# Starting condition investigation

Aim of paper/short communication: show how the starting condition of a simple age-structured model can affect B0 based reference points under a range of factors. Hopefully provide some advice or insight into this common phenomenon.

# Introduction

Many fisheries worldwide have experienced commercial exploitation prior to the establishment of consistent observational time-series such as indices of abundance and or age/length composition. In some extreme cases, reliable monitoring commenced centuries after the onset of initial exploitation e.g., Atlantic cod (Schijns et al. 2021). This characteristic of commercial fishing prior to reliable data can lead to uncertainty in starting conditions in stock assessment models and flow through into related reference points (Punt et al. 2003, Punt et al. 2001). As assessments become more sophisticated i.e., spatially explicit, this uncertainty is expected to be compounded. New data is often instrumental in informing model changes, leading to a potential mismatch in resolution between historic data and more recent data which is anticipated to impact initial conditions and related reference points in stock assessments. Developing a spatially-explicit stock assessment for sablefish in the Gulf of Alaska was the motivation for this research. We found during model development that based reference points were sensitive to the model assumptions associated to the initial conditions and we wanted to know if there were robust parameterizations for initial conditions that we could implement to reduce this model uncertainty.

Due to differences in life-histories, catch histories, institutional inertia and data availability, there are multiple parameterizations and assumptions for the initial condition used in stock assessments around the globe and even within geographic jurisdictions (Li 2021). Given this variability in methodology, we conducted simulations that focused on the initial condition assumptions for age-structured stock assessments and investigated factors that may interact with initial condition and assessment outcomes.

In general, there are two approaches for configuring the initial conditions in age-structured stock assessments:

1. Choose a model start year close to unfished (pre-exploitation) conditions at the beginning of the historic period, where historical catch is imputed and assumptions made for stock dynamics assumptions for the historical period.
2. Choose a model start year at the start of the data and estimate the initial age structure for the model when data is available.

The first approach requires catch to be known with a high degree of certainty over the historic period. However, historical catches can be contentious and uncertain (Pauly & Zeller 2016, Simmons et al. 2016). The second approach is often preferred (Punt 2023, Punt et al. 2001), but in practice, these initial parameters can be difficult to estimate (Roberts & Dunn 2017) which can lead to large uncertainty in unfished spawning biomass () and related reference points, or at worst, unstable assessment models.

# Methods

We configured an age-structured operating model (OM) and estimation model (EM) that consisted of two periods during the modelled time-series. The first period is referred to as the “historical period”, which has fishing but no observations (except for catch). The second period is referred to as the “data period” and is the period with reliable observational data including an index of abundance, age-composition and catch inputs.

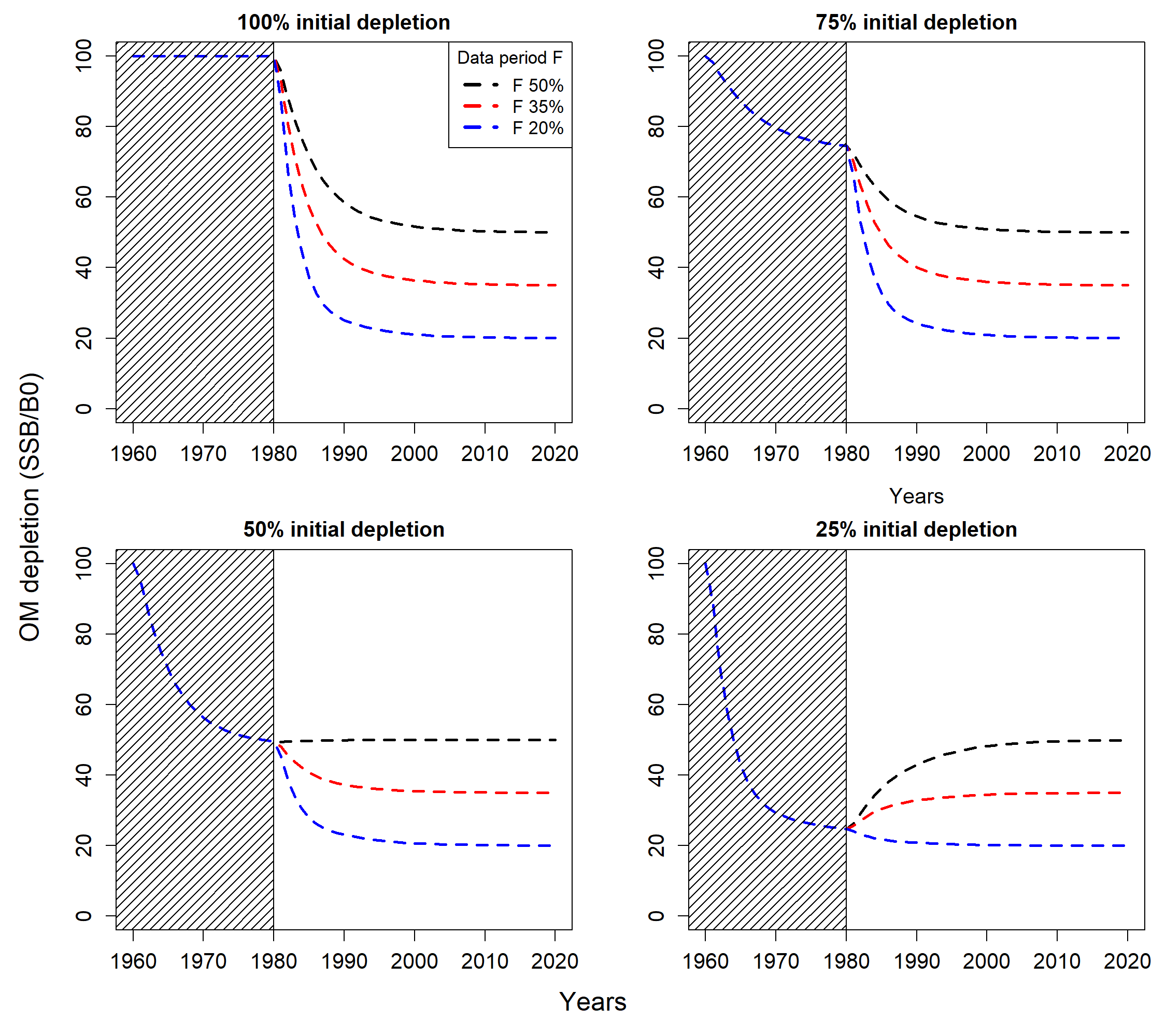
This simulation explored factors including life-history, length of observational time series, depletion level at the end of the “historic period” and fishing mortality trajectories during the data period. We focus on the estimation of and depletion / which are commonly used as an indicator of overfishing (New Zealand Ministry of Fisheries 2011, Mace 1994 **add more references here?**).

## Simulation

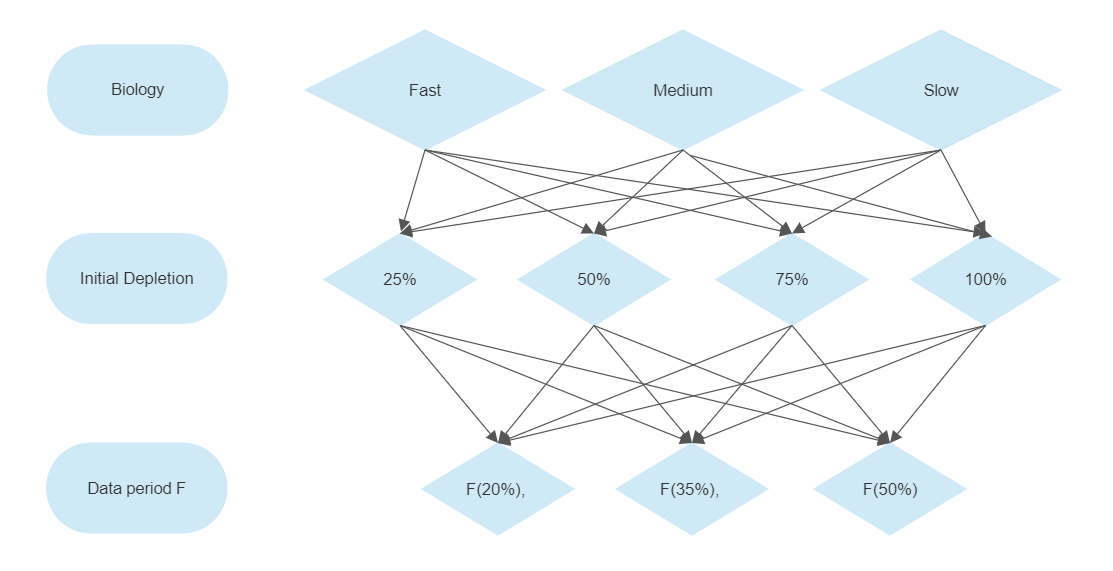
This simulation assumed the OM and EM had the same observation and process dynamics models (Appendix 1). The EM differed from the OM with respect to the initial conditions or catch assumptions during the historical period. Factors investigated with the OM included life-history (Table 1), which were based on life-history parameters from Wetzel & Punt (2016). For each life history we explored two nested factors which were the depletion level at the end of the historical period and the fishing mortality during the data period (***Figure 1***).

The following four levels of initial depletion were chosen 100%, 75%, 50% and 25%. It was anticipated that different initial condition assumptions would have differing outcomes based on the level of depletion when data became available. These depletion levels were found by applying a constant F during the historic period that achieved the desired depletion level under recruitment conditions. In reality when simulations were run there was stochastic recruitment through the historic period so not every simulation run would have achieved this exact depletion level, however on average the simulations would have.

The second factor was the fishing mortality (F) applied during the data period. The F values were , , where represents the fishing mortality value that leads to depletion. This factor was added to see if initial condition assumptions were sensitive to depletion trajectories during the data period i.e., whether there was a “one-way trip” or a rebuild over the data period, which was similar to the idea explored by Magnusson & Hilborn (2007). These OM factors are illustrated in ***Figure 2***, and resulted in 36 OMs (3 life histories x 4 initial depletions x 3 data period Fs). Each OM was run 250 times with stochastic recruitment and simulated data each year of the data period.



**Figure 1: Deterministic (constant recruitment set at ) depletion trajectories for the flat biology life-history. Each panel represents a different initial depletion level reached at the end of the historic period and each colored line represents different fishing mortalities assumed during the data period. The grey shaded area indicates the “historic period”. When simulations are run recruitment is assumed to be stochastic, this variability is illustrated in Figure ?? of Appendix C.**



**Figure 2: Schematic of factors that made up all OM scenarios.**

For each simulated data set, a collection of EM’s were applied to estimate the parameters and model quantities of interest ( and ). The EM’s varied based on initial condition formulation (explained in the next section) and how many years were in the data period either 40 years or 20 years respectively (indicated with model labels that have suffix \_00). The initial condition formulations were based on reviews of some of the most commonly used age-structured stock assessment platforms around the globe including, Stock Synthesis (Methot ), Multifan-cl (Fournier), WHAM (Millar) and Casal2 (Doonan et. al).

### Initial conditions used in EMs

Where , with estimable parameters which is the average unfished recruitment, are initial age deviations and is the initial fishing mortality parameters and is fishing selectivity associated with . The quantity is the recruitment adjustment factor used in Li et al. (2022). If the stock recruitment function is Beverton-holt (assumed in this study) and

Where, is the spawner-per-recruit (SPR) assuming and is the SPR under unfished conditions.

EM 1 unfished age structure

This formulation assumes the start year of the model is the first year of exploitation and only estimates the parameter i.e., & . This assumes catch to be known during the historical period and the model assumes catch is known with no error due to the use of the “hybrid” catch equation (reference stock synthesis manual). Three catch scenarios are explored with the EM1 formulation. The first, denoted by EM1 assumed catch was known perfectly and was unbiased, this is akin to the “self-test”, the second denoted by “EM1a” assumed catch was constantly underreported relative to the OM during the historic period by 25%, and the third denoted by “EM1b” assumed catch was over-reported by 25% relative to the OM during the historic period.

EM 2 estimate

This formulation assumes the start year of the model starts at the end of the historic period and estimates but not the initial age deviation parameters (. When only a single fishing fleet is modeled the choice of is straightforward. However, when models include multiple fleets the choice of needs further consideration. In this study was assumed to be the same as the fishing fleet operating during the data period.

EM 3 – estimate and

This formulation assumes the start year of the model also starts at the end of the historic period and estimates both and initial age deviation components. To aid in estimation the following penalty was added to the initial age-deviations

Where can be less than the maximum age and assumes ages beyond have no deviatios. This formulation extends EM2 by assuming a non-equilibrium initial age-structure through the estimable age deviation parameters denoted by . We assumed the initial age-deviations are from the same distribution as the recruitment deviations. This assumption could be loosened so that the initial age-deviations have their own estimable variance but for simplicity we assumed a pooled distribution with recruitment deviations.

### Performance metrics

The Relative error (RE) and median absolute relative error () were used to characterize both bias and precision simultaneously in and depletion (). For depletion performance metrics we displayed the maximum and minimum of these median relative errors across all years to characterize the range of bias in each scenario. The relative error for parameter model quantity is calculated

Nominal confidence interval coverage was also summarized to see how many of the simulations provided confidence intervals of and depletion that contained the value from the OM. Confidence intervals were calculated based on plus and minus two standard errors.

**Table 1: Life history parameters used in the simulation which are averaged values of male and female parameters from Wetzel & Punt (2016).**

|  |  |  |  |
| --- | --- | --- | --- |
|  | Fast (flatfish) | Medium | Long |
| Age plus group | 20 | 30 | 100 |
| Natural Mortality (M) | 0.15 | 0.08 | 0.05 |
| Steepness (h) | 0.85 | 0.65 | 0.50 |
| Maximum length ( | 58 | 34 | 64 |
| Growth coefficient () | 0.133 | 0.115 | 0.047 |
| Body weight | | | |
| Growth coefficient () |  |  |  |
| Growth coefficient () | 3.50 | 3.17 | 3.17 |
| Maturity (logistic) |  |  |  |
| Age at 50% maturity | 4.5 | 9 | 19.5 |
| Width for 95% mature | 1.8 | 3.2 | 6.4 |
| Fishery selectivity (logistic) | | | |
| Age at 50% selective () | 7 | 7 | 15 |
| Width for 95% selective () | 2 | 5 | 7 |
| Survey selectivity (logistic) | | | |
| Age at 50% selective () | 5 | 3 | 10 |
| Width for 95% selective () | 2 | 2 | 7 |
| Survey catchability () | 0.2 | 0.2 | 0.2 |
| Survey AF sample size () | 250 | 250 | 250 |
| Survey index standard deviation () | 0.15 | 0.15 | 0.15 |
| Fishery AF sample size () | 250 | 250 | 250 |
| Catch standard deviation () | 0.02 | 0.02 | 0.02 |

# Results

## Medium Biology

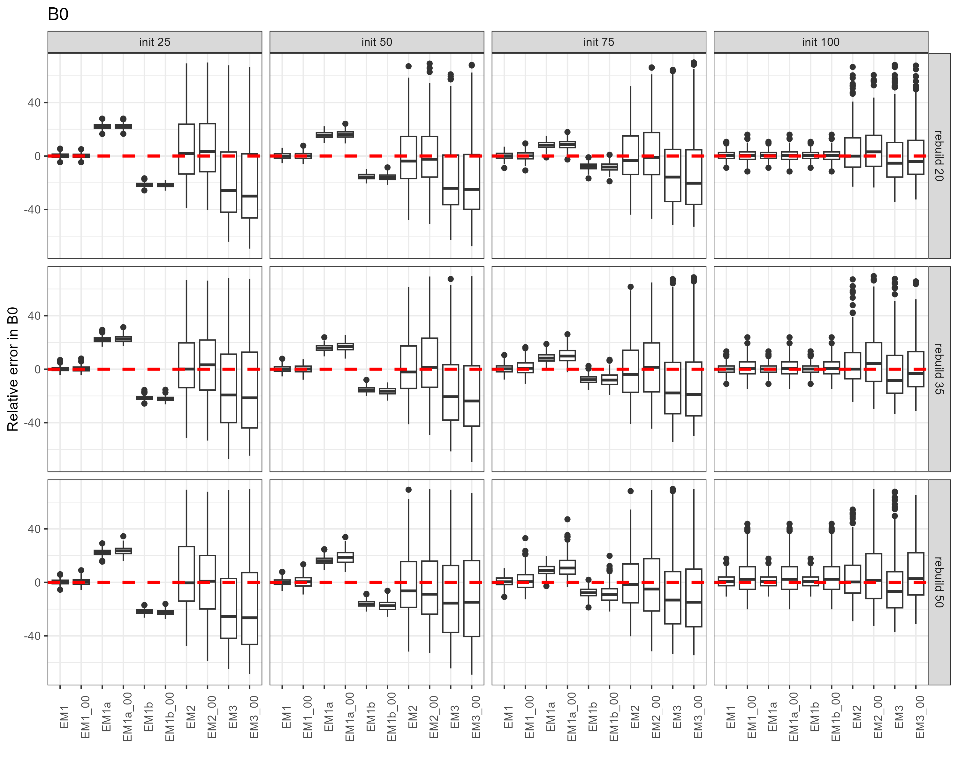


Figure : Relative error B0

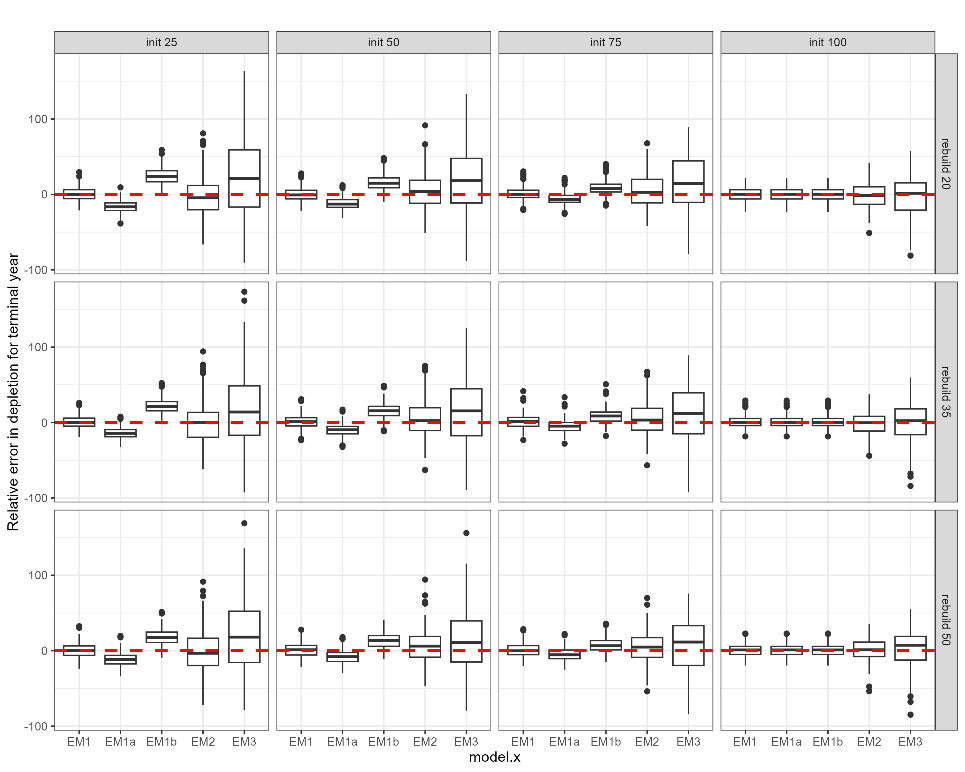


Figure : Relative error for terminal SSB

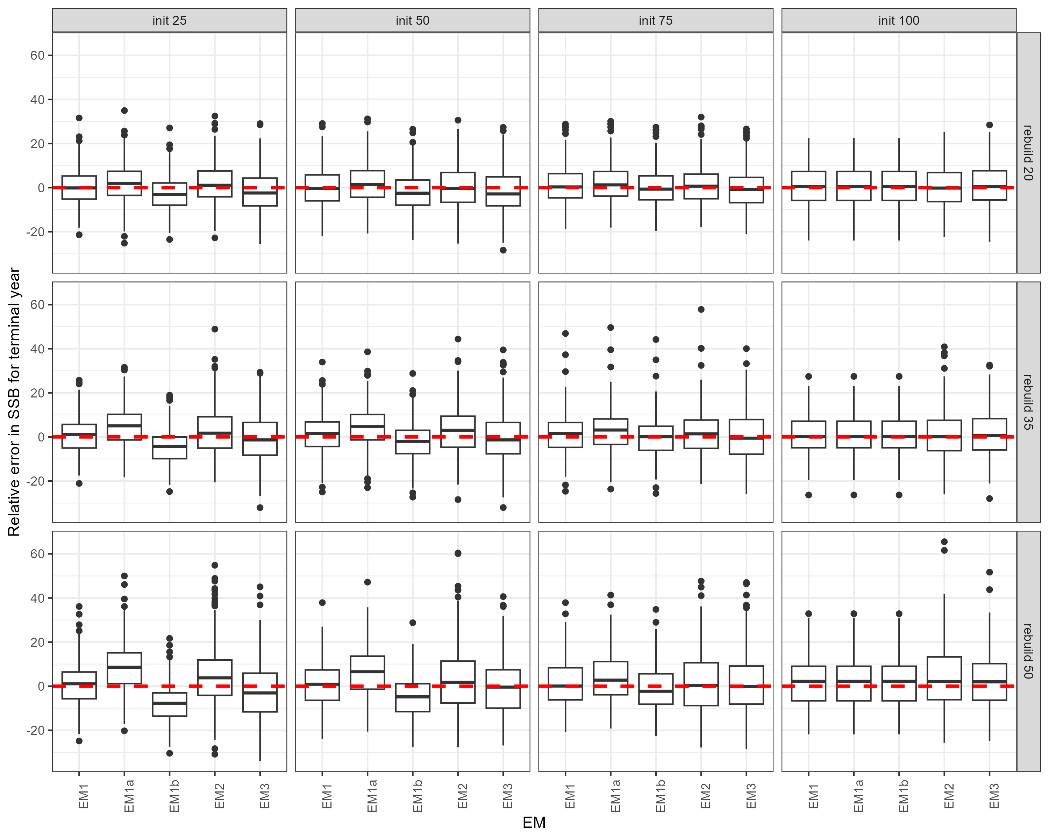


Figure : Relative error in absolute terminal SSB.

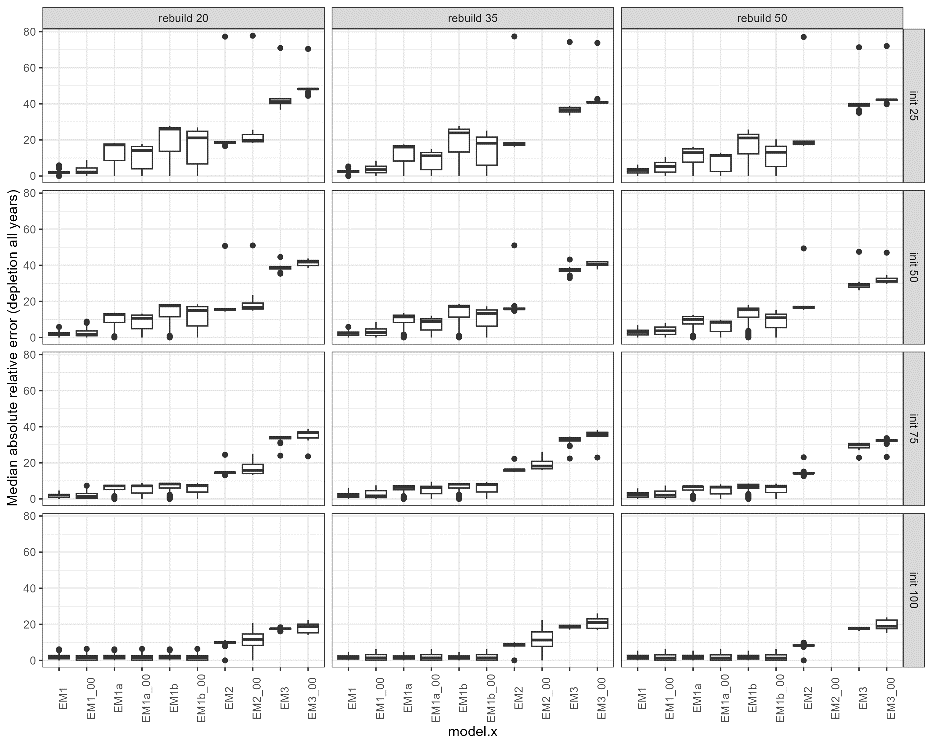


Figure : MARE for depletion over the entire time-series

Table : Nominal confidence interval coverage for B0.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| rebuild | init | EM1 | EM1a | EM1b | EM2 | EM3 |
| 20 | 25 | 0.948 | 0 | 0 | 0.22 | 0.164 |
| 35 | 25 | 0.94 | 0 | 0 | 0.26 | 0.204 |
| 50 | 25 | 0.932 | 0 | 0 | 0.288 | 0.22 |
| 20 | 50 | 0.956 | 0 | 0 | 0.156 | 0.168 |
| 35 | 50 | 0.972 | 0 | 0 | 0.204 | 0.176 |
| 50 | 50 | 0.956 | 0 | 0 | 0.232 | 0.224 |
| 20 | 75 | 0.964 | 0.132 | 0.176 | 0.152 | 0.196 |
| 35 | 75 | 0.936 | 0.216 | 0.256 | 0.192 | 0.172 |
| 50 | 75 | 0.936 | 0.328 | 0.44 | 0.312 | 0.264 |
| 20 | 100 | 0.94 | 0.94 | 0.94 | 0.176 | 0.268 |
| 35 | 100 | 0.944 | 0.944 | 0.944 | 0.252 | 0.232 |
| 50 | 100 | 0.956 | 0.956 | 0.956 | 0.42 | 0.332 |

## Flat Biology

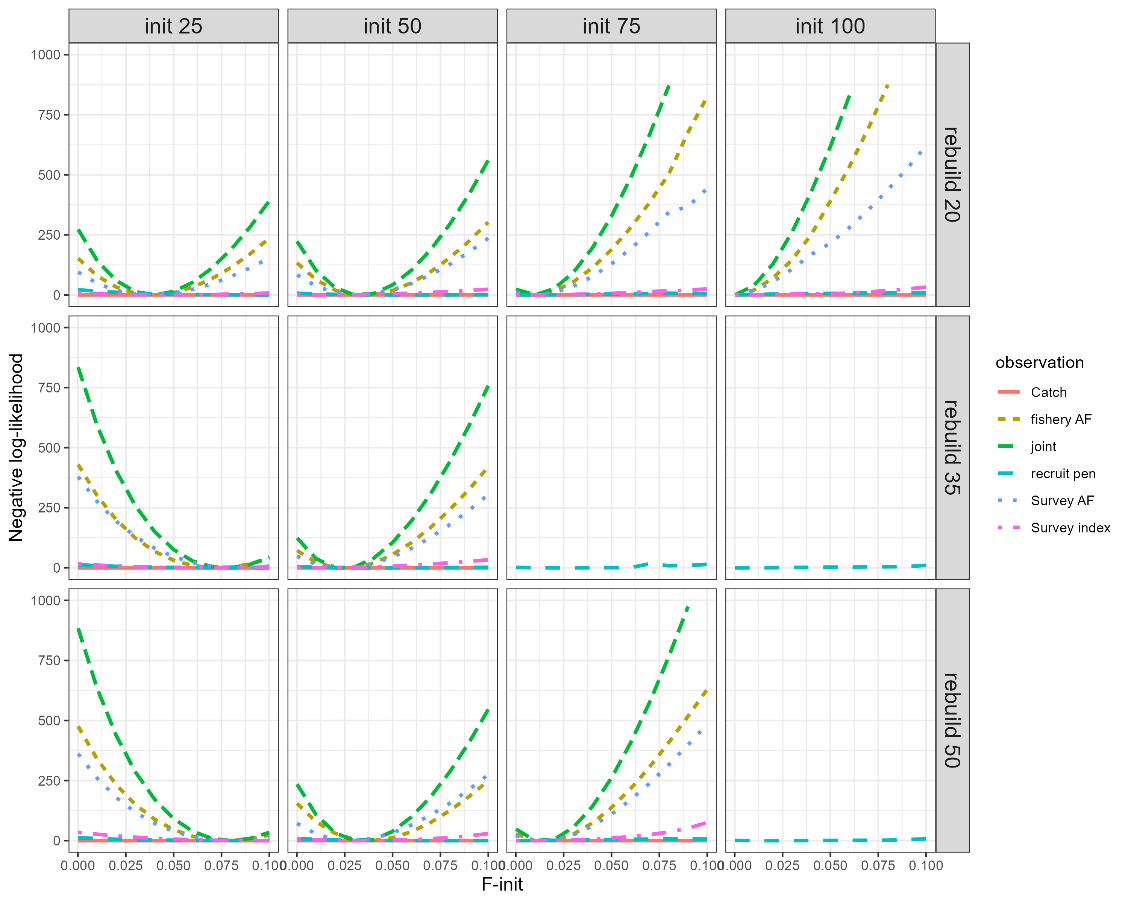


Figure : negative log-likelihood the F\_init parameter if EM3 medium biology for one simulation realization.

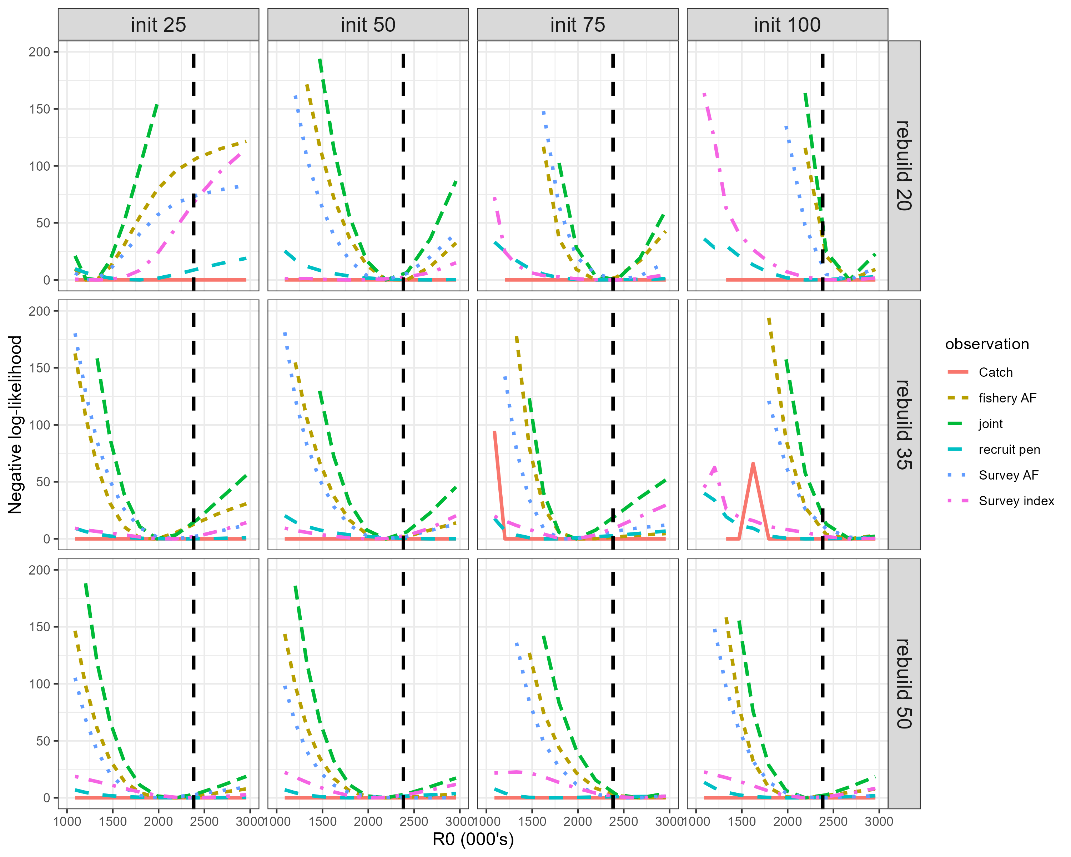


Figure : Negative log-likelihood the R0 parameter if EM3 medium biology for one simulation realization. The vertical broken line indicates the OM value.

# Conclusions

* B0 based reference points can be biased when catch history is uncertain.
* Models that estimate initial conditions (EM2 & EM3) have difficulty estimating B0. Generally lower this is relates to SR relationship assumed during and the length of historic exploition. The Z initialization used assumes that level of F is applied assuming , but do did estimate absolute SSB’s fairly well. This is likely to do with the initial F being applied as instantaneous rate when in fact there is trend in historical catch and so is approximating.
* Initial level of depletion was the most significant factor, the more depleted the stock when data begins the more difficult it is to retrieve B0
* More productive life-histories were slightly more robust to B0 and depletion estimates.

Future work/Caveats

* Father MSE testing required to explore robust BRP
* Suggest exploring B\_start data vs B\_current as in Punt (2001). Not biological or really meaningful but possibly robust
* No model misspecification was considered which is a weakness of this study, also no time-varying dynamics were considered which is also an unlikely situation.

# Appendix A

### Operating Model

#### Process dynamics y > 1

Where is the annual recruitment for age 1 which follows the Beverton-Holt stock recruitment relationship based on the steepness formulation from (**get mace and doonan reference**)

is the steepness parameter, is the spawning stock biomass in year , is the long term average unfished recruitment, is the spawning biomass that results from and applying only natural mortality, and are annual recruitment deviations which have the following penalty applied,

Where is a bias correction indicator variable, life-histories that have a lag between recruitment and selective ages in the observations had at the start and end years to encourage during periods of low to no data.

Spawning biomass is calculated as,

Where, is the numbers at age, is mean weight at age and is the proportion mature for age and is the proportion of total mortality that is applied before calculating SSB.

Total mortality

* is the sex and year specific fishery selectivity
* is the annual fishing mortality rate for fishery
* is the annual natural mortality rate.

Catch at age was derived using the Baranov catch equation,

With predicted annual catch biomass calculated as,

Both fishing and survey selectivity’s were assumed to be logistic following,

#### Observation dynamics

Each simulation generated a relative index of biomass from the survey with accompanying age-frequency, in addition to a fishery age-frequency.

Fishery dependent age-frequencies expected proportions were calculated as

Where, and observed numbers at age are denoted by and assumed to be multinomial distribution

Survey predicted numbers at age are denoted by are calculated as

Where, is the proportion of the year that the survey observations occur and is the survey selectivity.

The survey index of biomass in year is calculated as

Where, is the survey catchability. The observed relative index of biomass is assumed to be lognormally distributed,

Survey age-frequencies are similar to the fishery age-frequencies where, survey predicted numbers at age are normalized to sum to one over all ages in a given year,

Where, and observed numbers at age are denoted by and assumed to be multinomial distribution

Observed annual catch is also assumed to be lognormally distributed,

# Appendix B

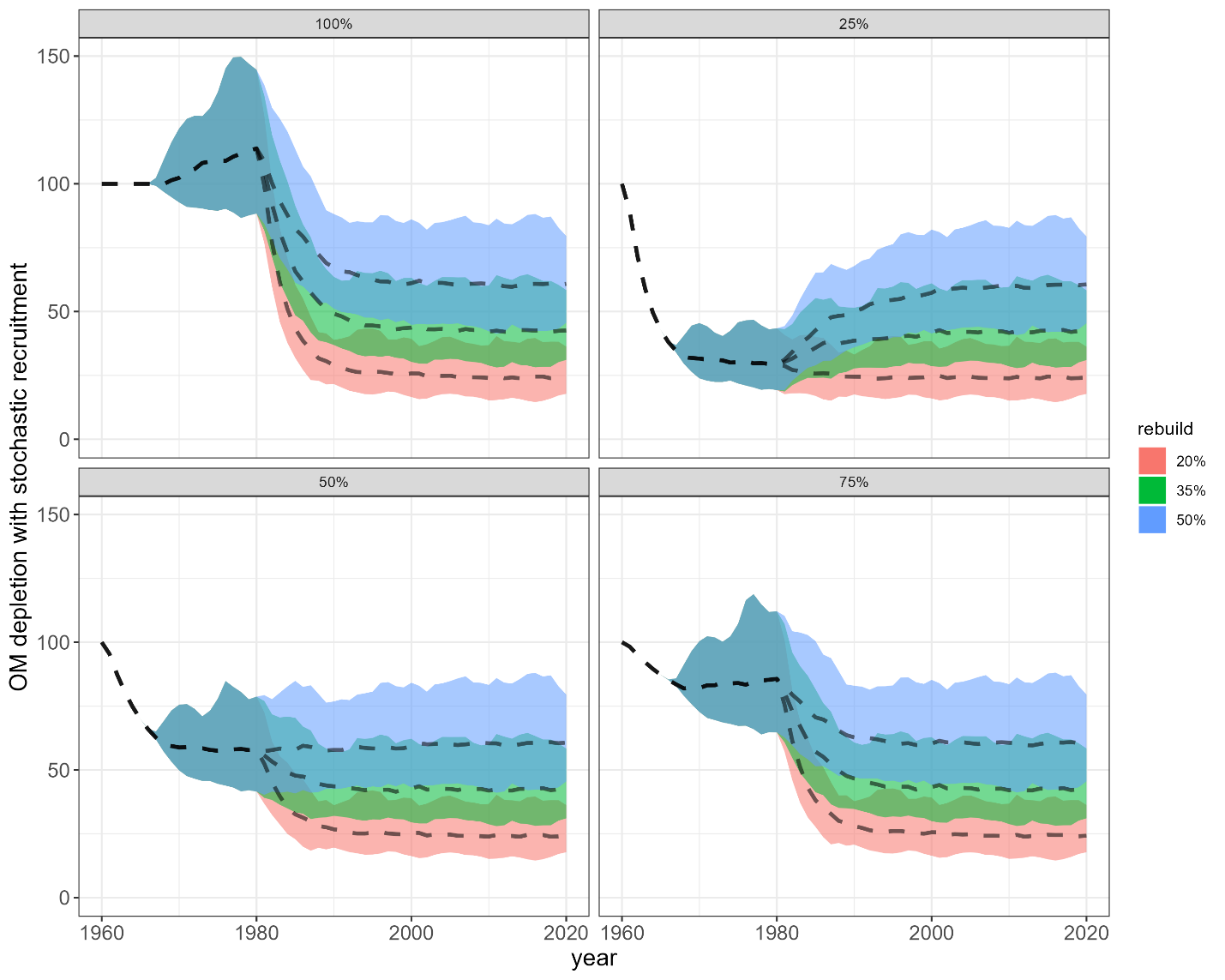


Figure : OM depletion across factors for the fast biology, which includes 100 simulated runs with stochastic recruitment.

# Appendix C: Sensitivities explore

Sensitivities for fast biology

Biannual data or double and half effective sample size (keep an eye on convergence)

Over/underreporting goes from 50% -> 0 via a linear interpolation during historic phase for EM1

# Appendix D

## Review core age-structured software and how they deal with this assumption

WHAM – Tim Miller

ASAP – Chris Legault

SAM – Anders Nielsen

SS – Rick Methot

CASAL2 – Me

Multifan-cl – Nick Davies

Email authors and ask them to check I have reflected their package correctly and review reference points and general input.

Ask if there other packages that I need to consider.

Ask for any other papers that they have come across on this topic that I have missed.

## Review age-structured stock assessment packages

Clarify some definitions, and are defined as the long term average recruitment and SSB that is expected with no fishing.

#### ASAP

Based on the document from (equation 9)

Where, and , where is an estimable initial fishing mortality by age. Ask about this estimated parameter?

#### SAM

This research focuses on non-state-space age-structured models, but for completeness we included the common initial conditions for age-structured state-space models using the paper from (Nielsen & Berg, 2014)This state-space age-structured model estimates the natural logarithm of numbers at age denoted by as an unobserved latent state. The initial conditions are estimated as random effects where

Sometimes a diffuse penalty/prior is needed on the initial stating state such as,

This formulation has no and parameters which means if the Beverton-Holt stock recruit is formulated as the traditional and parameterization described in

#### WHAM

I initially used Stock and Miller (2021) as my reference for this. However, I do not think it describes the initial age-structured conditions i.e. . I will check with authors, but for now, I am going to assume they are the same as ASAP (see below) or the same as SAM.

#### MULTIFAN-CL

There are multiple options in MULTIFAN-CL for estimating initial numbers at age (assuming a single region model). The first option is similar to SAM, which allows users to estimate initial numbers at age as fixed-effect parameter (Is there a transformation on this? i.e., log NAA)

The second approach is similar to the ASAP but changes the definition of and removes the age-specific deviations . The initial numbers at age are,

, where is an estimable parameter and is the recruitment deviation which assumes.

The third approach is the same as the second approach but assumes , where is the average fishing mortality over the set of years denoted by , generally the some initial year period. This assumes you are estimating annual fishing mortality rates as fixed effect parameters. If you are deriving F as catch conditioned using a Newton Raphson algorithm then you may need to estimate an initial Fishing mortality.

#### Stock synthesis (SS)

Stock synthesis has all the options that have been discussed above, with one exception. SS has an additional option that allows users to estimate the parameter denoted by which is a multiplier on during initialization. This allows for more or less average recruitment during initialization.

#### Coleraine

We used the description from Magnusson & Hilborn (2007), they had an addition Rinit parameter which scaled recruitment during the initialization calculations.

#### Casal2

#### vs

vs was a conversation I had with Dana Hanselman. The conversation come up with what reference points to use when stock assessments estimate different values. I believe there was confusion on what each of these parameters represent. Ignoring time-varying changes in productivity i.e., growth, natural mortality etc. Then depletion-based reference point () is proportional to the reference point. The first measures whether a stock is an overfished state or not, whereas the latter measures over-fishing. The optimal management outcome would be to fish at maintaining the desired . So when there is large uncertainty in estimates of it is difficult for us to identify if the stock is over-fished but we can still use to specify whether we are over-fishing.

is the equilibrium spawning biomass from assuming recruitment = and total mortality = natural mortality.

### Reference points

Static depletion

Dynamic depletion

Depletion based on initial year SSB (not )

Spawner per recruit (SPR)

Set and assume , where , and , where is the fishery selectivity

Where, is the weight at age and the proportion mature for age , is the proportion of total mortality () taken before SSB is calculated. Using the same idea you can also calculate Yield per recruit assuming the Baranov catch equation.

Yield per recruit (YPR)

Set and assume , where , and , where is the fishery selectivity

Where, is the weight at age and the proportion mature for age . Using the same idea you can also calculate Yield per recruit assuming the Baranov catch equation.

YPR is used to derive the reference points which is the F that maximize the YPR curve and which is the F corresponding to when the gradient of equals 0.1.

Maximum sustainable yield ()

Estimating Reference points

We used the same minimization criteria to estimate reference points as described by (Albertsen & Trijoulet 2020). Estimation of reference points was done inside the EM with other estimated parameters. This was done to leverage the automatic standard error derivation that TMB does which will include parameter uncertainty from related estimated parameters.

Table : OM and EM combinations for a given life-history

|  |  |  |
| --- | --- | --- |
| OM scenarios (these will be repeated for each life-history x3) | | |
| Label (OM\_initial\_rebuild) | Initial depletion | Constant F |
| OM\_100\_50 | 100% | 50% |
| OM\_100\_35 | 100% | 35% |
| OM\_100\_10 | 100% | 10% |
| OM\_75\_50 | 75% | 50% |
| OM\_75\_35 | 75% | 35% |
| OM\_75\_10 | 75% | 10% |
| OM\_50\_50 | 50% | 50% |
| OM\_50\_35 | 50% | 35% |
| OM\_50\_10 | 50% | 10% |
| OM\_25\_50 | 25% | 50% |
| OM\_25\_35 | 25% | 35% |
| OM\_25\_10 | 25% | 10% |
| EM scenarios (these will be applied to each OM scenario) | | |
| Label (EM\_assumption\_terminal) | Initial conditions | Terminal year |
| EM\_self\_1980 | EM1 | 1980 |
| EM\_under\_1980 | EM1a | 1980 |
| EM\_over\_1980 | EM1b | 1980 |
| EM\_F\_init\_1980 | EM2 | 1980 |
| EM\_F\_n\_init\_1980 | EM3 | 1980 |
| EM\_self\_2020 | EM1 | 2020 |
| EM\_under\_2020 | EM1a | 2020 |
| EM\_over\_2020 | EM1b | 2020 |
| EM\_F\_init\_2020 | EM2 | 2020 |
| EM\_F\_n\_init\_2020 | EM3 | 2020 |