pM20lim) maintain lower average spawning biomass, and thus realize a smaller stock decline than less extreme events (e.g. pM40) in which spawning biomass is allowed to build to high levels (compare Figures 5a and 6a). Because of this, the pulse20 scenarios are similar to the NCAM estimated M history, with periodic increases and decreases in SSB (Figures 6a, 7a). In addition, recruitment affects the SSB trajectory, with low recruitment events contributing to stock declines, as in the conM scenario. Occasionally, recruitment will drop 3 years before the mortality pulse, combining to reduce the SSB even further than the high M events. Due to these combined forces of recruitment and mortality, the retrospective pattern in assessed stock biomass creates a lag leading to large spikes in realized fishing mortality exceeding historic levels, resulting in overfishing following precipitous declines in SSB (Figures 5c, 6c, 7c). However, with less frequent pulses recovery from these events is rapid due to the lower average value of M over the projected period, as well as the lack of autocorrelation in the mortality time series (compare Figures 5a, 6a).

Generally, recruitment and mortality can independently and in combination create precipitous declines in spawning stock biomass, leading to large assessment errors and spikes in realised fishing mortality. This phenomenon is observable in the single replicate retrospective analyses where small pulses of fishing mortality occur 3 years after a low recruitment event in the constant M scenario (Figure 4a), and larger pulses in the pulse M scenarios when low recruitment and high mortality events combine (Figures 5a, 6a and 7a). The same phenomenon is observable in the aggregate fishing mortality envelope plots, where the pulse M scenarios have large spikes in the aggregate performance, with higher spikes for the 1.5R scenarios (Figure 13).

In spite of the complex nature of the dynamical relationship between M and R, the envelope plots of biomass depletion as a fraction of and catch show similar behaviour for each mortality scenario (Compare Figures 8, 9, 10, 11 for .5R). For lower average M scenarios (conM, pM40) the distributions in the envelopes are somewhat more concentrated, while the higher average M scenarios (pM20, pM20lim) have more variability. Comparing the same mortality scenarios between 1.5R and .5R recruitment scenarios shows the same general behaviour, but inflated by a factor of 3 as in the single replicates.

## Management procedure evaluation

The "No-fishing" scenarios illustrate the average dynamics of the simulated population across the range of natural mortality and recruitment scenarios we tested (Tables 8 and 9). This provides a benchmark for the remaining management procedures within each scenario.

The conM mortality scenario is the most conservative “best case” future scenario, resulting in the highest average catch for both recruitment scenarios and best times to and. The pM scenarios are the least conservative, resulting in a lower average catch and higher probabilities of being below , even in the absence of fishing (Tables 8 and 9). The introduction of harvesting moves the system to a less conservative state in all scenarios.

The two variable F MPs performed largely the same across scenarios. Differences were primarily observed in the 2 yield performance criteria, average catch and average annual variation (AAV) (Tables 8 and 9). In the short term, maxTAC realises higher average catch than noMaxTAC due to the TAC ceiling exceeding the HCR at low abundance (Figure 2), while they are both similar in the long term. AAV differed the most when mortality rates were higher on average, with maxTAC realising lower AAV than noMaxTAC in the pulse M scenarios. The maxTAC MP was designed to reduce AAV while SSB is at low levels, and this is evident in the simulation results. Note however, that when explored for the full set of simulations the aggregate difference in catch and depletion between the MPs is minor (Figures 8, 9, 10, 11).

The two constant F MPs performed similarly in dynamics. They both tracked spawning stock biomass with stability, and the AAV was the lowest for both MPs in all scenarios. The main difference between the two was in average catch, with F\_SAR consistently realising about 200% of the conF average catch over 3, 5 and 10 years across scenarios. Due to this, the probability of leaving the critical zone, and the time it took to do so, were higher for F\_SAR than conF.

The limit reference point is used to define the upper limit of the critical stock status zone at 885Kt according to NCAM estimates (Table 7). The main differences in performance of MPs reaching the limit reference point (, , ) or upper stock reference point (, , ) were between natural mortality scenarios rather than between MPs (Tables 8 and 9). Scenarios with lower average natural mortality were found to reach more quickly, sometimes within 5 years of beginning the management procedure. MPs in the 1.5R scenarios were the only cases where the USR was reached with any probability during the projection period, caused by the higher average recruitment.

# Discussion

We ran 40 simulations, combining 5 management procedures and 8 scenarios combining 4 mortality scenarios with 2 recruitment scenarios. We found natural mortality and recruitment of 23JKL cod were important contributors to the simulation model dynamics and the management outcomes as measured by the performance metrics defined in section 2.2.4. These two main drivers also combined in interesting ways, giving rise to large assessment errors and spikes in realised fishing mortality in projected scenarios.

The importance of natural mortality and recruitment is highlighted by the and metrics, which measure the time that and , respectively, are first exceeded in 50%, 75% and 95% of simulation replicates. Small increases in the probability of high mortality significantly slow the pace that 23JKL cod reaches , with less than half of the management procedures in .5R scenarios reaching with 75% probability. However, the same scenarios with a 3-fold increase in average recruitment show a marked difference in their performance, reaching the USR with 50% probability within 10 years in all cases.

On its own, the relative frequency of high impact M events has a counter-intuitive effect on spawning stock biomass. Higher frequency M events in the pM20 and pM20lim scenarios reduce the capacity of the stock to increase to high levels, reducing the relative magnitude of the assessment error preceding declines and producing smaller spikes in fishing mortality and less catastrophic collapses. In contrast, the lower frequency in pM40 events allow biomass to reach high projected SSB, as well as the largest magnitude collapses.

## Limitations

The suite of operating models examined here is not exhaustive with respect to potential future productivity, fishing and natural mortality scenarios. However, we believe that the diversity of scenarios and incorporation of realistic assessment errors is sufficient to support our general findings that management procedures for 23JKL Northern cod require evaluation by closed loop simulation to discover properties important to future fishery management decisions, such as the link between high mortality frequency and its impact to SSB.

Currently, the model assumes no link between SSB and age-1 recruitment, using average R recruitment dynamics with white-noise or red-noise deviations. Using average R recruitment causes the behaviour seen in the depletion envelope plots, where median depletion approaches a constant fraction. More variability could be introduced by using a stock recruitment relationship like the Beverton-Holt function to directly link SSB and age-1 recruitment.

## Future Work

In cases where extra heterogeneity in survey variances are desired, the CVs can be made to vary from year to year via independent and identically distributed draws from, for example, inverse-gamma (IG) distributions specified by period. The IG distribution parameters are obtained via moment matching to user-defined means and standard deviations for each period. Although such extra variation is really an operating model issue, providing all survey specifications in the MP seems less complicated.

Harvest control rules that follow expected DFO management procedures can be included, stepping through higher exploitation rates over different depletion levels. This would allow for more optimistic management procedures that seek to take advantage of situations similar to the high recruitment scenarios.

Finally, AMdata and OM are parameterised to data ending in 2014. Fitting AMdata and OM to the most up-to-date data would allow for a more accurate comparison between NCAM, AM and OM (Figure 12, Table 7)

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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 |
| *T*2 | Year in which the simulation ends |
| *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) |
| *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 |  |  |  |  | FMSY | BMSY | MSY |
| ConM\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.28 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM40\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20lim\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| ConM\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.28 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM40\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20lim\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |

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 |  |
| **Fixed life history 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 |  |
| **Survey and proportion-at-age observations** | |
| OM2.21 |  |
| OM2.22 |  |
| OM2.23 |  |
| OM2.24 |  |

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 | 788 | 255 | 0.32 | 0.342 |

Table 8. Management procedure (MP) performance for the scenarios with average age 1 recruitment half of the 1980s average age 1 recruitment. 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 the given probability in the projection period (20 years). Emboldened entries indicate the best performing management procedure in each metric for each scenario (except for no fishing procedures)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **0.5R Recruitment Proj** |  |  |  | **Simulation outcome** | | |  |  | **Performance Metrics** | | | |  |  |  |
| **Operating Model Scenario** | **MP** |  |  |  |  |  |  |  |  |  |  |  | |  | **AAV** |
| Constant M | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .58 | .06 | 37 | 37 | 39 | NA | NA | | NA | 0.0 |
|  | conF | 10.42 | 26.01 | 46.31 | 1.0 | .67 | .19 | 37 | 38 | NA | NA | NA | | NA | 25.23 |
|  | maxTAC | 8.33 | 17.5 | **87.64** | 1.0 | .66 | .21 | 37 | 38 | NA | NA | NA | | NA | 63.33 |
|  | noMaxTAC | 3.93 | 21.05 | 79.74 | 1.0 | .62 | .21 | 37 | 38 | NA | NA | NA | | NA | 63.24 |
|  | F\_SAR | **24.02** | **56.13** | 94.35 | 1.0 | .80 | .40 | 38 | NA | NA | NA | NA | | NA | **25.20** |
| Pulse M every 40 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .60 | .23 | 37 | 37 | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.34 | 25.95 | 40.70 | 1.0 | .73 | .32 | 37 | NA | NA | NA | NA | | NA | 31.41 |
|  | maxTAC | 8.33 | 21.75 | **67.18** | 1.0 | .71 | .35 | 37 | NA | NA | NA | NA | | NA | 37.85 |
|  | noMaxTAC | 3.76 | 21.45 | 66.82 | 1.0 | .68 | .36 | 37 | NA | NA | NA | NA | | NA | 97.07 |
|  | F\_SAR | **24.48** | **58.06** | 84.37 | 1.0 | .83 | .47 | 38 | NA | NA | NA | NA | | NA | **29.32** |
| Pulse M every 20 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .65 | .40 | 37 | NA | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.38 | 24.69 | 34.71 | 1.0 | .75 | .49 | 38 | NA | NA | NA | NA | | NA | **30.88** |
|  | maxTAC | 8.33 | 17.5 | 48.57 | 1.0 | .74 | .51 | 37 | NA | NA | NA | NA | | NA | 60.34 |
|  | noMaxTAC | 3.65 | 19.98 | **55.47** | 1.0 | .72 | .52 | 37 | NA | NA | NA | NA | | NA | 69.62 |
|  | F\_SAR | **23.43** | **56.84** | 71.10 | 1.0 | .85 | .61 | NA | NA | NA | NA | NA | | NA | 31.63 |
| Pulse M 20 when | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .65 | .31 | 37 | 44 | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.38 | 24.69 | 40.61 | 1.0 | .75 | .42 | 38 | NA | NA | NA | NA | | NA | **27.64** |
|  | maxTAC | 8.33 | 17.5 | 52.96 | 1.0 | .74 | .45 | 37 | NA | NA | NA | NA | | NA | 58.61 |
|  | noMaxTAC | 3.65 | 19.98 | **59.39** | 1.0 | .72 | .46 | 37 | NA | NA | NA | NA | | NA | 67.61 |
|  | F\_SAR | **23.43** | **56.84** | 76.79 | 1.0 | .85 | .56 | 49 | NA | NA | NA | NA | | NA | 30.36 |

Table 9. Management procedure (MP) performance for the scenarios projected with an average age 1 recruitment as 150% of the 1980s average age 1 recruitment. 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 the given probability in the projection period (20 years). Emboldened entries indicate the best performing management procedure in each metric for each scenario (except for no fishing procedures).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **1.5R Recruitment Proj** |  |  |  | **Simulation outcome** | | |  |  | **Performance Metrics** | | | |  |  |  |
| **Operating Model Scenario** | **MP** |  |  |  |  |  |  |  |  |  |  |  | |  | **AAV** |
| Constant M | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .25 | .0 | 37 | 37 | 37 | 38 | 39 | | 40 | 0.0 |
|  | conF | 10.10 | 22.27 | 92.66 | 1.0 | .30 | .0 | 36 | 37 | 37 | 38 | 40 | | 42 | **29.90** |
|  | maxTAC | 8.33 | 15.0 | **265.57** | 1.0 | .29 | .0 | 37 | 37 | 37 | 38 | 40 | | NA | 45.01 |
|  | noMaxTAC | 3.59 | 19.5 | 258.05 | 1.0 | .33 | .0 | 37 | 37 | 37 | 38 | 40 | | NA | 43.72 |
|  | F\_SAR | **23.0** | **51.10** | 193.65 | 1.0 | .38 | .0 | 37 | 37 | 37 | 39 | 40 | | NA | 31.86 |
| Pulse M every 40 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .35 | .13 | 37 | 37 | 52 | 39 | 40 | | NA | 0.0 |
|  | conF | 7.48 | 22.2 | 72.67 | 1.0 | .38 | .14 | 37 | 37 | NA | 39 | 43 | | NA | 34.87 |
|  | maxTAC | 8.33 | 15.0 | **204.23** | 1.0 | .38 | .15 | 37 | 37 | NA | 39 | NA | | NA | 43.0 |
|  | noMaxTAC | 3.41 | 16.16 | 200.24 | 1.0 | .36 | .15 | 37 | 37 | NA | 39 | NA | | NA | 46.81 |
|  | F\_SAR | **23.0** | **48.81** | 165.38 | 1.0 | .44 | .15 | 37 | 37 | NA | 39 | 53 | | NA | **33.78** |
| Pulse M every 20 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .40 | .22 | 37 | 38 | NA | 39 | NA | | NA | 0.0 |
|  | conF | 9.62 | 22.48 | 66.0 | 1.0 | .46 | .24 | 37 | 39 | NA | 40 | NA | | NA | **34.12** |
|  | maxTAC | 8.33 | 17.5 | **170.82** | 1.0 | .45 | .25 | 37 | 40 | NA | 40 | NA | | NA | 50.34 |
|  | noMaxTAC | 3.29 | 17.5 | 167.87 | 1.0 | .42 | .26 | 37 | 40 | NA | 40 | NA | | NA | 53.22 |
|  | F\_SAR | **22.57** | **49.66** | 133.02 | 1.0 | .52 | .25 | 37 | 40 | NA | 40 | NA | | NA | 35.87 |
| Pulse M 20 when | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .37 | .10 | 37 | 37 | 41 | 39 | 40 | | 45 | 0.0 |
|  | conF | 9.63 | 22.49 | 74.32 | 1.0 | .44 | .12 | 37 | 37 | 43 | 39 | 41 | | 46 | **29.67** |
|  | maxTAC | 8.33 | 17.5 | 188.61 | 1.0 | .43 | .12 | 37 | 37 | 43 | 39 | 42 | | NA | 46.71 |
|  | noMaxTAC | 3.29 | 17.51 | **205.22** | 1.0 | .40 | .11 | 37 | 37 | 43 | 39 | 42 | | NA | 47.72 |
|  | F\_SAR | **22.57** | **49.66** | 149.15 | 1.0 | .51 | .14 | 37 | 38 | 44 | 39 | 42 | | 46 | 31.82 |



Figure 1. The harvest control rule (HCR) defined in section 2.2.3, with a 2 stage increase in target fishing mortality F. In the critical zone (left of the red line) where the first stage increases slowly between F = 0 and F = 0.05, then for the target F increases more rapidly to 0.18, where it levels off in the healthy zone (to the right of the orange line).



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. 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 4. Single simulation replicate of the noMaxTAC management procedure under the Constant M scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 5. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 40 years scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 6. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 20 years scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass..



Figure 7. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 20 years while scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 8. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the constant M scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/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).



Figure 9. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 40 years scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/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).



Figure 10. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 20 years scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/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).



Figure 11. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 20 years while SSB is less than scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/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).



Figure 12. 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 13. Fishing mortality envelope plots for the maxTAC management procedure under all pM20 and conM 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. Higher average recruitment means that the peak biomass may reach much higher levels before a decline, leading to higher peaks of envelopes in the lower panels.