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Review and Update of the State-Space Management Strategy Evaluation for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO with mseSurv

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Abstract

A new simulation framework (R package mseSurv) was developed and applied for the management strategy evaluation (MSE) for the Greenland halibut stock in NAFO Subarea 2 and Divisions 3KLMNO. The key steps in the simulation process is to initiate the simulations and model the population and fishery processes conditioned on outputs from the state-space assessment model (SSM) for the stock, generate fishery survey data, apply survey-based candidate management procedures (CMP) to the simulated data, and continue the update of the population and fishery processes to the number of years prescribed. At the end of the simulation period, stock and fishery based performance metrics PMs are calculated to evaluate the performance of the CMP.

Introduction

A Management Strategy Evaluation (MSE) is a simulation process includes the components outlined below. For each item, the implementation in mseSurv is described.

1. Operating model (OM)

   a. Biology and fishery model – describes the population dynamics and fisheries (simulates the real system—assumed true)

[1] This document closely resembles the one submitted for the June 2023 Scientific Council meeting. Updates include the reorganization of the Operating Models (OM) and inclusion of results for OM5a and OM5b, as was decided during the January 2024 SC meeting.

The population dynamics and fisheries processes are conditioned on a state-space stock assessment model (SSM) originally described in Regular et al. (**2017**). For this document, simulations are initialized on the final year the SSM fit to data up to 2021 (**Gullage, Regular, and Varkey 2023**).

b. Observation model – produces data with error (e.g. survey data) for the estimation model

Canadian and EU Survey data that are included in the operating model (i.e. the assessment model) are simulated with error. The observation error standard deviations are derived from the model fits for the individual surveys.

c. Implementation model – implements TAC decisions to calculate actual annual removals

Implementation is assumed to be accurate in the base-case model version; this means that the catch taken is the same as the TAC advised. However, TAC overages are included in one of the robustness tests.

For the base case OM of the MSE for Greenland halibut, the parameters from the SSM model are used to project the stock into the future (see **Methods** section). Three additional OMs (or alternate realities) were specified following an extensive selection process (**NAFO 2017**) to deal with structural uncertainties or implementation uncertainties. For this year's review process, the number of OMs have been expanded to account for more uncertainties, especially with regards to survey implementation issues.

2. Candidate Management Procedures (CMP)

a. Model based – estimation model fits to the data generated by the operating model. Model based CMPs are not yet implemented.

b. Empirically-based rules are prescribed based on recent surveys, or other monitoring data-related outputs

Three empirical rule based CMPs were implemented previously for the Greenland halibut stock in NAFO Subarea 2 and Divisions 3KLMNO. The CMPs are calculated by i) comparing current survey data to survey data in a reference period (target), ii) computing the trend in recent survey data (slope), and, iii) a combination of target and slope. Extensive review within WG-RBMS (e.g. **NAFO 2017**) and further testing (Rademeyer and Butterworth 2023a) led to the selection of three rules that are be presented in the later sections.

3. Performance metrics (PM)

Biomass and catch based PMs are calculated at the end of the simulation based on the performance of simulations against biomass based (B_{MSY}) and F-based (F_{MSY}) performance statistics (Annex 3; **NAFO 2023**). Since the SSM does not estimate a stock-recruitment relationship (recruitment is assumed to be random; **Regular et al. 2017**), long-term simulations were used to determine the level of F that maximizes equilibrium yield (**Varkey et al. 2020**). This optimization approximates F_{max}, however, $F_{0.1}$ and $F_{40\%SPR}$ were considered more conservative proxies of MSY.

Methods

State-space model

Parameters from the SSM utilizing the base case series of surveys updated to 2021 (**Gullage, Regular, and Varkey 2023**) were utilized to update the simulations. Specifically, the following survey indices were utilized:

- Canada Autumn 2J3K (1996-2021),
- Canada Autumn 3LNO (1996-2020),
- Canada Spring 3LNO (1996-2019),
- EU 3M 0-1400m (2004-2021),
- EU 3M 0-700m (1995-2003), and
- EU-Spain 3L (2003-2019), and
- EU-Spain 3NO (1997-2021).

Though these values were utilized in the SSM, it will not be possible to utilize all of these surveys in an index based CMPs. The EU survey of 3M will continue to collect data up to 1400m, hence, like in the 2017 MSE process, the superseded series that covered 0-700m will not be utilized. However, for this MSE review, the Canada Spring 3LNO survey will not be utilized in CMPs being tested. Ongoing comparative fishing exercises were incomplete for this survey due to an early retirement of the *CCGS Alfred Needler* Reasearch Vessel (RV). As such, it is unlikely that conversion factor estimates will be available for the Spring survey and, because of this, it will not be possible to utilize data from the new Canadian Spring survey of 3LNO in the CMPs being tested under the ongoing MSE review. Sufficient comparative fishing data should be available for the Canada Autumn 2J3K and 3LNO surveys and special measures will be included in our simulation framework to account for uncertainty associated with the conversion factors (see below).

Simulation framework

The key steps in the simulation process are described in detail.

1. Initiate the simulations and model the population process conditioned on outputs from the state-space assessment model (SSM) for the stock.

a. Start projection from 2021 Numbers-at-age from the SSM model

$$N_{2021,a} = N_{2021,a} e^{\delta_a} \qquad (1)$$

b. For years 2022 to end of simulation generate Numbers at age

- Age 1 – recruits were sampled from a log-normal distribution using the mean and sd values estimated by the SSM,
- Age 2+ - follow cohort equation with age 10 as plus group. M=0.12. Age 10 is a plus group.

$$N_{a,t} = \begin{cases} Lognormal(\mu, \sigma^2), & \text{if} \quad a = 1 \\ N_{a-1,t-1} e^{-Z_{a-1,t-1}+\delta_{a,y}}, & \text{if} \quad 1 < a < 10 \\ \Sigma_{a=9}^{10} N_{a,t-1} e^{Z_{a,t-1}+\delta_{a,t}}, & \text{if} \quad a \geq 10 \end{cases} \quad \text{where } \delta_{a,t} \sim N(0, \sigma_\delta) \qquad (2)$$

2. Generate Canadian and EU survey data

a. Calculate the perfect index:

$$\hat{I}_{y,s} = \Sigma_{a=1}^{10} \frac{q_{a,y,s} e^{\epsilon_{a,s}}}{\rho_{a,s}} N_{a,y} e^{-Z_{a,y} t_s} w_a, \quad \text{where } \epsilon_{a,s} \sim N\left(0, \sigma_{\rho,a,s}\right) \qquad (3)$$

Notice the age and survey specific conversion factor (relative catchability of the old compared to the new RV), $\rho_{a,s}$, and the multiplicative uncertainty associated with this conversion factor, $\epsilon_{a,s}$. Mean ($\rho_{a,s}$) and SD ($\sigma_{\rho,a,s}$) values currently used are in Table 4. Conversion factors are not required for the remaining survey, so these parameters were fixed 1 and 0, respectively.

b. Add observation error to each index series. In the SSM model, the observation error standard deviations vary by age-group and survey.

$$I_{y,s} = \left(\Sigma_{a=1}^{10} q_{a,y,s} N_{a,y} e^{-Z_{a,y} t_s} w_a e^{\varepsilon_{a,s}}\right) \rho(B)_s, \quad \text{where } \varepsilon_{a,s} \sim N\left(0, \sigma_{a,s}\right) \qquad (4)$$

Notice the application of biomass based, age-aggregated, conversion factor, $\rho(B)_s$. While the application of $\rho(B)_s$ may seem redundant and presumably cancel out with $\rho_{a,s}$, the relative catchability of biomass that emerges from converting numbers at age and multiplying by weights at age may not equal the relative catchability estimated using biomass indices. Yet, a deterministic adjustment of biomass indices will be required in the future to convert biomass indices (mean weight per tow) from the new RV to the scale of biomass indices from the old RV, otherwise the indices would not be comparable and output from CMPs utilizing these indices will be biased. Utilizing age and biomass based conversion factors will therefore permit the assessment of the potential effects of a biased biomass conversion factor. A value of 0.9101 and 1.1122 for ρ_s^B is currently being used for the Canada Fall 2J3K and 3LNO surveys, respectively, until final biomass conversion factors are produced following an upcoming Canadian peer review process of conversion factor analyses. Conversion factors are not required for the remaining survey, so ρ_s^B was fixed to 1.

c. Index sum mean weight $I_{y,s}$ is passed to step 3f for the application of CMPs and the calculation of TACs.

d. For year 2021 and 2022, observed survey indices were used (see Table 1):

3. Model the fisheries process and apply survey-based CMP to the simulated data

a. Selectivity is sampled from one of last 10 years

b. Selectivity calculated by scaling the fishing mortality estimates from SSM.

$$Sel_a = \frac{F_a}{\frac{\Sigma_{a=5}^{9} F_a}{5}} \qquad (5)$$

c. Weight at age sampled from last 10 years (same weights used for stock weights and catch weights)

d. For first year of the simulation: Selectivity and weight-at-age vector for 2021 are taken directly from SSM output for 2021.

e. For years 2022 to 2023

- TACs were specified (15039t, 15864t, 15156t).
- Calculate corresponding F by minimizing the difference between proposed TAC and expected yield.
- Calculate catch based on F

$$C_{a,t} = \frac{F_{a,t}}{Z_{a,t}}(1 - e^{-Z_{a,t}t})N_{a,t} \qquad (6)$$

$$Y_t = \Sigma_{a=1}^{10} C_{a,t} w_{a,t} \qquad (7)$$

f. For years 2024 to 2042

- Calculate TAC based on CMP (three CMP options are available and described below). Under all CMP rules, the maximum annual change (Δ) was limited to 10% during the MSE (Δ of 10% was final decision but other values were in mix earlier in the process). Also note the lags in calculation of TAC; when a TAC is set in year y for year y+1, indices will be available only up to year y-1. Therefore $J_{current}$ in CMP(t) is based on years y-3:y-1 and slope calculation in CMP(s) is based on years y-5:y-1.

$$TAC_{t+1} = \begin{cases} TAC_t(1 - \Delta_{down}), & \text{if } TAC_{(t+1)} < TAC_t(1 - \Delta_{down}) \\ TAC_{t+1}, & \text{if } TAC_t(1 - \Delta_{down}) < TAC_{t+1} < TAC_t\left(1 + \Delta_{up}\right) \\ TAC_t\left(1 + \Delta_{up}\right), & \text{if } TAC_{t+1} < TAC_t\left(1 + \Delta_{up}\right) \end{cases} \qquad (8)$$

i. Target based CMP (**t**)

TAC is defined based on the ratio of the shifting 3-year average and a target 5-year average:

$$TAC_{y+1} = TAC_t\left(1 + \gamma_{up/down}(J_t - 1)\right) \qquad (9)$$

$$J_t = \frac{\Sigma_{i=1}^{5} \frac{1}{(\sigma_i)^2} \frac{J_i^{current}}{J_i^{target}}}{\Sigma_{i=1}^{5} \frac{1}{(\sigma_i)^2}} \qquad (10)$$

$$J_i^{current} = \frac{1}{q} \Sigma_{t'=t-q}^{t-1} I_i^{t'} \qquad (11)$$

$$J_i^{target} = \alpha \frac{1}{q} \Sigma_{t'=2011}^{2015} I_i^{t'} \qquad (12)$$

It is possible to calculate the target based rule if there is at least one index available in the last three years. If this condition is not met, the survey with insufficient values will be excluded and the number of surveys contributing to the weighted means will be adjusted accordingly.

ii. Slope based CMP (**s**)

TAC is defined based on the slope of recent survey indices:

$$TAC_{y+1} = TAC_y \left(1 + \lambda_{up/down}(m_t - X)\right) \qquad (13)$$

$$\lambda = \begin{cases} 1.0, & m_t > 0 \\ 2.0, & m_t < 0 \end{cases} \qquad (14)$$

$$m_t = \frac{\Sigma_{s=1}^{5} \frac{sl_{s,t}}{\sigma_s^2}}{\Sigma_{s=1}^{5} \frac{1}{\sigma_s^2}} \qquad (15)$$

where, m_t is the weighted measure of the current (immediate past) trend in the survey indices. The weighting is on inverse variance for the surveys. The trend is calculated as the slope $sl_{s,t}$ of linear regression of previous five years of log unweighted survey indices $ln_{s,t-5:t-1}$ against years t-5:t-1 for each survey series. It is possible to calculate the slope based rule if there are at least two index available in the last five years. If this condition is not met, the survey with insufficient values will be excluded and the number of surveys contributing to the weighted means will be adjusted accordingly.

iii. Combined CMP (**t+s**)

In this case, the TAC is calculated as the average between the previous two methods:

$$TAC_{t+1} = \mu \left(\frac{TAC_{t+1}^{target} + TAC_{t+1}^{slope}}{2} \right) \qquad (16)$$

where μ is a tuning parameter for TACs.

4. Implement the CMP recommendation and continue the update of the population and fishery processes to the number of years prescribed.

The F level corresponding to the TAC generated by the CMP is calculated as noted in 3e and this F value is used to calculate the population numbers for the following year. The steps are repeated for N years of the simulation.

Reference points

The reference point $F_{40\%SPR}$ was calculated and used as a proxy of F_{MSY} for Greenland Halibut. Functions like Yield-per-recruit (YPR), spawner-biomass-per-recruit (SBPR) and SPR indicate various levels of stock status at given levels of *f*, and are typically used to derive harvest reference points. SPR is the ratio of equilibrium spawning-stock biomass (SSB) from fishing at some level *f* to the unfished or virgin SSB (i.e. the equilibrium SSB under no fishing). For our projection model, this is defined as

$$SPR(f) = SSB^{f}_{y=100}/SSB^{0}_{y=100},$$

where *y* is the number of simulated years in our equilibrium projection and *f* is the fixed fishing mortality rate throughout the projection. SPR is a ratio ranging from 0 to 1, and indicates the total percentage of SSB from its virgin SSB that would be fished from some fishing level *f*. The $F_{40\%SPR}$ reference point is defined as the *f* such that $SPR = 0.4$, and can be derived as

$$F_{40\%SPR} = min_f\left(\left(SSB^{f}_{y=100}/SSB^{0}_{y=100} - 0.4\right)^2\right).$$

Various population metrics, such as total biomass (B), biomass at ages 5-9 (B_{5-9}), and population weighted average F for ages 5-9 ($\bar{F}_{5-9}$) were calculated after 100 years of fishing at F_{40%SPR}.

Performance statistics

At the end of the simulation period, stock and fishery based performance statistics are calculated to evaluate the performance of the CMP. Performance statistics used for the evaluation of the MSE are based on Annex 3 of NAFO (**2023**), with some minor modifications (see Table 6). $F_{0.1}^{5-9}$ was used as a proxy for F_{MSY}, and associated equilibrium levels of $B_{0.1}^{5-9}$ was treated as a proxy for B_{MSY}.

Control parameters for the CMPs

The parameters for the CMPs were derived from extensive tuning during the 2017 MSE process (**NAFO 2019**) and further tuning in the 2023 MSE process (**Rademeyer and Butterworth 2023a**). CMP control parameters are presented in Table 2. The J_{target} values which vary for each survey series in the OM are presented in Table 3. The weights used in the inverse variance weighting of survey indices (parameter σ_s) for the ***t*** and ***s*** CMPs in section 3f above are based on the survey standard deviations estimated in the statistical catch-at-age (SCAA) OM (**Rademeyer and Butterworth 2023b**). With the update of the SCAA OM, there are some changes to the control parameters used in the CMPs in the MSE from the previous implementation in 2017 (also in Table 3 3).

Robustness tests

A preliminary investigation was done to compare the MSE simulation outputs from the 2017 base case to the 2023 base case produced using mseSurv to ensure stock trajectories did not deviate too greatly from those expected based on the 2017 evaluation.

Next, mseSurv was used to simulate data under 13 different OMs and assess their performance with respect to predefined performance statistics. Four of these OMs were carried over from the previous 2017 process (OM1, OM7, OM10, and OM13). Details on each OM are as follows:

OM1: The projection model follows the same structure as the SSM.

OM2: For the future, include a hockey-stick S/R relationship, where the recruitment drops linearly to the origin from the lowest value of spawning stock biomass (SSB; biomass for ages 10+). Mean recruitment estimated by the SSM is applied when SSB is above the lowest estimate from the SSM. This imposes more realism to the projections as the base case SSM assumes that recruitment is random and independent of SSB.

OM3[2]: Assume that M follows an allometric shape (i.e., Lorenzen M), where Ma = 0.12 * WAA ^ -0.305. This may introduce more realism to the model as M is expected to decrease as size increases.

OM5a: Assume provisional conversion factors are biased. Assume that a biased conversion factor is applied to the future Canadian 2J3K and 3LNO indices. Specifically, increase the true conversion factor by 10%. The intent here is to test the potential consequence of getting the conversion factor wrong before being final.

OM5b: Assume the 3LNO Fall survey conversion factor is biased. Assume the 3LNO Fall survey conversion factor is biased (10%): The conversion factor for the 3LNO Fall survey is mainly based on data from the 2J3K Fall survey Comparative Fishing program, as the one for 3LNO Fall survey was incomplete and there is no chance to finish it. This bias is for taking into account the differences that could be between the conversion factors of 3LNO and 2J3K.

OM7: The plus group for the stock (age 10+), which also acts as the mature/spawning portion of the stock, is not fished, and selectivity for age-10+ fish for all years is fixed at 0. This test the ability of the CMP to pass fisheries related performance statistics assuming the 10+ group is inaccessible.

OM9: Decrease starting values N(2022, a) by 10% for all ages a to allow for a possible decrease in abundance while some surveys were absent.

OM10: Recruitment for the first eight years of the projection are half of the mean log-recruitment estimate from the SSM; afterwards, recruitment returns to its base value. This tests the ability of the CMP to recover the stock following an series of years of poor recruitment.

OM11[2]: Assume senescence, whereby M increases from 0.12 at age 9 to 0.5 for ages 10+. Though the values chosen are biologically extreme, this scenario aims primarily to partially address concerns over cryptic biomass in the 10+ group.

OM12[2]: Assume that M increases from 0.12 to 0.2 in the first 8 years of the projections (similar structure to the **OM10** OM). This scenario is intended to assess the ability of the CMP to recover the stock following a sequence of years with heightened values of M.

OM13: TAC for each year of the projection is increased by 10% from the value returned by the CMP to account for implementation error. This simulates behavior assuming TAC overruns are be a chronic issue in the future.

OM14: Repeat baseline OM but, at the start of the projections, exclude the EU-Spain 3L series and Canada Autumn 3LNO surveys for 8 years from 2022 to 2029. This is intended to test the sensitivity of the CMP to survey gaps of moderate severity.

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[2] This OM requires reconditioning of the SSM to data as it is a structural assumption that affects past estimates.

Stochastic projections for all OMs were run up to 2044, and simulations were run over 1000 iterations. Median values for each year were derived for total abundance, total biomass, total biomass for ages 5 to 9, total biomass for age-10 fish (synonymous to SSB), the proportion of age-10 fish biomass to total biomass, fishing mortality rate (F), population weighted F, total allowable catch (TAC), total yield (i.e. sum of weighted catches across ages), and the proportion of yields which come from age-10 fish. 80% probability envelopes were also calculated for the simulation outputs. CMPs are applied to the simulated observed survey mean-weights-per-tow (MWPT, i.e. indices). Medians for biomass output and simulated indices were compared to identify any disparities in stock trajectories between the robustness tests. Finally, performance metrics (PMs) for each OM were also derived and tabulated for comparison.

Results and Discussion

Preliminary results indicated that updates to the SSM and MSE framework did not incur notable impacts on stock and index trajectories for the base OM, and most predicted values from the 2017 evaluation did not deviate much from the realized and predicted values from the 2023 evaluation (Figures 1 & 2).

Projected median stock and index trends (Figures 4-18) from most OMs were similar to the base case OM, with some exceptions. **OM10** and **OM12** appear to have similar impacts, with the impacts on exploitable biomass and yield being lagged under **OM10**. **OM3** and **OM7** were relatively optimistic, but **OM3** appears to be more variable than the rest. Finally, the OMs that focus on survey implementation issues (**OM5a**, **OM5b**, **OM9**, and **OM14**) are largely the same as the **OM1**.

The revised combined target and slope based CMP appears to be preforming like it had in the 2017 simulation testing where, despite variation in stock size, catches are relatively stable (Figure 19). The combo CMP is also passing most performance statistics under the **OM1** (Table 7; Figure 20). The CMP appears to be performing well under most OMs. The CMP fails some statistics under the **OM10** and **OM12** OMs, these failures can largely be attributed to the pessimism of both of those OMs; in both of these cases, the stock recovers following the return to base levels of recruitment and mortality. Interestingly, the CMP is especially precautions under the **OM12** scenario.

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References

Gullage, N., P. M. Regular, and D. Varkey. 2023. "Update of Base Case SSM and Investigation of Impacts of EU-Spain 3L Survey Data for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO." *NAFO SCR Doc* 23/014. **https://www.nafo.int/Portals/0/PDFs/sc/2023/scr23-014.pdf**.

NAFO. 2017. "Report of the NAFO Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) Meeting." *COM-SC Doc. 17-06* 17/06. **https://www.nafo.int/Portals/0/PDFs/COM-SC/2017/com-sc%20doc17-06.pdf**.

———. 2019. "Report of the Scientific Council, 31 May – 13 June 2019, Halifax, Canada." *NAFO SCS Doc* 19/020. **https://www.nafo.int/Portals/0/PDFs/sc/2019/scs19-20.pdf**.

———. 2023. "Report of the NAFO Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) Meeting." *COM-SC Doc. 23-02* 23/02. **https://www.nafo.int/Portals/0/PDFs/COM-SC/2023/com-scdoc23-02.pdf**.

Rademeyer, R. A., and D. S. Butterworth. 2023a. "Results for Greenland Halibut Candidate Management Procedure Trials." *NAFO SCR Doc* 23/010. **https://www.nafo.int/Portals/0/PDFs/sc/2023/scr23-010.pdf**.

———. 2023b. "Updated SCAA Base Case Assessment and Sensitivities for Greenland Halibut." *NAFO SCR Doc* 23/008. **https://www.nafo.int/Portals/0/PDFs/sc/2023/scr23-008.pdf**.

Regular, P. M., N. G. Cadigan, M. J. Morgan, and B. P. Healey. 2017. "A Simple SAM-Style State-Space Stock Assessment Model for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO." *NAFO SCR Doc* 17/010. **https://www.nafo.int/Portals/0/PDFs/sc/2017/scr17-010.pdf**.

Varkey, D., R. Kumar, P. Regular, and N. Gullage. 2020. "Performance Metrics Based on the State-Space Stock Assessment Model for Greenland Halibut Stock in NAFO Subarea 2 and Divisions 3KLMNO." *NAFO SCR Doc* 20/048. **https://www.nafo.int/Portals/0/PDFs/sc/2020/scr20-048.pdf**.

Tables

Table 1. Observed survey indices. Years 2011 to 2015 are used to calculate the 'target'. Note that when a TAC is set in year 'y' for year 'y+1', indices will be available only up to year 'y-1'. Current levels in the target based rule uses years y-3:y-1 and slope based rule uses years y-5:y-1. Therefore, observed indices from 2018 onwards would be used in the calculation of TAC for 2024 in the MSE simulations.

Year	Canada Autumn 2J3K	Canada Autumn 3LNO	EU-Spain 3L	EU-Spain 3NO	EU 3M 0-1400m
2011	26.74	2.21	14.61	7.09	26.15
2012	23.5	1.71	14.67	7.37	19.2
2013	29.79	2.53	17.31	5.46	19.11
2014	33.34	NA	24.09	6.24	23.92
2015	22.29	0.87	23.9	9.49	47.52
2016	18.54	1.31	21.26	8.8	28.3
2017	15.1	1.25	34.83	16.63	42.66
2018	17.05	1.89	21.75	7.88	29.8
2019	16.28	1.87	29.69	8.82	16.89
2020	15.84	2.71	NA	NA	13.23
2021	21.15	NA	NA	8.09	16.31
2022	NA	NA	NA	10.28	13.49

Table 2. Control parameter values for the MPs. Parameter ‘q’ indicates the number of years from ‘y-3’ to ‘y-1’ that are used for the calculation of current indices for the target based rule. Missing survey values are treated as missing in the calculation of the rule. In such cases, 'q' is reduced according to the number of years of within the time-span for which survey data are available. In the initial years of the TAC calculation in the MSE, observed survey indices form Table 1 contribute to the calculation of the TAC.

Parameter	Value
γ	0.150
q	3.000
α	0.972
λ_{up}	1.000
λ_{down}	2.000
X	-0.006
Δ_{up}	0.100
Δ_{down}	0.100
μ	0.963

Table 3. Target levels and observation error standard deviations used for inverse variance weighting of survey indices in the MPs.

Surveys	**Means over years (2011 to 2015)**	$\mathbf{J_{target}}$	$\boldsymbol{\sigma_s}$
Canada Autumn 2J3K	27.132	26.372	0.230
Canada Autumn 3LNO	1.830	1.778	0.254
EU-Spain 3L	18.918	18.388	0.239
EU-Spain 3NO	7.131	6.931	0.405
EU 3M 0-1400m	27.179	26.418	0.299

Table 4. Age-based conversion factors currently used in the projections for the Canadian Autumn 3LNO and 2J3K surveys. Estimates may change once conversion factors are finalized.

	Canada Autumn 3LNO		Canada Autumn 2J3K	
Age	Mean	SD	Mean	SD
1	0.6566	0.0892	1.1467	0.0975
2	0.8362	0.0555	1.0024	0.0462
3	0.9689	0.0591	0.9348	0.0402
4	1.0029	0.0627	0.9274	0.0388
5	0.9567	0.0653	0.9498	0.0403
6	0.9173	0.0729	0.9755	0.0458
7	0.9180	0.0875	0.9875	0.0514
8	0.9522	0.1161	0.9846	0.0637
9	1.0091	0.1626	0.9741	0.0837
10+	1.0807	0.2224	0.9607	0.1059

Table 5. Proxy MSY based reference points identified using long-term simulations of equilibrum yield across a range of F values.

Proxy	**OM**	**Biomass**	**Biomass (5-9)**	**Yield**	**Average F (5-9)**	**Combined Index (~5-9)**
$F_{40\%\mathrm{SPR}}$	OM1	350,510	116,124	21,149	0.118	2.2
$F_{40\%\mathrm{SPR}}$	OM7	345,174	110,789	18,297	0.144	2.1
$F_{40\%\mathrm{SPR}}$	OM3	482,628	133,004	24,262	0.115	2.4
$F_{40\%\mathrm{SPR}}$	OM11	216,529	124,059	22,045	0.134	1.5
$F_{40\%\mathrm{SPR}}$	OM2	350,510	116,124	21,149	0.118	2.2

Table 6. Provisional management objectives and the performance statistics for the Greenland halibut MSE. Objectives in bold have been identified as the primary required objectives and the remaining are desirable secondary objectives.

Management Objectives	Performance Statistics	Criteria
Restore to within a prescribed period of time or maintain at $\mathbf{B_{MSY}}$	$B_{2044}^{5-9}/B_{\text{MSY}}^{5-9}$	median and 80% PI
	$\mathbf{B_{2044}^{5-9} < B_{MSY}^{5-9}}$	$\mathbf{P \leq 0.5}$
	$B_{2030}^{5-9} < 0.8B_{\text{MSY}}^{5-9}$	$P \leq 0.25$
	$B_{2044}^{5-9} < 0.8B_{\text{MSY}}^{5-9}$	$P \leq 0.25$
The risk of failure to meet the Bmsy target and interim biomass targets within a prescribed period of time should be kept moderately low	$B_{\text{lowest}}^{5-9}/B_{\text{MSY}}^{5-9}$	median and 80% PI
	$B_{2030}^{5-9} < B_{2025}^{5-9}$	$P \leq 0.25$
Low risk of exceeding F_{MSY}	$P(F_y^{5-9} > F_{MSY}^{5-9}) > 0.3$	count; y = 2025-2044
	$P(F_y^{5-9} > F_{MSY}^{5-9} \mid B_y^{5-9} < B_{MSY}^{5-9}) > 0.3$	count; y = 2025-2044
Very low risk of going below an established threshold	$B_{2044}^{sp}/B_{2025}^{sp}$	median and 80% PI
	$B_{2044}^{5-9}/B_{2025}^{5-9}$	median and 80% PI
	$\mathbf{P(B_y^{5-9} < 0.3B_{MSY}^{5-9}) \geq 0.1}$	$\mathbf{count; y = 2025 - 2044}$
	$\mathbf{B_{lowest}^{5-9}/B_{MSY}^{5-9} < 0.3}$	$\mathbf{P \leq 0.1}$
Maximize yield in the short, medium and long term	$\bar{C}_{2025-2029} = \Sigma_{y=2025}^{2029} C_y/5$	median and 80% PI
	$\bar{C}_{2025-2034} = \Sigma_{y=2025}^{2034} C_y/10$	median and 80% PI
	$\bar{C}_{2025-2044} = \Sigma_{y=2025}^{2044} C_y/20$	median and 80% PI
The risk of steep decline of stock biomass should be kept moderately low	$B_{2030}^{5-9} < 0.75B_{2025}^{5-9}$	$P \leq \begin{cases} 0.1, & B_{2025}^{5-9} < 0.8B_{\text{MSY}}^{5-9} \\ 0.25, & B_{2025}^{5-9} > 0.8B_{\text{MSY}}^{5-9} \end{cases}$
Keep inter-annual TAC variation below an established threshold	$\text{AAV}_{2025-2029} = \frac{1}{5}\Sigma_{y=2025}^{2029} \frac{\mid C_y - C_{y-1} \mid}{C_{y-1}}$	median and 80% PI
	$\text{AAV}_{2025-2044} = \frac{1}{20}\Sigma_{y=2025}^{2044} \frac{\mid C_y - C_{y-1} \mid}{C_{y-1}}$	median and 80% PI

Table 7. Performance statistics for the combined CMPs across OMs. Objectives and statistics in bold are focal metrics. Items in red indicate failing metrics.

Management Objectives	Performance Statistics and Criteria	OM	Estimate	
Restore to within a prescribed period of time or maintain at Bmsy	$B^{5-9}_{2044}/B^{5-9}_{\text{MSY}}$ median and 80% PI	OM1	1.13	(0.77, 1.58)
		OM2	1.10	(0.77, 1.59)
		OM3	1.11	(0.77, 1.63)
		OM5a	1.08	(0.76, 1.56)
		OM5b	1.09	(0.76, 1.58)
		OM7	1.06	(0.67, 1.57)
		OM9	1.01	(0.72, 1.44)
		OM10	1.22	(0.86, 1.70)
		OM11	1.23	(0.84, 1.81)
		OM12	1.21	(0.85, 1.70)
		OM13	1.11	(0.77, 1.59)
		OM14	1.12	(0.78, 1.60)
	$\mathbf{P(B^{5-9}_{2044} < B^{5-9}_{MSY}) \leq 0.5}$	**OM1**	**0.35**	
		OM2	**0.37**	
		OM3	**0.36**	
		OM5a	**0.39**	
		OM5b	**0.38**	
		OM7	**0.43**	
		OM9	**0.47**	
		OM10	**0.24**	
		OM11	**0.24**	
		OM12	**0.26**	
		OM13	**0.36**	
		OM14	**0.34**	
	$P(B^{5-9}_{2030} < 0.8B^{5-9}_{\text{MSY}}) \leq 0.25$	OM1	0.10	
		OM2	0.10	
		OM3	0.11	
		OM5a	0.11	
		OM5b	0.11	
		OM7	0.10	
		OM9	0.20	
		OM10	0.91	
		OM11	0.07	
		OM12	0.67	
		OM13	0.13	
		OM14	0.08	
	$P(B^{5-9}_{2044} < 0.8B^{5-9}_{\text{MSY}}) \leq 0.25$	OM1	0.12	
		OM2	0.13	
		OM3	0.14	

Management Objectives	Performance Statistics and Criteria	OM	Estimate	
		OM5a	0.13	
		OM5b	0.12	
		OM7	0.21	
		OM9	0.19	
		OM10	0.05	
		OM11	0.07	
		OM12	0.07	
		OM13	0.12	
		OM14	0.12	
The risk of failure to meet the Bmsy target and interim biomass targets within a prescribed period of time should be kept moderately low	$B^{5-9}_{\text{lowest}}/B^{5-9}_{\text{MSY}}$ median and 80% PI	OM1	0.73	(0.58, 0.89)
		OM2	0.74	(0.58, 0.89)
		OM3	0.73	(0.58, 0.89)
		OM5a	0.73	(0.57, 0.87)
		OM5b	0.72	(0.58, 0.88)
		OM7	0.71	(0.54, 0.88)
		OM9	0.66	(0.53, 0.81)
		OM10	0.44	(0.32, 0.58)
		OM11	0.78	(0.61, 0.95)
		OM12	0.54	(0.42, 0.68)
		OM13	0.72	(0.56, 0.87)
		OM14	0.75	(0.59, 0.91)
	$P(B^{5-9}_{2030} < B^{5-9}_{2025}) \leq 0.25$	OM1	0.44	
		OM2	0.39	
		OM3	0.35	
		OM5a	0.42	
		OM5b	0.43	
		OM7	0.42	
		OM9	0.39	
		OM10	0.97	
		OM11	0.42	
		OM12	0.53	
		OM13	0.43	
		OM14	0.42	
Low risk of exceeding Fmsy	$\Sigma^{2044}_{y=2025}[P(F_y > F_{MSY}) > 0.3]$	OM1	4.00	
		OM2	5.00	
		OM3	5.00	
		OM5a	9.00	
		OM5b	6.00	
		OM7	13.00	
		OM9	1.00	
		OM10	7.00	
		OM11	0.00	

Management Objectives	Performance Statistics and Criteria	OM	Estimate	
		OM12	6.00	
		OM13	13.00	
		OM14	3.00	
	$\Sigma_{y=2025}^{2044}[P(F_y^{5-9} > F_{MSY}^{5-9} \mid B_y^{5-9} < B_{MSY}^{5-9}) > 0.3]$	OM1	0.00	
		OM2	0.00	
		OM3	0.00	
		OM5a	0.00	
		OM5b	0.00	
		OM7	3.00	
		OM9	1.00	
		OM10	7.00	
		OM11	0.00	
		OM12	6.00	
		OM13	1.00	
		OM14	0.00	
Very low risk of going below an established threshold	$B_{2044}^{sp}/B_{2025}^{sp}$ median and 80% PI	OM1	3.09	(1.59, 5.84)
		OM2	3.00	(1.64, 5.37)
		OM3	3.49	(1.80, 6.41)
		OM5a	2.81	(1.52, 5.06)
		OM5b	2.97	(1.69, 5.52)
		OM7	2.90	(1.55, 5.34)
		OM9	3.39	(1.90, 6.09)
		OM10	3.03	(1.67, 5.40)
		OM11	1.85	(0.92, 3.61)
		OM12	4.66	(2.62, 8.32)
		OM13	2.78	(1.53, 5.41)
		OM14	3.11	(1.73, 5.64)
	$B_{2044}^{5-9}/B_{2025}^{5-9}$ median and 80% PI	OM1	1.05	(0.67, 1.65)
		OM2	1.04	(0.67, 1.67)
		OM3	1.11	(0.72, 1.77)
		OM5a	1.04	(0.65, 1.65)
		OM5b	1.04	(0.66, 1.67)
		OM7	0.98	(0.60, 1.59)
		OM9	1.12	(0.73, 1.72)
		OM10	1.14	(0.73, 1.76)
		OM11	1.10	(0.67, 1.79)
		OM12	1.64	(1.07, 2.59)
		OM13	1.07	(0.67, 1.64)
		OM14	1.05	(0.67, 1.62)
	$\mathbf{\Sigma_{y=2025}^{2044}[P(B_y^{5-9} < 0.3B_{MSY}^{5-9}) \geq 0.1]}$	**OM1**	**0.00**	
		OM2	**0.00**	
		OM3	**0.00**	
		OM5a	**0.00**	

Management Objectives	Performance Statistics and Criteria	OM	Estimate
		OM5b	**0.00**
		OM7	**0.00**
		OM9	**0.00**
		OM10	**0.00**
		OM11	**0.00**
		OM12	**0.00**
		OM13	**0.00**
		OM14	**0.00**
	$\mathbf{P(B_{lowest}^{5-9}/B_{MSY}^{5-9} < 0.3) \leq 0.1}$	**OM1**	**0.00**
		OM2	**0.00**
		OM3	**0.00**
		OM5a	**0.00**
		OM5b	**0.00**
		OM7	**0.00**
		OM9	**0.00**
		OM10	**0.07**
		OM11	**0.00**
		OM12	**0.00**
		OM13	**0.00**
		OM14	**0.00**
Maximize yield in the short, medium and long term	$\bar{C}_{2025-2029}$ median and 80% PI	OM1	16,352 (14,471, 18,075)
		OM2	16,359 (14,524, 18,022)
		OM3	16,597 (14,780, 18,377)
		OM5a	16,736 (14,891, 18,532)
		OM5b	16,542 (14,608, 18,238)
		OM7	16,069 (14,446, 17,920)
		OM9	15,249 (13,474, 16,873)
		OM10	15,751 (14,062, 17,477)
		OM11	15,744 (14,033, 17,529)
		OM12	13,741 (12,513, 15,322)
		OM13	17,914 (15,786, 19,846)
		OM14	15,346 (13,881, 16,928)
	$\bar{C}_{2025-2034}$ median and 80% PI	OM1	17,161 (14,555, 19,921)
		OM2	17,313 (14,586, 20,231)
		OM3	17,868 (15,237, 20,985)
		OM5a	17,636 (15,052, 20,764)
		OM5b	17,417 (14,675, 20,363)
		OM7	16,748 (14,299, 19,489)
		OM9	15,500 (13,142, 18,092)
		OM10	14,197 (12,145, 16,306)
		OM11	15,999 (13,573, 18,949)
		OM12	12,396 (10,943, 14,364)
		OM13	18,434 (15,776, 21,794)

Management Objectives	Performance Statistics and Criteria	OM	Estimate	
		OM14	16,258	(13,945, 18,797)
	$\bar{C}_{2025-2044}$ median and 80% PI	OM1	18,560	(15,090, 23,480)
		OM2	18,994	(15,164, 23,712)
		OM3	20,836	(16,519, 26,400)
		OM5a	19,439	(15,823, 24,771)
		OM5b	19,073	(15,326, 24,051)
		OM7	17,762	(14,416, 21,886)
		OM9	15,964	(13,057, 19,977)
		OM10	13,067	(10,916, 15,843)
		OM11	15,867	(13,121, 19,788)
		OM12	12,612	(10,559, 15,494)
		OM13	19,838	(15,875, 24,638)
		OM14	17,908	(14,466, 22,754)
The risk of steep decline of stock biomass should be kept moderately low	$P(B_{2030}^{5-9} < 0.75B_{2025}^{5-9}) \leq \begin{cases} 0.1, & B_{2025}^{5-9} < 0.8B_{\text{MSY}}^{5-9} \\ 0.25, & B_{2025}^{5-9} > 0.8B_{\text{MSY}}^{5-9} \end{cases}$	OM1	0.14	
		OM2	0.14	
		OM3	0.12	
		OM5a	0.14	
		OM5b	0.14	
		OM7	0.15	
		OM9	0.12	
		OM10	0.86	
		OM11	0.16	
		OM12	0.22	
		OM13	0.17	
		OM14	0.14	
Keep inter-annual TAC variation below an established threshold	$AAV_{2025-2029}$ median and 80% PI	OM1	0.04	(0.02, 0.07)
		OM2	0.04	(0.02, 0.07)
		OM3	0.04	(0.02, 0.07)
		OM5a	0.04	(0.02, 0.07)
		OM5b	0.04	(0.02, 0.07)
		OM7	0.04	(0.02, 0.07)
		OM9	0.04	(0.02, 0.06)
		OM10	0.04	(0.02, 0.06)
		OM11	0.04	(0.02, 0.06)
		OM12	0.05	(0.03, 0.08)
		OM13	0.04	(0.02, 0.07)
		OM14	0.04	(0.02, 0.06)
	$AAV_{2025-2044}$ median and 80% PI	OM1	0.05	(0.03, 0.06)
		OM2	0.05	(0.03, 0.06)
		OM3	0.05	(0.04, 0.07)
		OM5a	0.05	(0.03, 0.06)
		OM5b	0.05	(0.03, 0.06)
		OM7	0.05	(0.03, 0.06)

Management Objectives	Performance Statistics and Criteria	OM	Estimate	
		OM9	0.04	(0.03, 0.06)
		OM10	0.05	(0.04, 0.07)
		OM11	0.04	(0.03, 0.06)
		OM12	0.05	(0.04, 0.06)
		OM13	0.05	(0.03, 0.06)
		OM14	0.05	(0.03, 0.06)

Figures

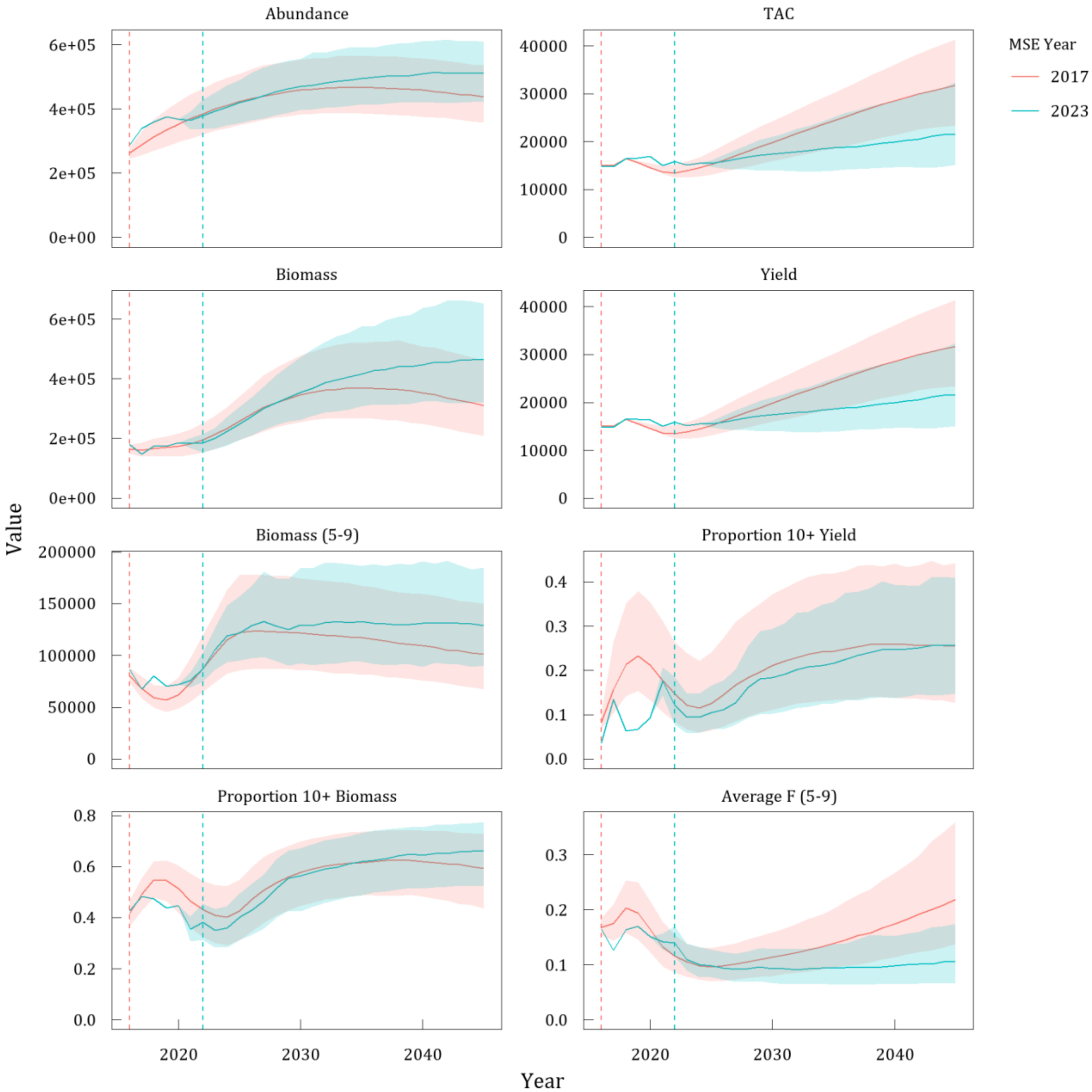

Figure 1. Median and 80% CIs for various stock values from the 2017 and 2023 MSE projections.

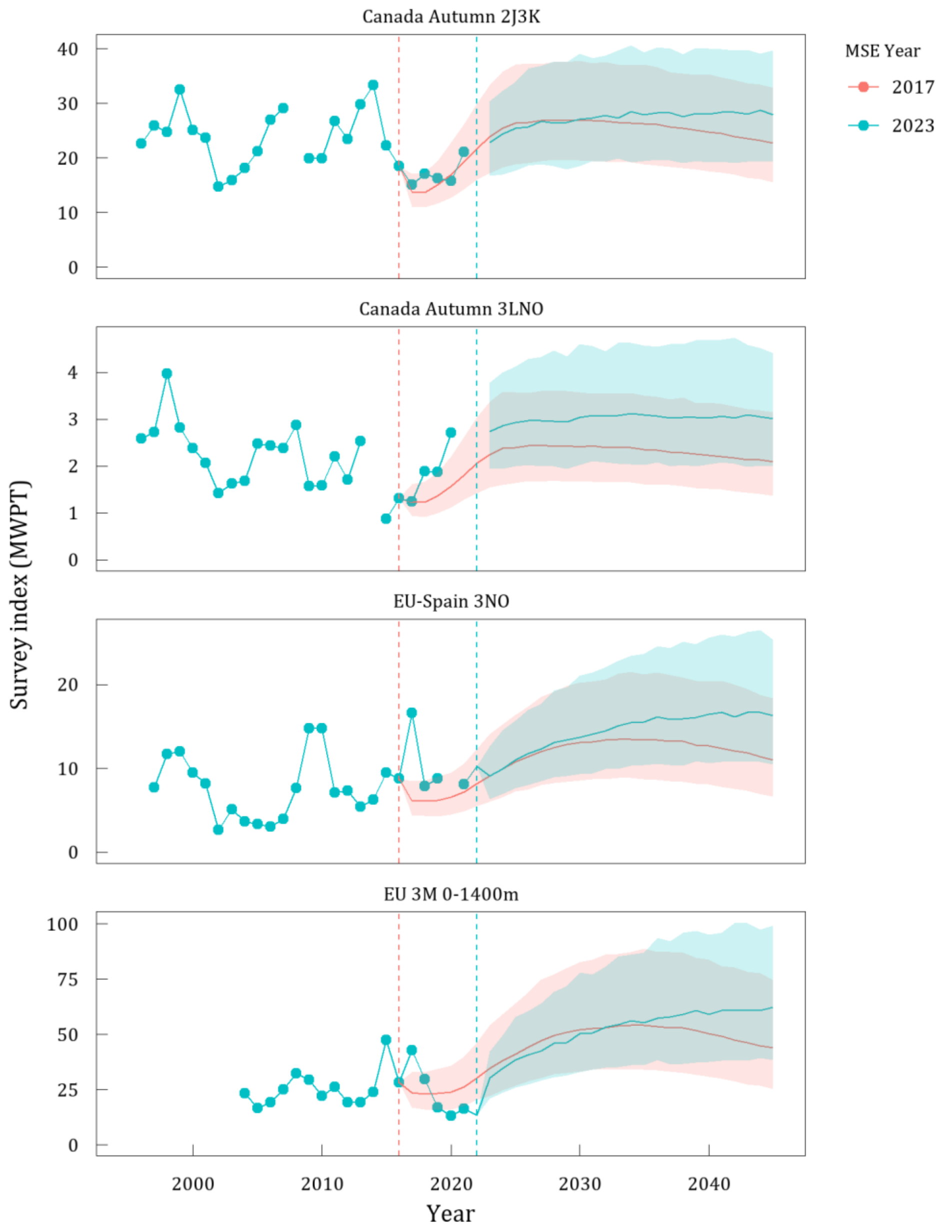

Figure 2. Median and 80% CIs for expected and observed survey indices from the 2017 and 2023 MSE projections.

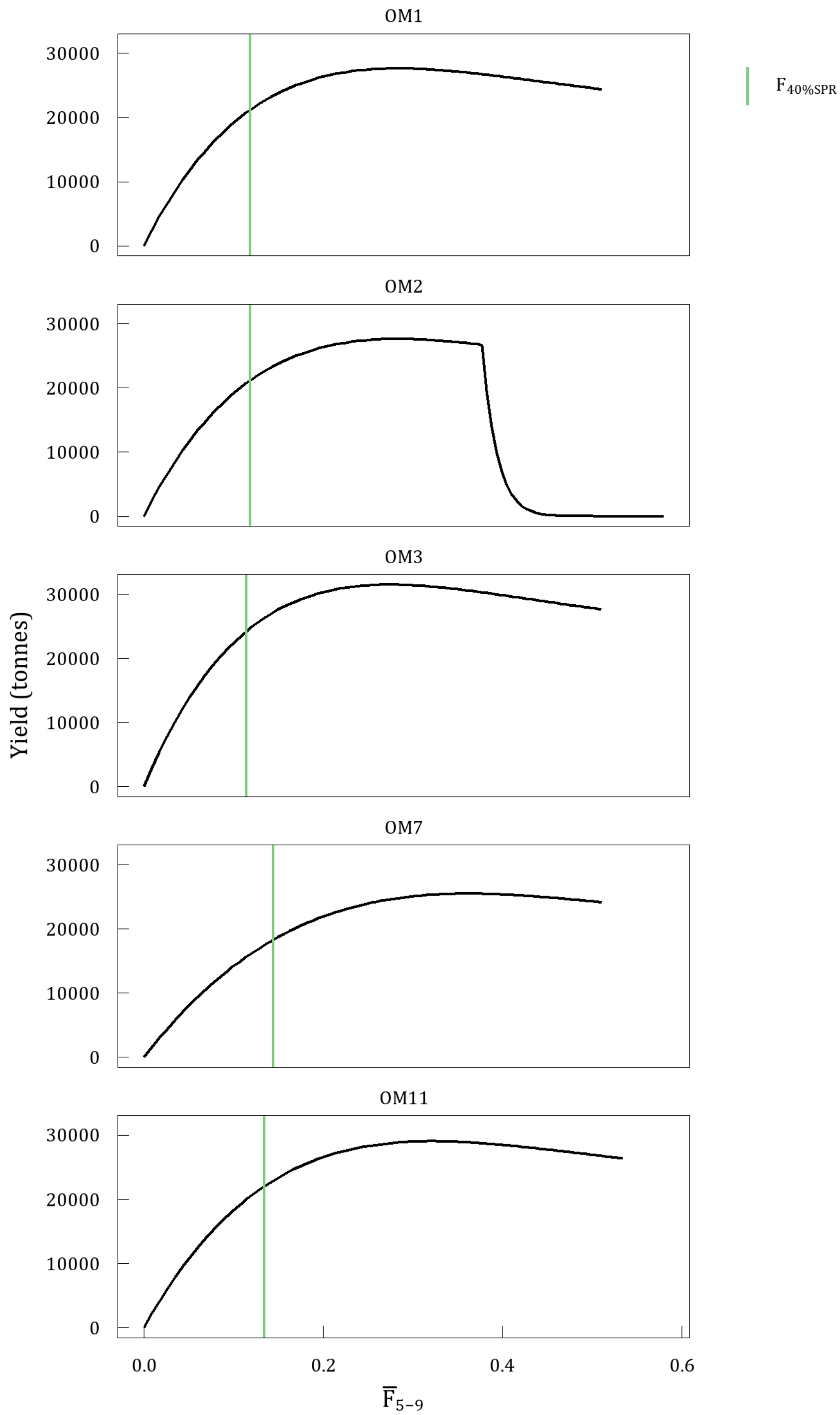

Figure 3. Yields and yield proportions across range of $\bar{F}_{5-9}$ across SSM OMs. The green line shows $F_{40\%SPR}$, which is treated as a proxy for F_{MSY}.

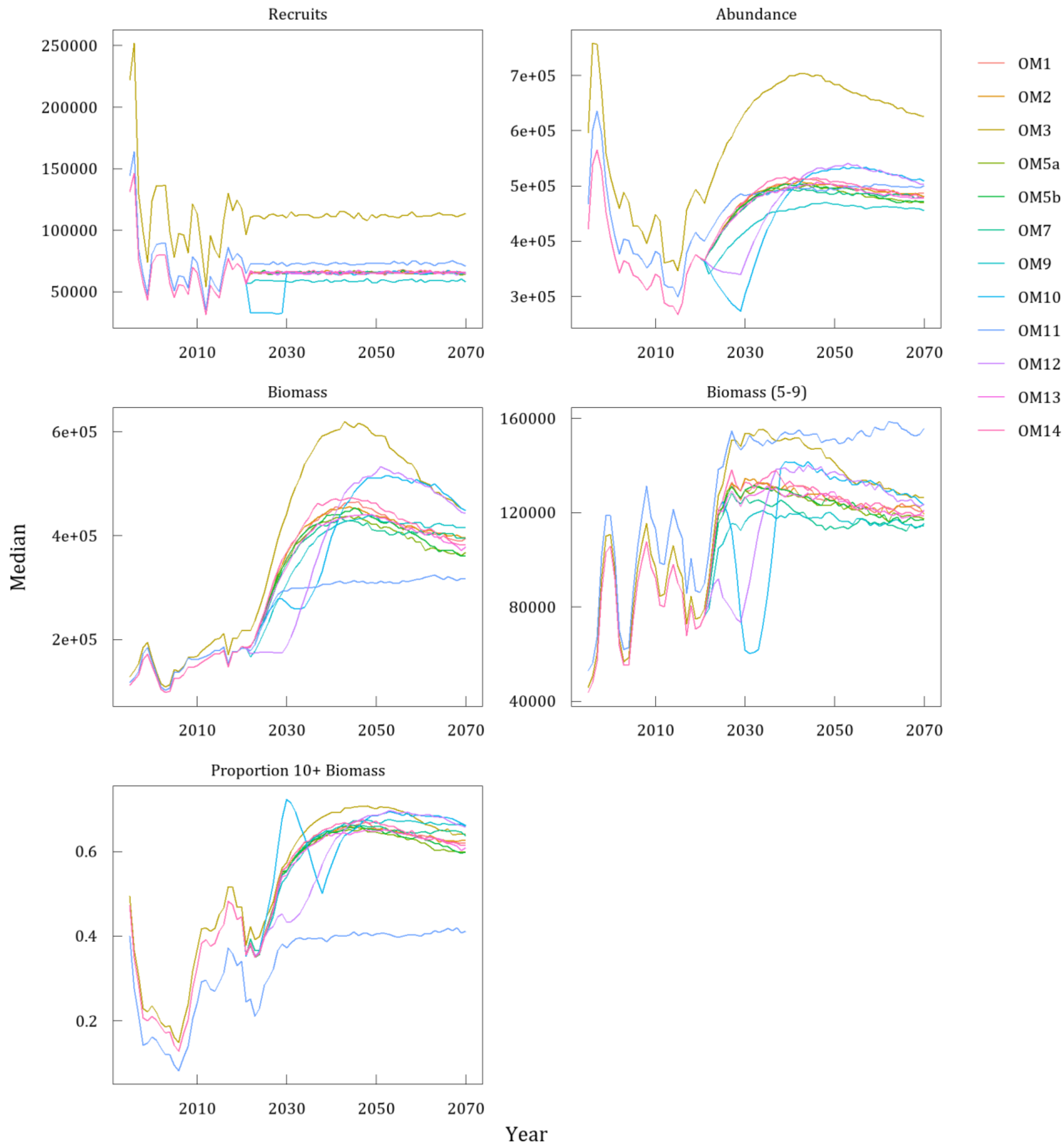

Figure 4. Medians for various stock values across OMs.

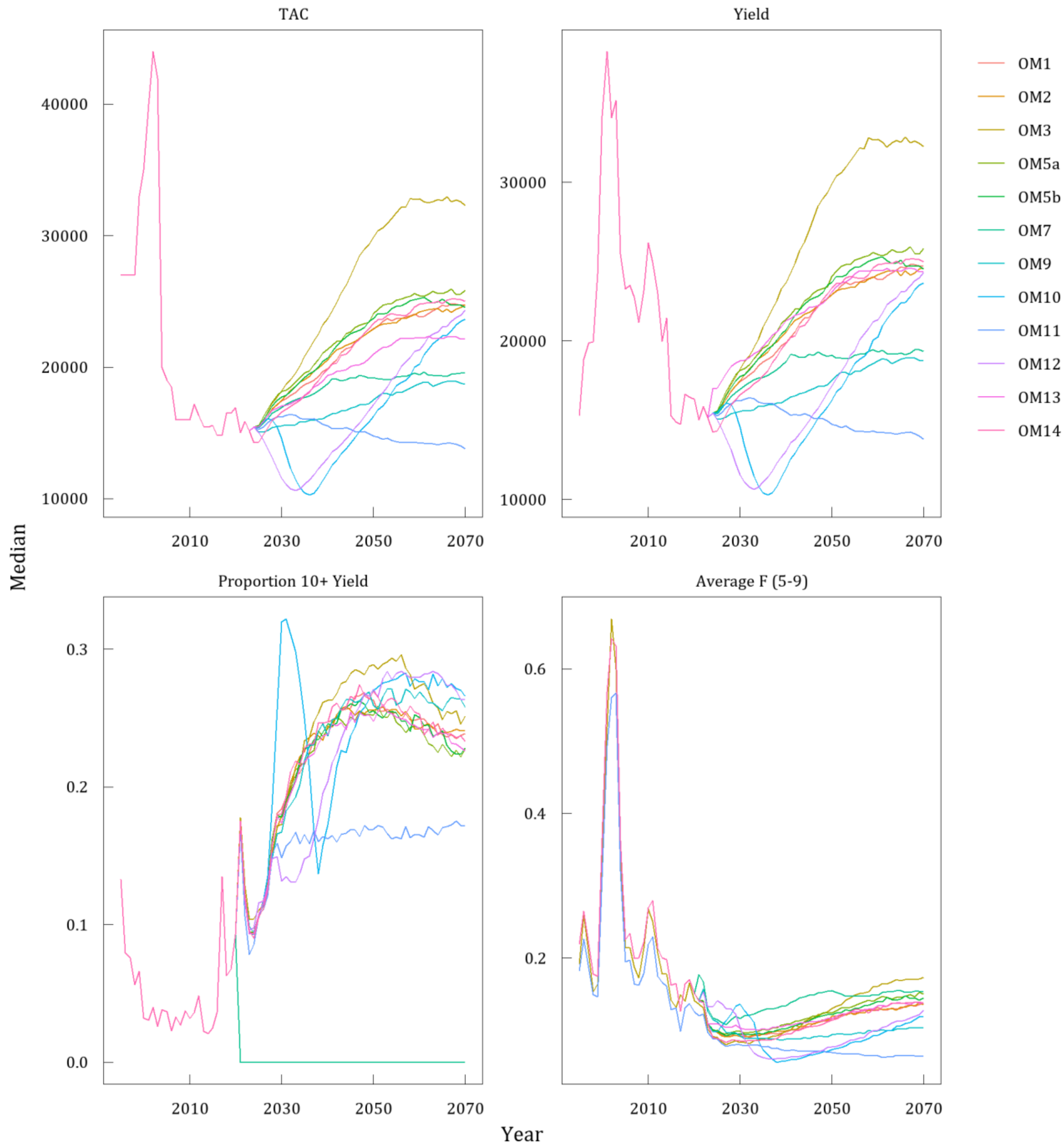

Figure 5. Medians for various catch values across OMs.

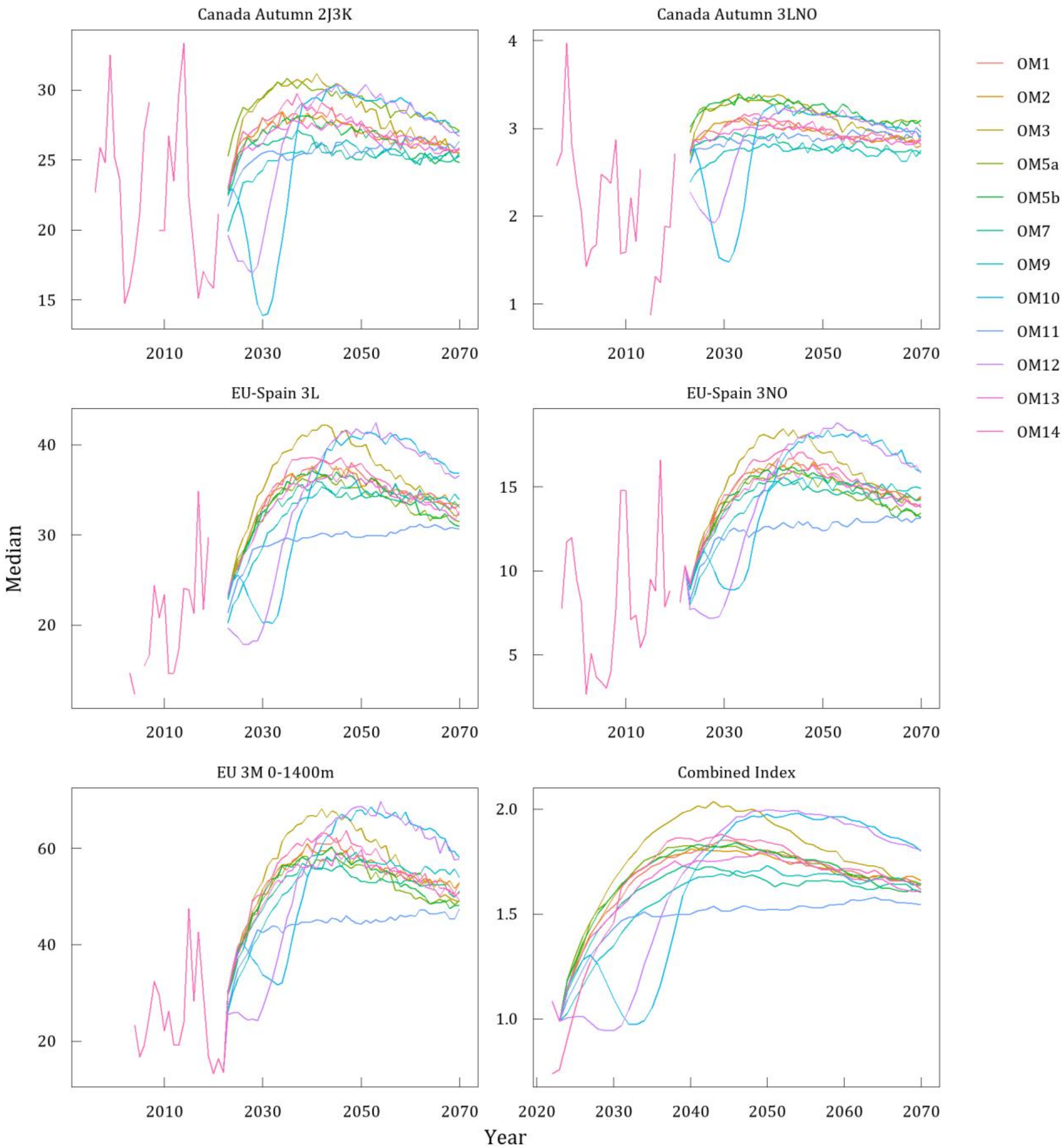

Figure 6. Medians of projected survey indices across OMs.

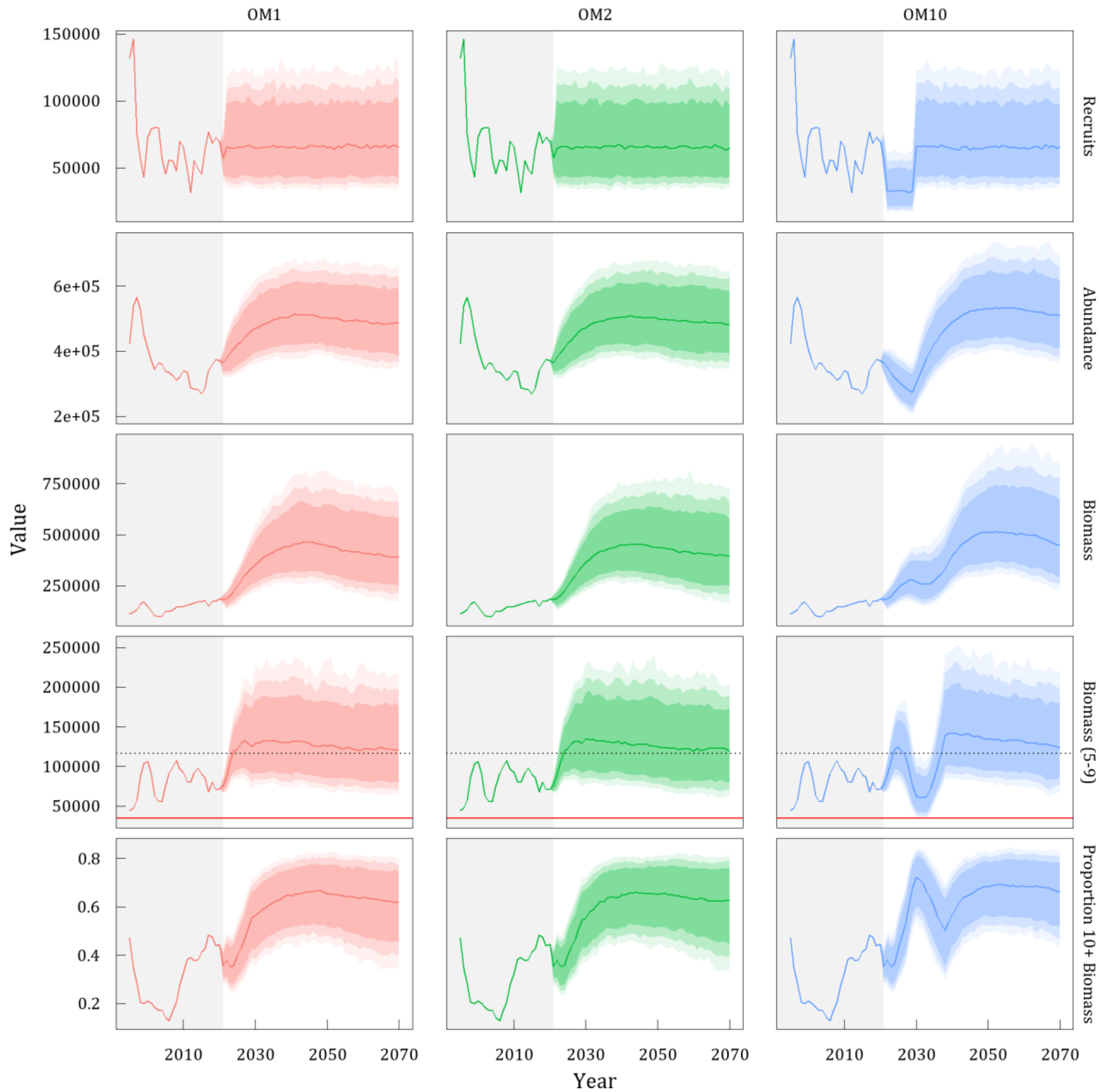

Figure 7. Medians for various stock values across OMs focused on recruitment uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. B^{5-9}_{MSY} and 30% B^{5-9}_{MSY} indicated using a dotted black line and solid red line, respectively.

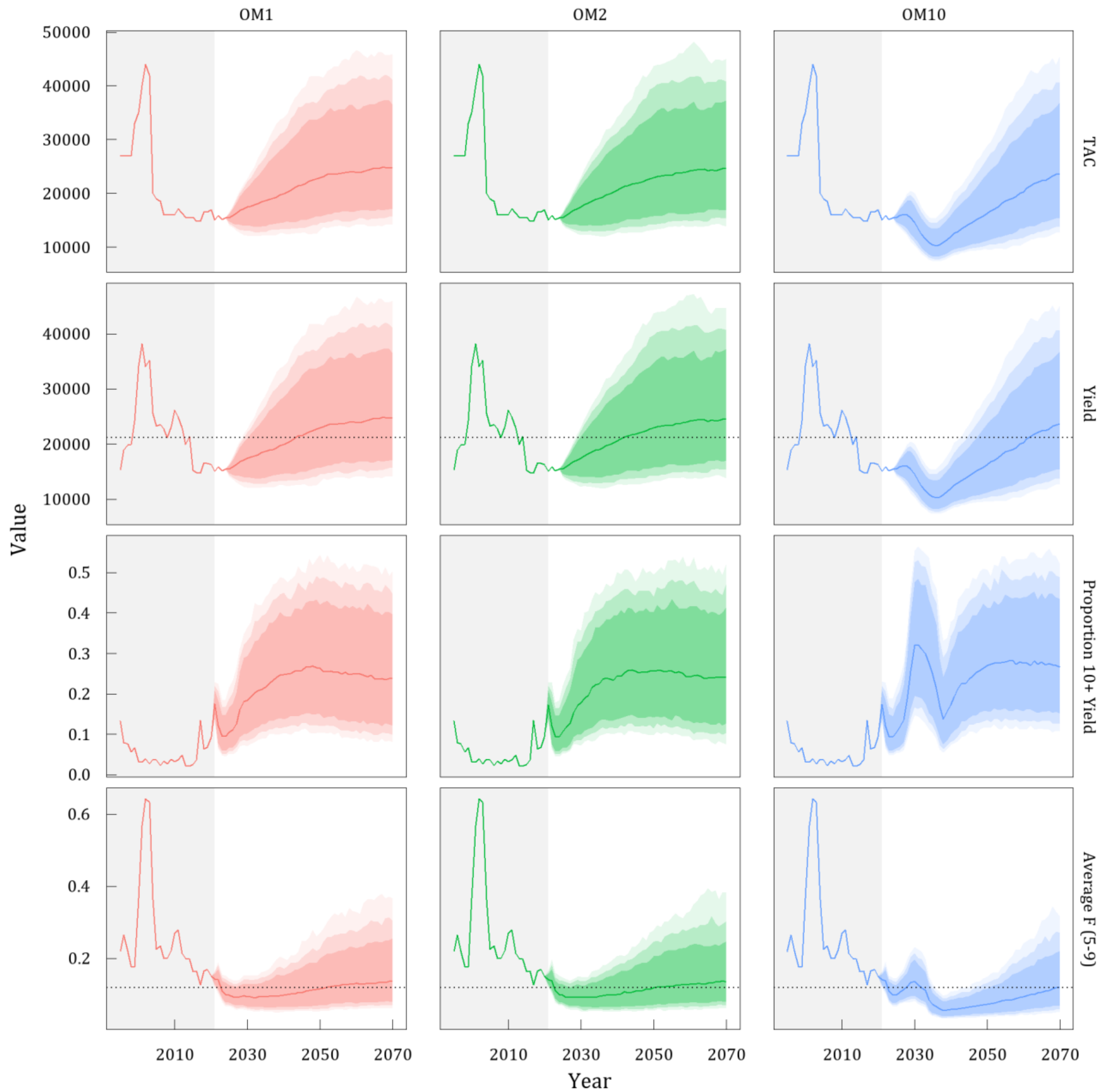

Figure 8. Medians for various catch values across OMs focused on recruitment uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. MSY and F_{MSY}^{5-9} indicated using dotted lines.

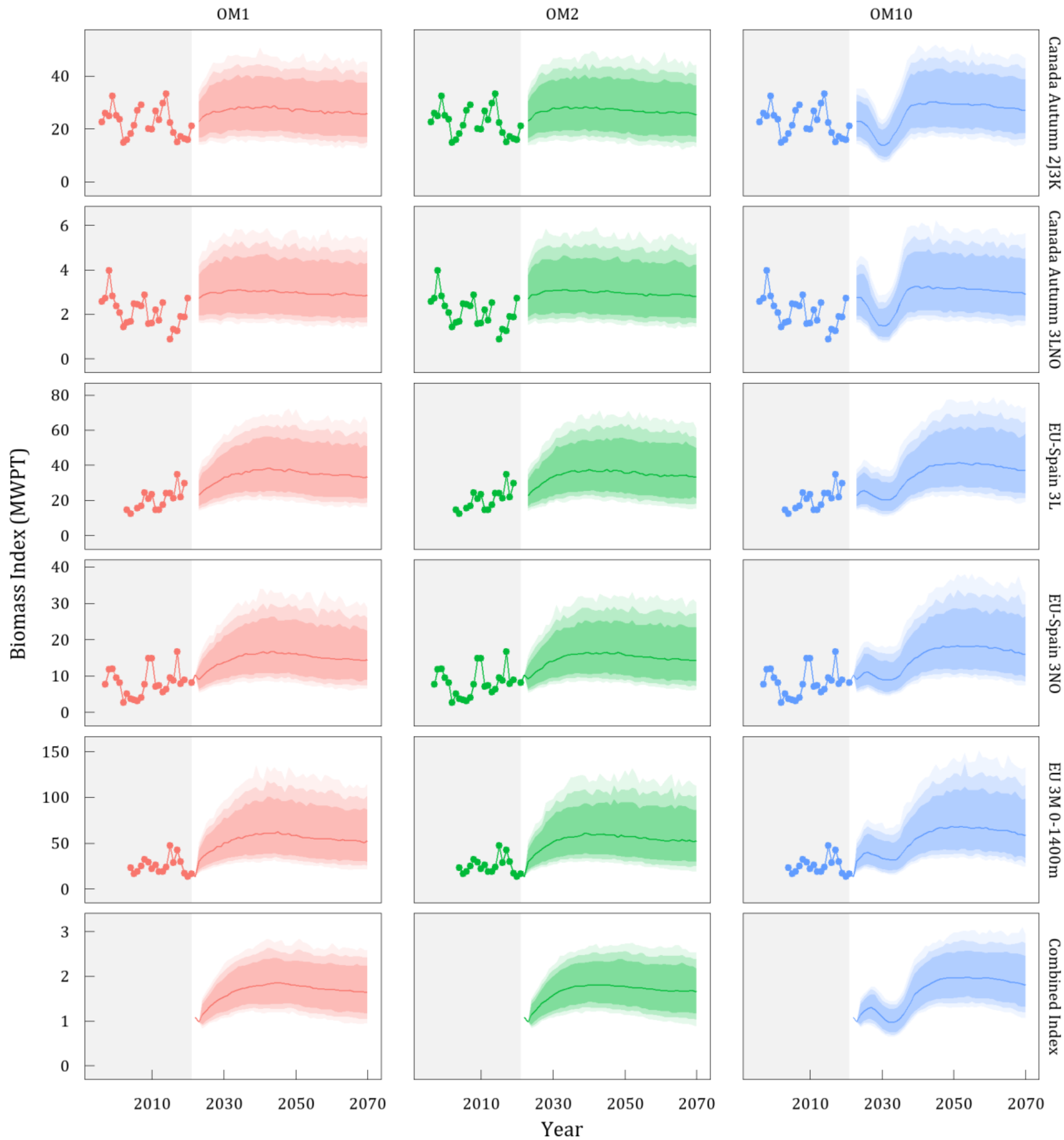

Figure 9. Median for expected and observed survey indices across OMs focused on recruitment uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. Points represent observed values.

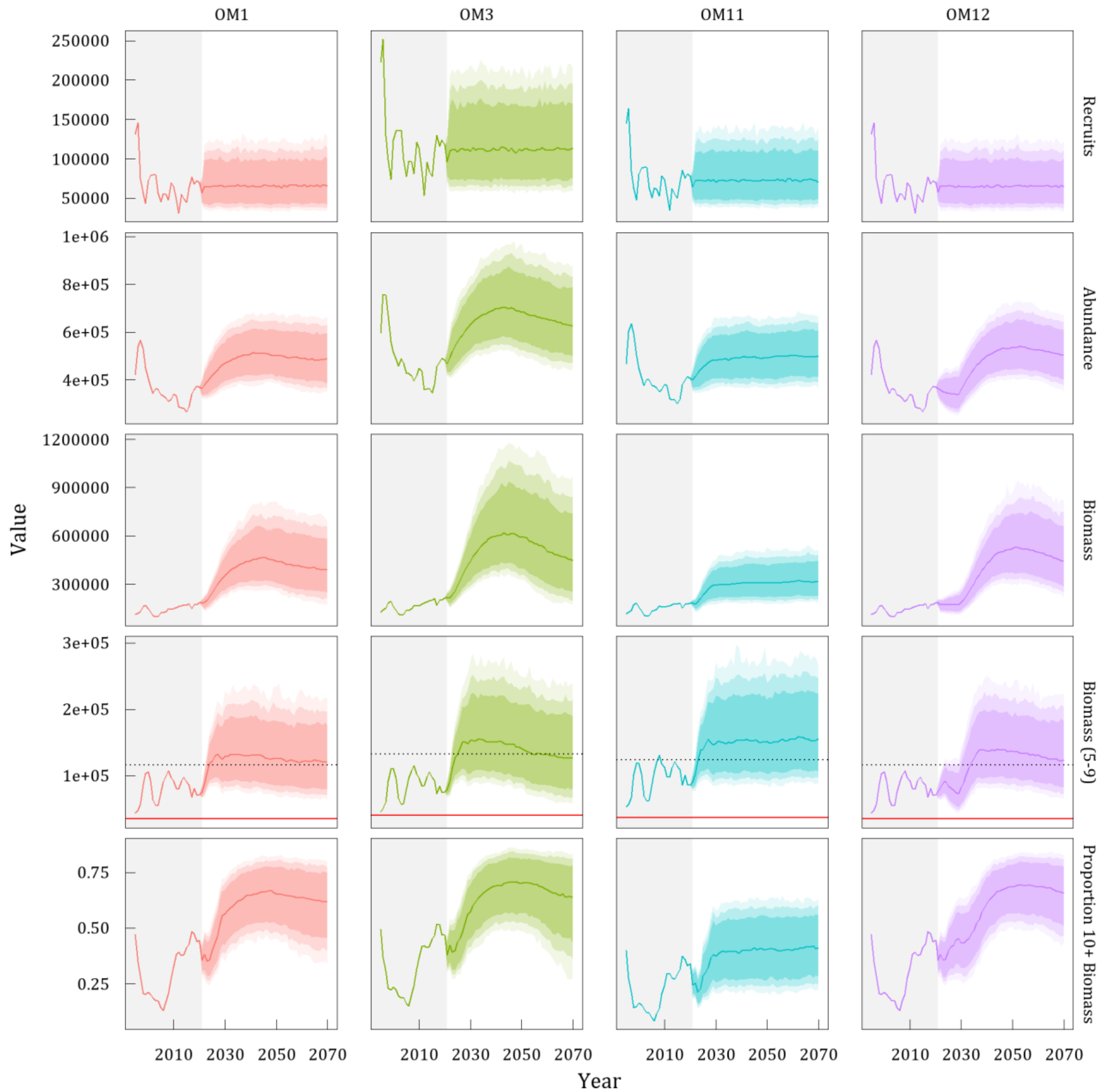

Figure 10. Medians for various stock values across OMs focused on natural mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. B^{5-9}_{MSY} and 30% B^{5-9}_{MSY} indicated using a dotted black line and solid red line, respectively.

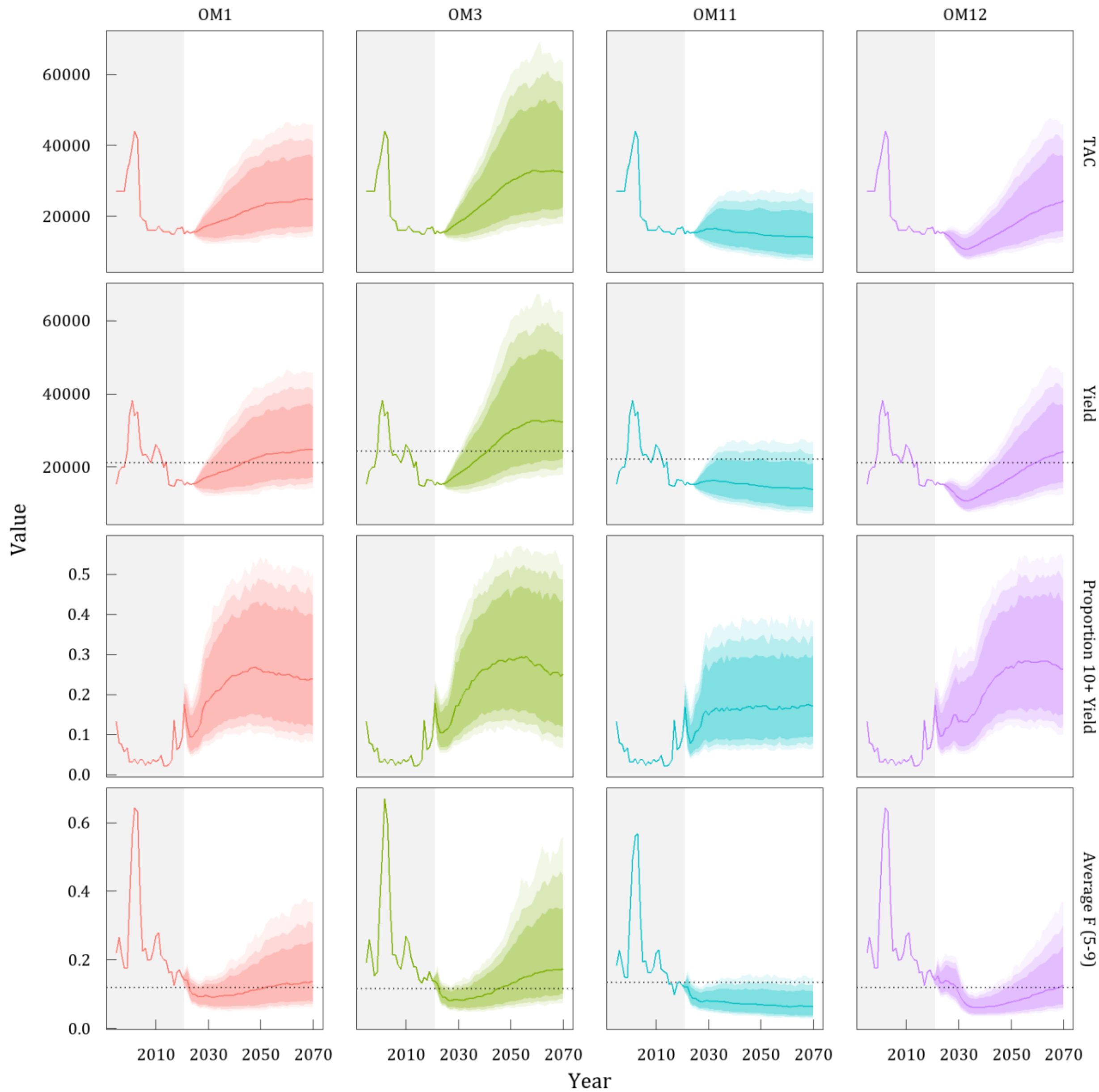

Figure 11. Medians for various catch values across OMs focused on natural mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. MSY and F_{MSY}^{5-9} indicated using dotted lines.

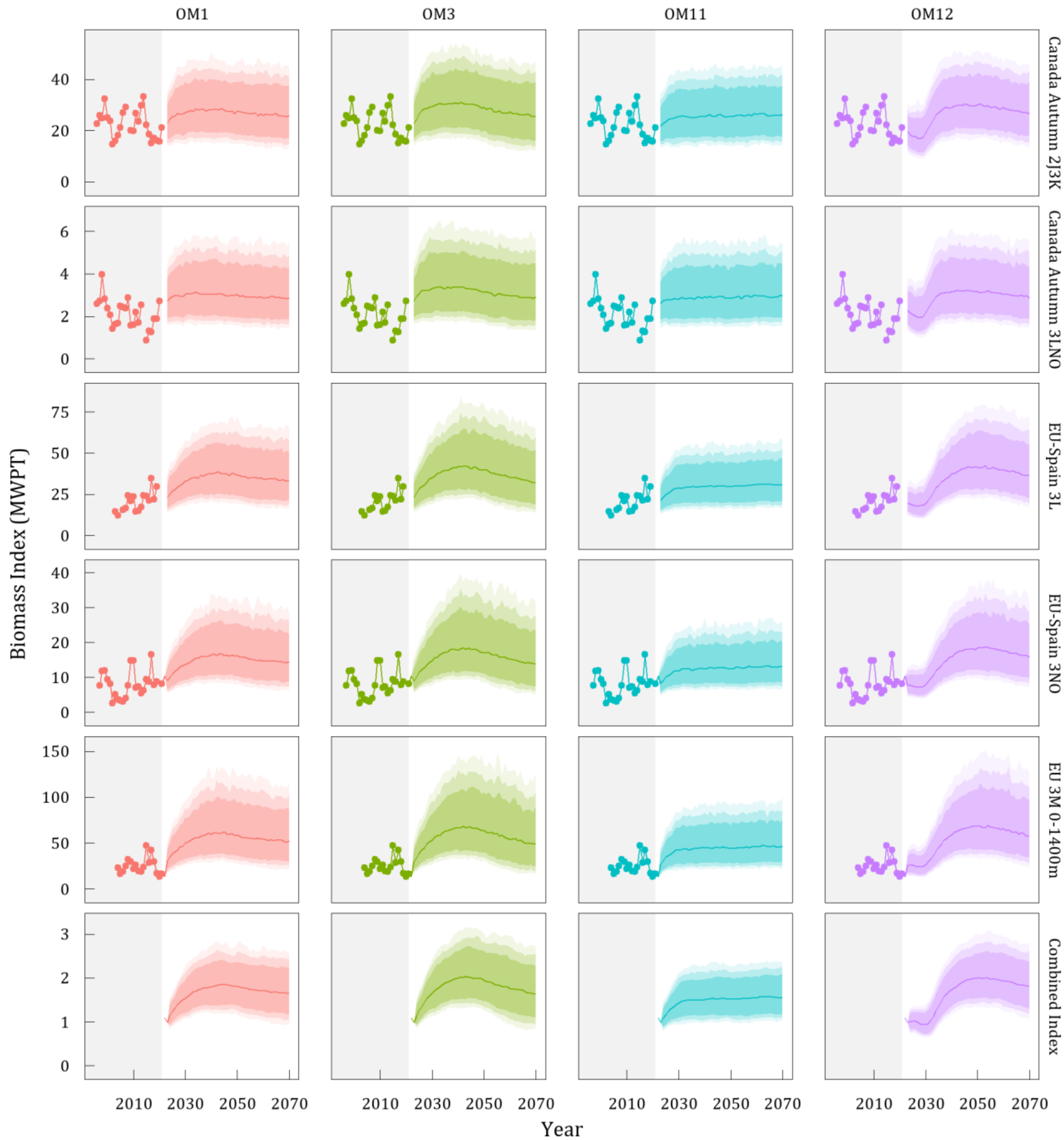

Figure 12. Median for expected and observed survey indices across OMs focused on natural mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. Points represent observed values.

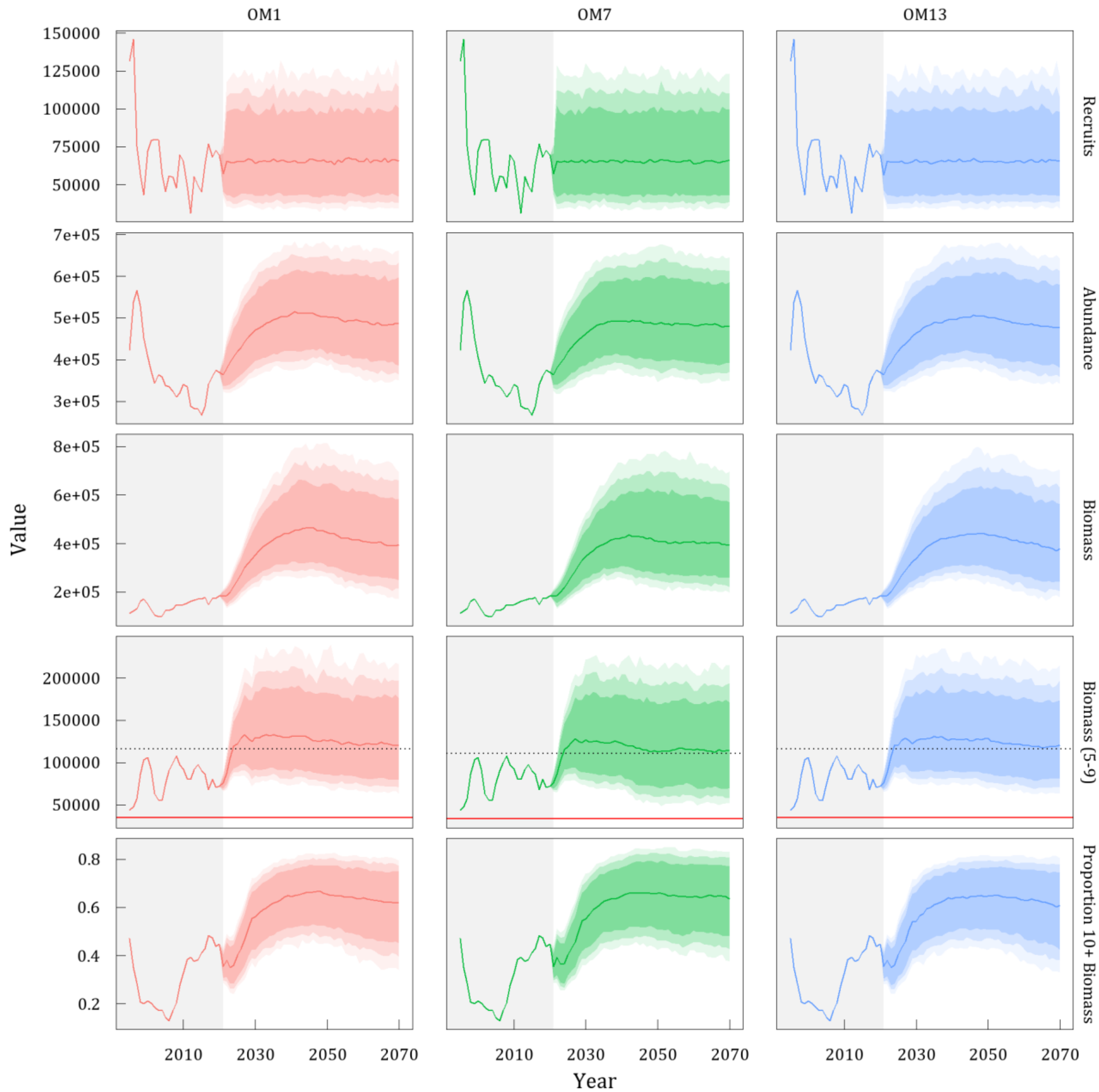

Figure 13. Medians for various stock values across OMs focused on fishing mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. B_{MSY}^{5-9} and 30% B_{MSY}^{5-9} indicated using a dotted black line and solid red line, respectively.

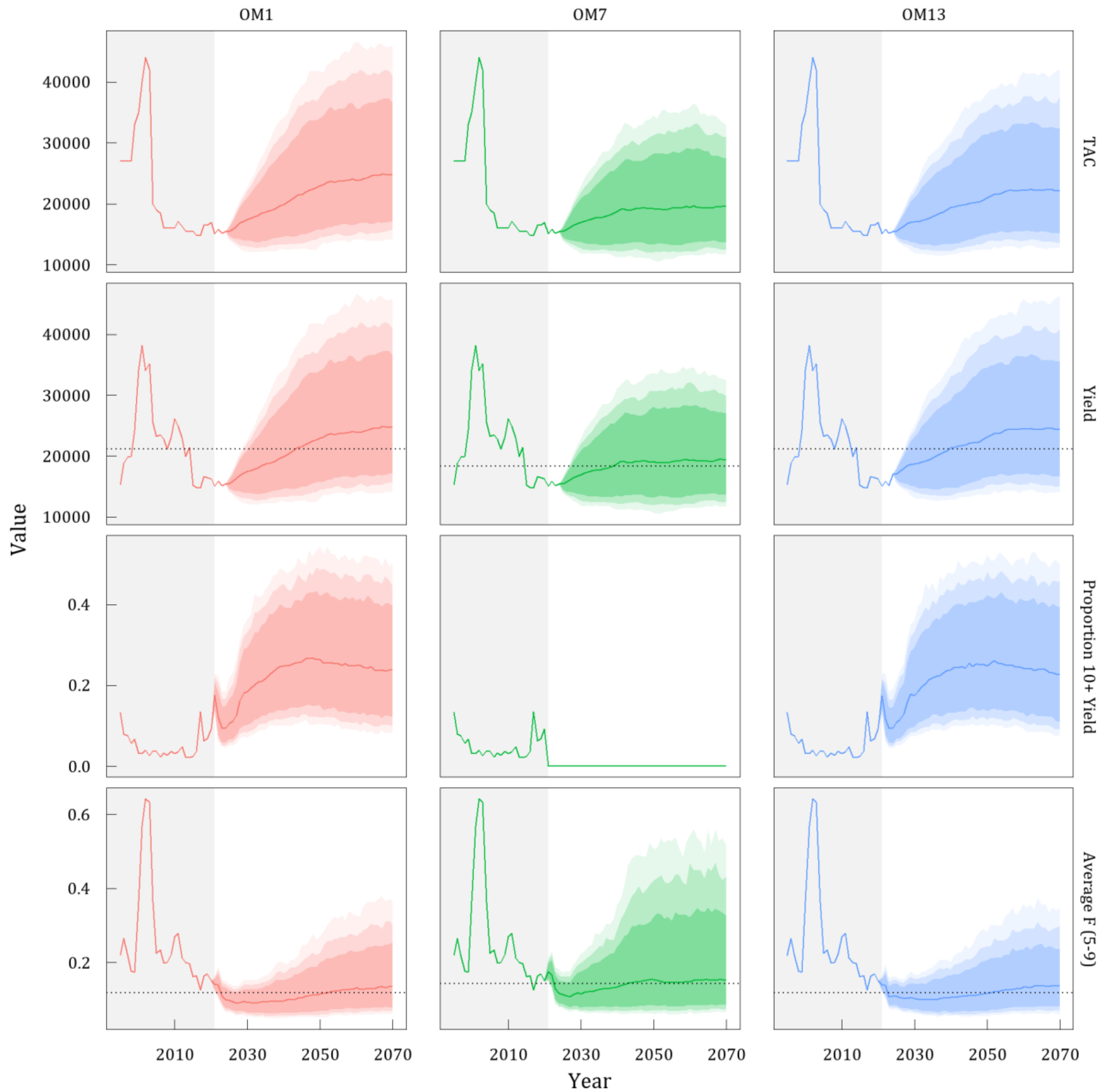

Figure 14. Medians for various catch values across OMs focused on fishing mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. MSY and F_{MSY}^{5-9} indicated using dotted lines.

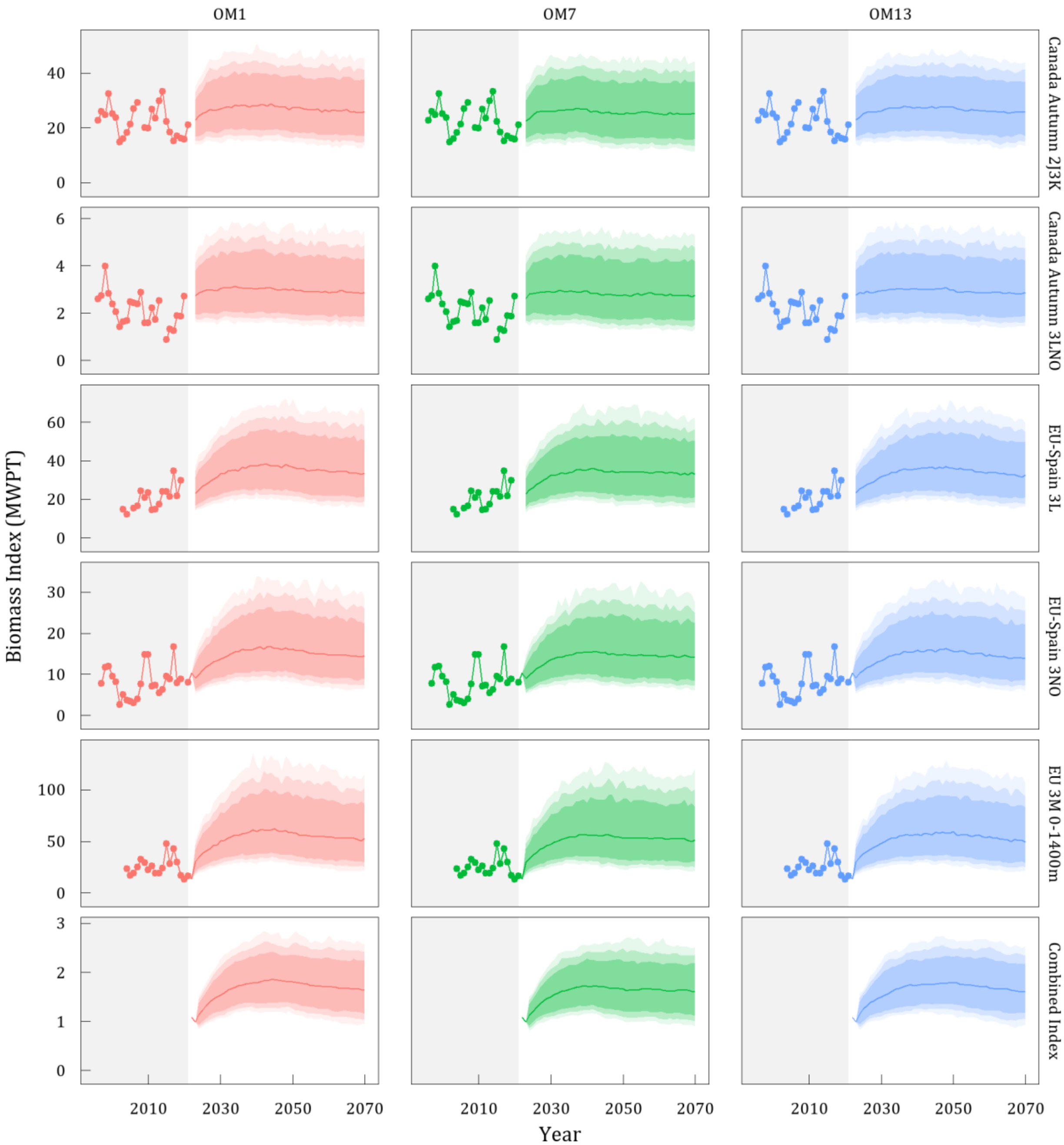

Figure 15. Median for expected and observed survey indices across OMs focused on fishing mortality uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. Points represent observed values.

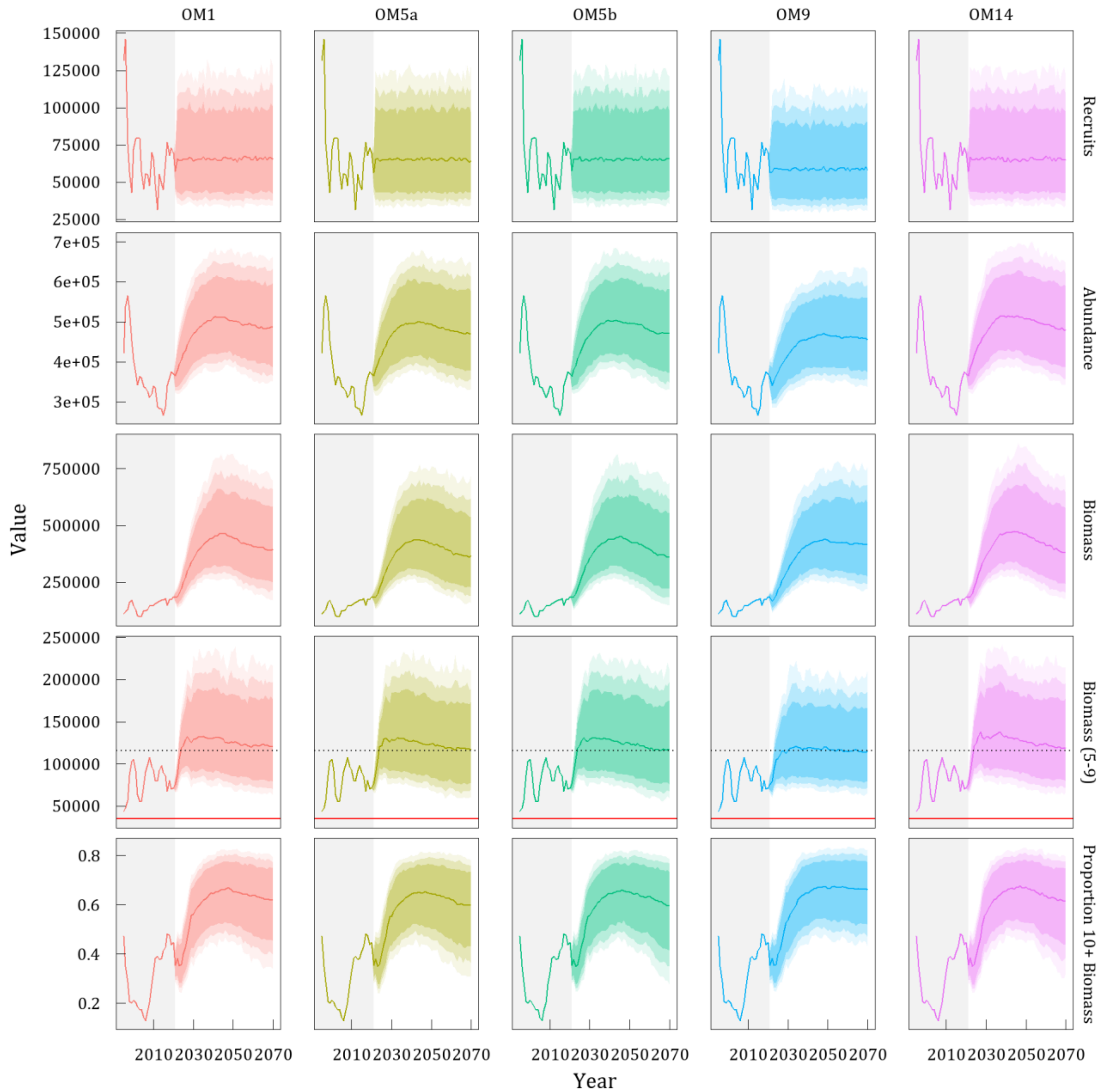

Figure 16. Medians for various stock values across OMs focused on survey uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. B_{MSY}^{5-9} and 30% B_{MSY}^{5-9} indicated using a dotted black line and solid red line, respectively.

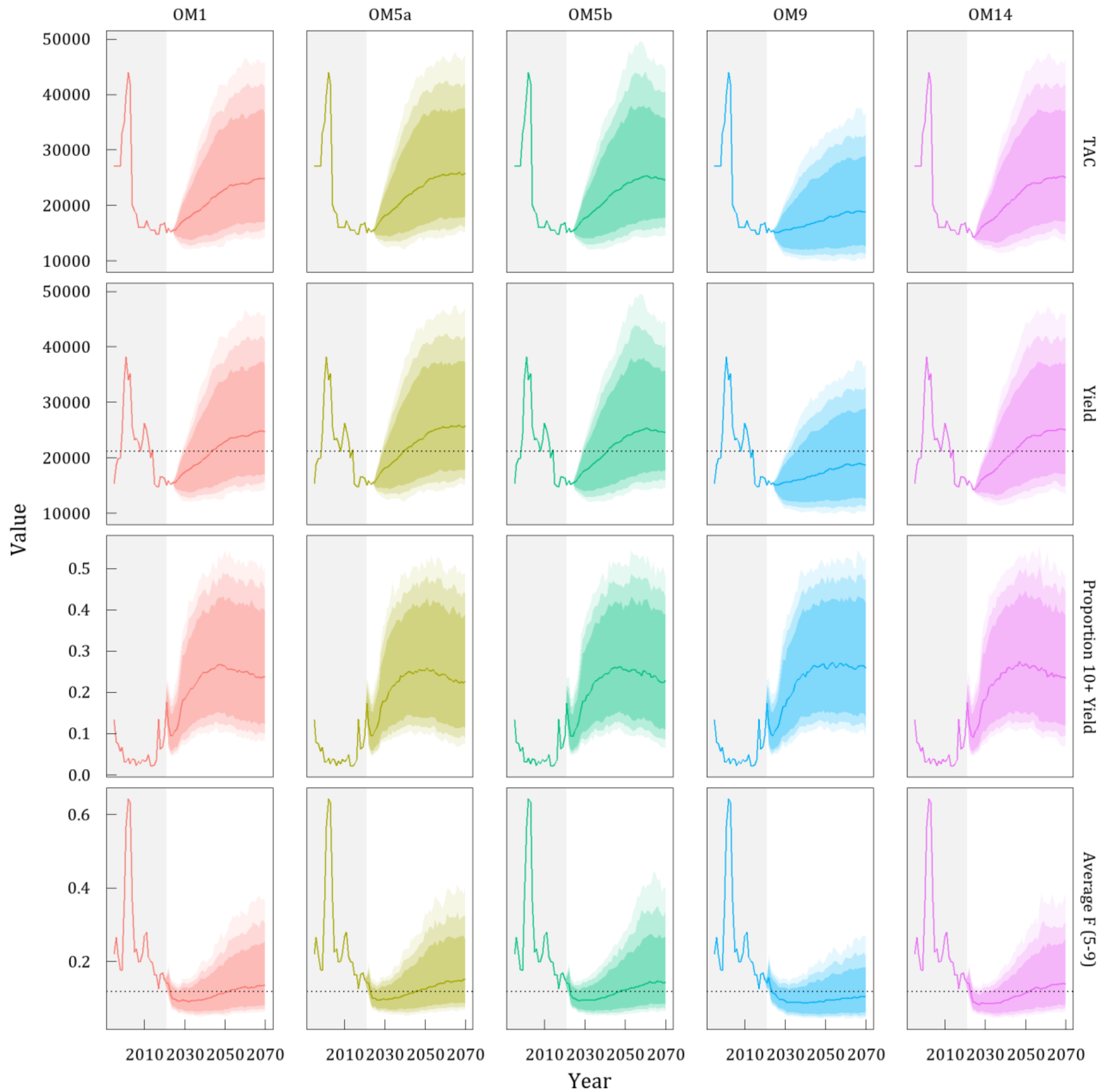

Figure 17. Medians for various catch values across OMs focused on survey uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. MSY and F_{MSY}^{5-9} indicated using dotted lines.

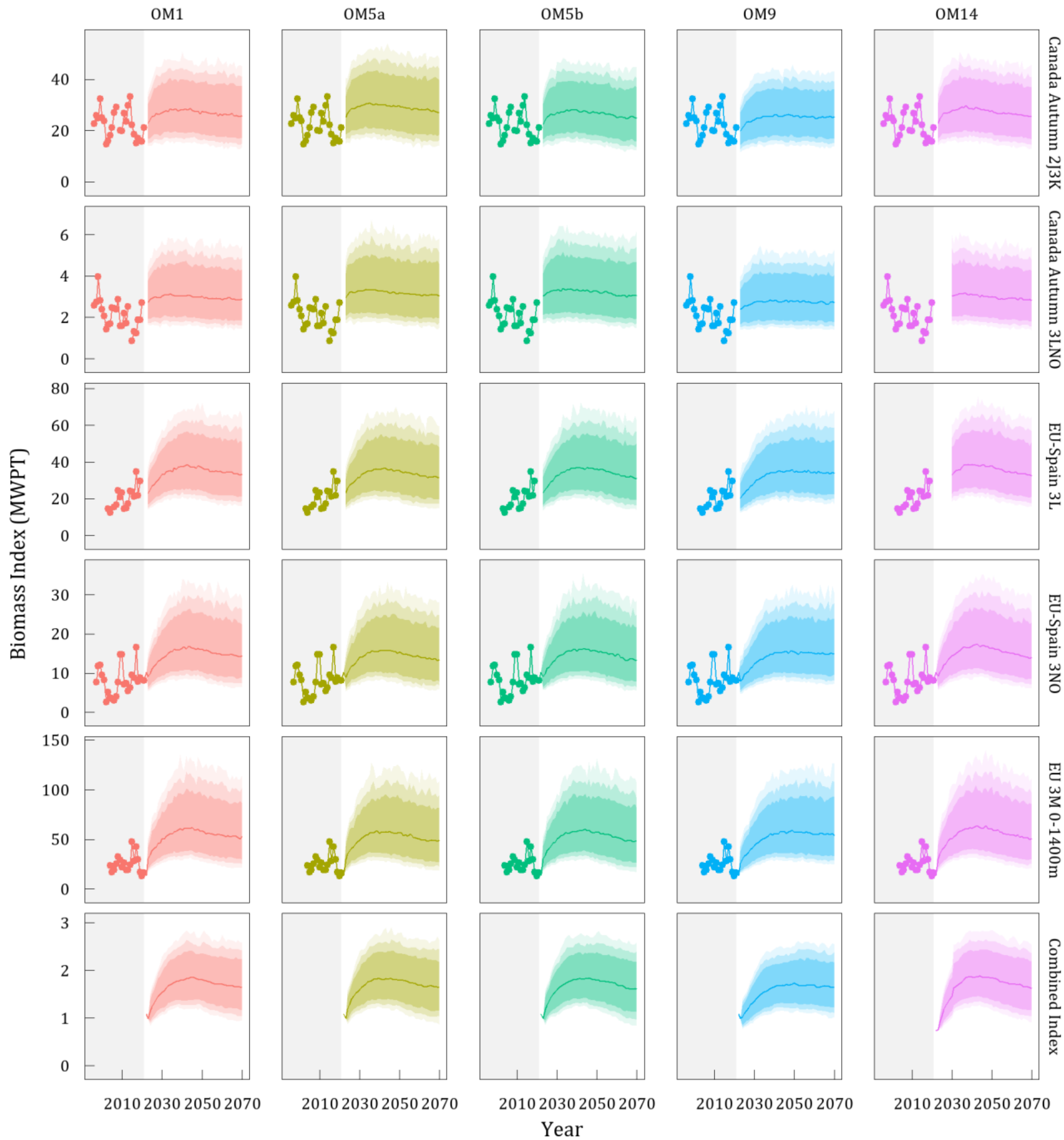

Figure 18. Median for expected and observed survey indices across OMs focused on survey uncertinty. Light to dark shaded regions represent the 95%, 90%, and 80% probability envelopes. Points represent observed values.

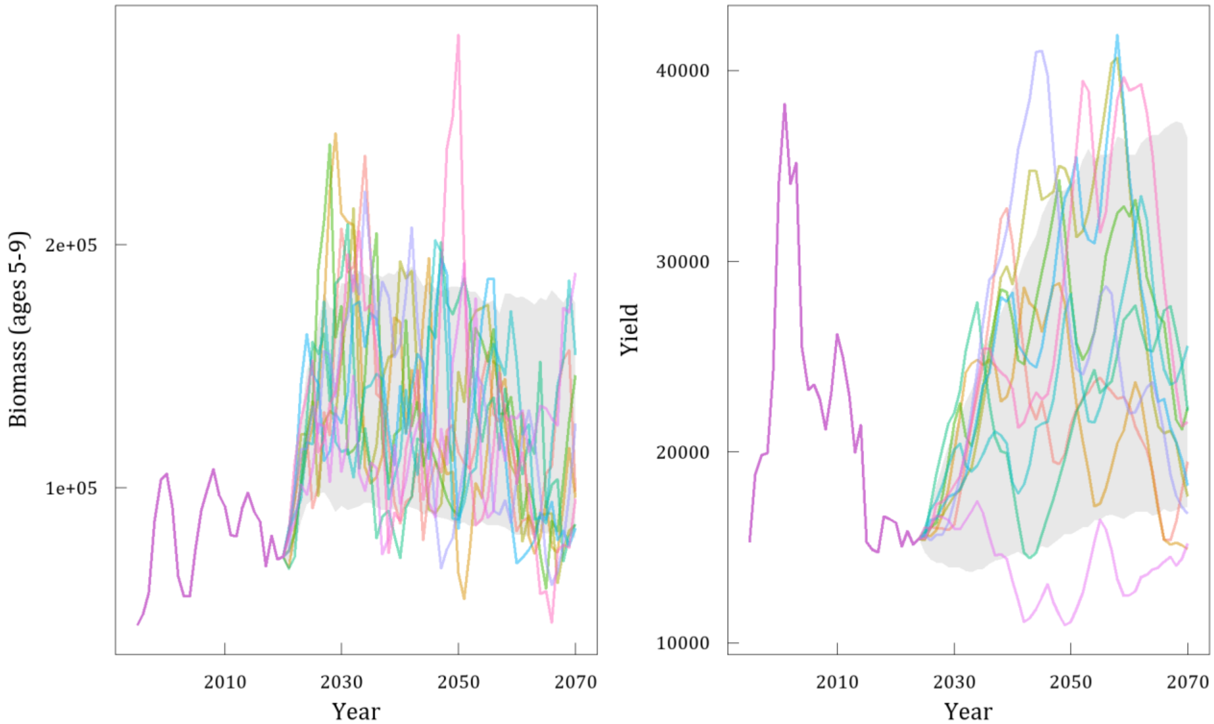

Figure 19. Spaghetti plot of potential stock and yield trajectories under the base case OM and combined slope and target CMP.

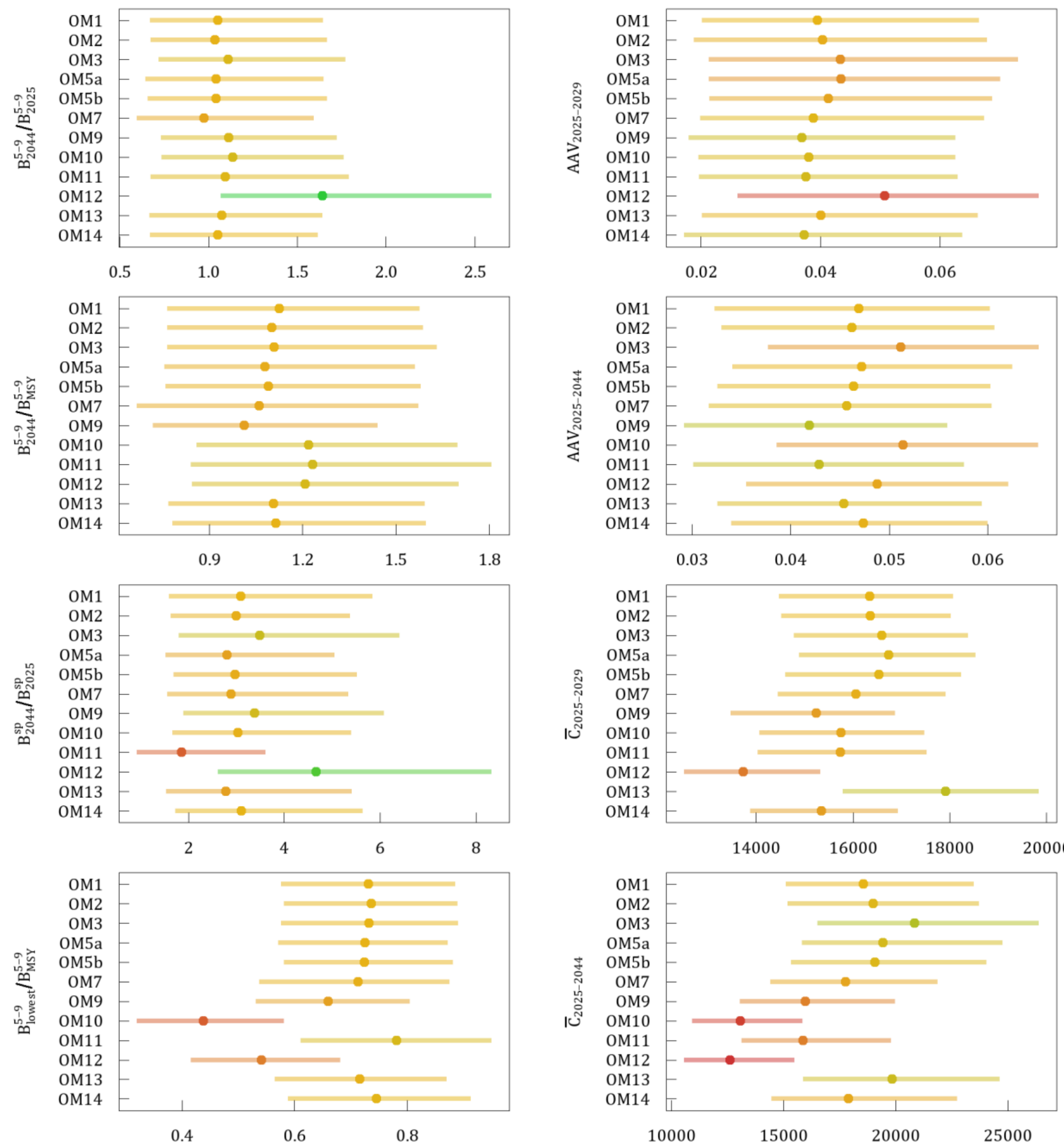

Figure 20. Median and 80% probability intervals for various performance statistics across OMs.

Appendix A: Diagnostics and output from OMs conditioned on data

Tables

Table 8. Negative log likelihood (nll), number of parameters (k), AIC, maximum gradient (maxgrad) for each model.

model	nll	k	AIC	maxgrad
base	1540	88	3256	0.0004
lorM	1625	88	3425	0.0007
senM	1541	88	3257	0.0005
flatF	1649	88	3474	0.0011

Table 9. Key parameter estimates from each sensitivity test. See Gullage, Regular, and Varkey (2023) for parameter descriptions.

Parameter	base	lorM	senM	flatF
$\sigma_{\text{Canada Autumn 2J3K, 1-3}}$	0.29	0.29	0.29	0.29
$\sigma_{\text{Canada Autumn 2J3K, 4-7}}$	0.32	0.30	0.32	0.31
$\sigma_{\text{Canada Autumn 2J3K, 8-10}}$	0.45	0.43	0.45	0.44
$\sigma_{\text{Canada Autumn 3LNO, 1-3}}$	0.68	0.68	0.67	0.67
$\sigma_{\text{Canada Autumn 3LNO, 4-7}}$	0.39	0.38	0.38	0.37
$\sigma_{\text{Canada Autumn 3LNO, 8-10}}$	0.65	0.64	0.65	0.64
$\sigma_{\text{Canada Spring 3LNO, 1-3}}$	0.68	0.68	0.68	0.68
$\sigma_{\text{Canada Spring 3LNO, 4-7}}$	0.52	0.51	0.51	0.50
$\sigma_{\text{Canada Spring 3LNO, 8-10}}$	0.66	0.66	0.66	0.65
$\sigma_{\text{EU-Spain 3NO, 1-3}}$	0.79	0.79	0.79	0.78
$\sigma_{\text{EU-Spain 3NO, 4-7}}$	0.58	0.58	0.58	0.59
$\sigma_{\text{EU-Spain 3NO, 8-10}}$	0.40	0.40	0.40	0.41
$\sigma_{\text{EU-Spain 3L, 1-3}}$	0.74	0.74	0.73	0.73
$\sigma_{\text{EU-Spain 3L, 4-7}}$	0.48	0.48	0.48	0.48
$\sigma_{\text{EU-Spain 3L, 8-10}}$	0.38	0.38	0.39	0.39
$\sigma_{\text{EU 3M, 1-3}}$	1.48	1.48	1.48	1.48
$\sigma_{\text{EU 3M, 4-7}}$	0.55	0.55	0.54	0.55
$\sigma_{\text{EU 3M, 8-10}}$	0.40	0.40	0.40	0.39
σ_{main}	0.56	0.56	0.56	0.56
σ_{Δ}	0.35	0.35	0.34	0.34
σ_{X}	0.19	0.25	0.18	0.43
σ_{r}	0.32	0.32	0.32	0.34

Parameter	base	lorM	senM	flatF
r	11.09	11.63	11.20	10.97
σ_F	0.20	0.16	0.20	0.03
σ_δ	0.16	0.17	0.17	0.17
$\varphi_{F,y}$	0.98	0.98	0.97	0.97
$\varphi_{F,a}$	0.50	0.86	0.51	0.55

Table 10. Estimates of recruitment (age 1; millions) from each sensitivity test.

Year	base	lorM	senM	flatF
1975	64.4	107.9	71.1	58.9
1976	61.1	101.2	67.1	54.3
1977	61.5	110.0	67.8	57.2
1978	56.4	94.1	62.9	50.4
1979	53.9	101.8	60.1	51.9
1980	66.6	113.3	74.3	58.5
1981	70.4	116.6	79.8	61.9
1982	65.6	110.3	75.0	57.5
1983	68.5	118.5	77.4	64.4
1984	72.6	124.5	81.2	68.7
1985	77.5	125.0	85.1	67.8
1986	72.4	118.9	78.5	63.6
1987	80.7	141.2	87.5	76.3
1988	70.0	118.3	75.8	64.6
1989	67.9	116.6	73.6	63.4
1990	62.8	105.4	68.1	56.8
1991	62.8	105.5	69.8	54.8
1992	58.3	102.6	65.2	53.2
1993	72.1	125.6	80.2	64.5
1994	109.8	184.5	120.5	97.1
1995	131.3	221.8	144.1	115.7
1996	146.0	252.0	164.0	132.3
1997	75.5	129.2	84.3	67.3
1998	56.8	98.6	63.3	50.4
1999	43.2	73.7	47.6	37.5
2000	72.3	124.2	80.8	64.8
2001	79.1	136.0	88.3	70.6
2002	80.1	135.9	89.3	70.7
2003	79.6	136.7	89.5	71.3
2004	56.8	98.7	64.0	50.8
2005	45.5	77.9	50.6	39.6
2006	55.8	97.1	62.9	49.7
2007	54.9	96.1	61.9	48.8
2008	47.7	81.5	53.0	41.2
2009	69.8	121.3	78.4	62.4

Year	base	lorM	senM	flatF
2010	65.5	113.7	73.9	58.8
2011	48.8	85.1	55.9	44.3
2012	31.3	53.7	35.0	27.3
2013	55.3	95.5	62.4	49.5
2014	49.2	84.2	55.2	43.6
2015	45.0	77.6	50.0	39.2
2016	63.4	108.6	70.4	55.4
2017	76.9	129.8	85.8	67.9
2018	68.0	115.9	75.6	60.3
2019	72.8	124.3	80.9	64.8
2020	69.4	117.7	77.3	61.5
2021	57.1	97.4	63.7	50.5

Table 11. Estimates of exploitable biomass (ages 5-9; Kt) from each sensitivity test.

Year	base	lorM	senM	flatF
1975	91.8	90.8	107.4	88.9
1976	93.9	88.9	108.2	85.9
1977	111.0	112.2	125.2	106.1
1978	118.8	123.0	132.0	119.0
1979	116.3	120.9	129.3	115.2
1980	95.4	98.7	105.8	94.6
1981	83.5	84.9	93.1	77.0
1982	81.9	85.2	91.3	75.3
1983	76.7	82.0	85.7	68.9
1984	69.1	76.4	78.0	62.6
1985	91.8	98.7	105.4	79.4
1986	79.5	85.9	93.6	68.9
1987	95.2	99.7	114.0	83.3
1988	98.4	100.9	119.9	85.8
1989	111.2	113.3	135.6	103.2
1990	122.8	122.1	147.1	118.3
1991	138.8	137.1	163.0	131.7
1992	130.3	127.6	150.7	117.4
1993	105.1	105.2	121.0	94.6
1994	71.0	71.8	82.7	61.5
1995	43.6	45.8	52.9	35.4
1996	47.9	50.6	56.3	40.3
1997	56.9	60.4	67.1	48.0
1998	86.4	92.0	101.5	73.6
1999	103.3	110.0	118.8	89.7
2000	105.8	110.8	118.7	92.5
2001	91.9	95.4	101.6	80.8
2002	63.5	66.6	69.8	57.0
2003	55.3	56.8	61.8	48.3
2004	55.3	58.5	62.9	48.1
2005	74.9	79.8	86.7	63.2
2006	90.6	96.7	105.5	74.8
2007	99.9	107.2	119.2	79.4
2008	107.8	115.5	131.2	81.4
2009	96.9	102.3	118.0	72.2

Year	base	lorM	senM	flatF
2010	92.4	96.8	113.1	68.4
2011	80.7	84.5	98.8	59.1
2012	80.0	85.4	97.9	59.9
2013	91.8	98.1	111.5	67.8
2014	98.1	106.0	121.4	69.6
2015	90.1	97.4	114.0	60.2
2016	86.2	92.8	109.4	57.8
2017	67.7	72.6	85.7	46.7
2018	80.4	84.4	100.6	55.3
2019	70.5	74.8	87.0	51.5
2020	71.8	75.6	86.2	53.8
2021	75.4	78.7	88.8	57.5

Table 12. Estimates of average F (ages 5-9; Kt) from each sensitivity test.

Year	base	lorM	senM	flatF
1975	0.2	0.2	0.2	0.2
1976	0.2	0.2	0.1	0.2
1977	0.3	0.2	0.2	0.2
1978	0.3	0.3	0.3	0.3
1979	0.3	0.3	0.3	0.3
1980	0.3	0.3	0.2	0.4
1981	0.4	0.3	0.3	0.4
1982	0.2	0.2	0.2	0.3
1983	0.3	0.3	0.3	0.3
1984	0.3	0.3	0.2	0.3
1985	0.2	0.2	0.2	0.2
1986	0.2	0.1	0.1	0.2
1987	0.2	0.2	0.2	0.3
1988	0.2	0.1	0.1	0.1
1989	0.1	0.1	0.1	0.1
1990	0.2	0.2	0.2	0.3
1991	0.3	0.3	0.2	0.3
1992	0.4	0.4	0.3	0.4
1993	0.6	0.6	0.5	0.7
1994	0.8	0.8	0.7	1.0
1995	0.2	0.2	0.2	0.3
1996	0.3	0.3	0.2	0.4
1997	0.2	0.2	0.2	0.3
1998	0.2	0.2	0.1	0.2
1999	0.2	0.2	0.1	0.2
2000	0.4	0.4	0.3	0.5
2001	0.6	0.5	0.5	0.7
2002	0.6	0.7	0.6	0.9
2003	0.6	0.6	0.6	0.8
2004	0.4	0.3	0.3	0.5
2005	0.2	0.2	0.2	0.3
2006	0.2	0.2	0.2	0.3
2007	0.2	0.2	0.2	0.3
2008	0.2	0.2	0.2	0.3
2009	0.2	0.2	0.2	0.3

Year	base	lorM	senM	flatF
2010	0.3	0.3	0.2	0.4
2011	0.3	0.2	0.2	0.4
2012	0.2	0.2	0.2	0.3
2013	0.2	0.2	0.2	0.2
2014	0.2	0.2	0.2	0.3
2015	0.2	0.1	0.1	0.2
2016	0.2	0.1	0.1	0.2
2017	0.1	0.1	0.1	0.2
2018	0.2	0.1	0.1	0.2
2019	0.2	0.2	0.1	0.2
2020	0.2	0.1	0.1	0.2
2021	0.1	0.1	0.1	0.2

Figures

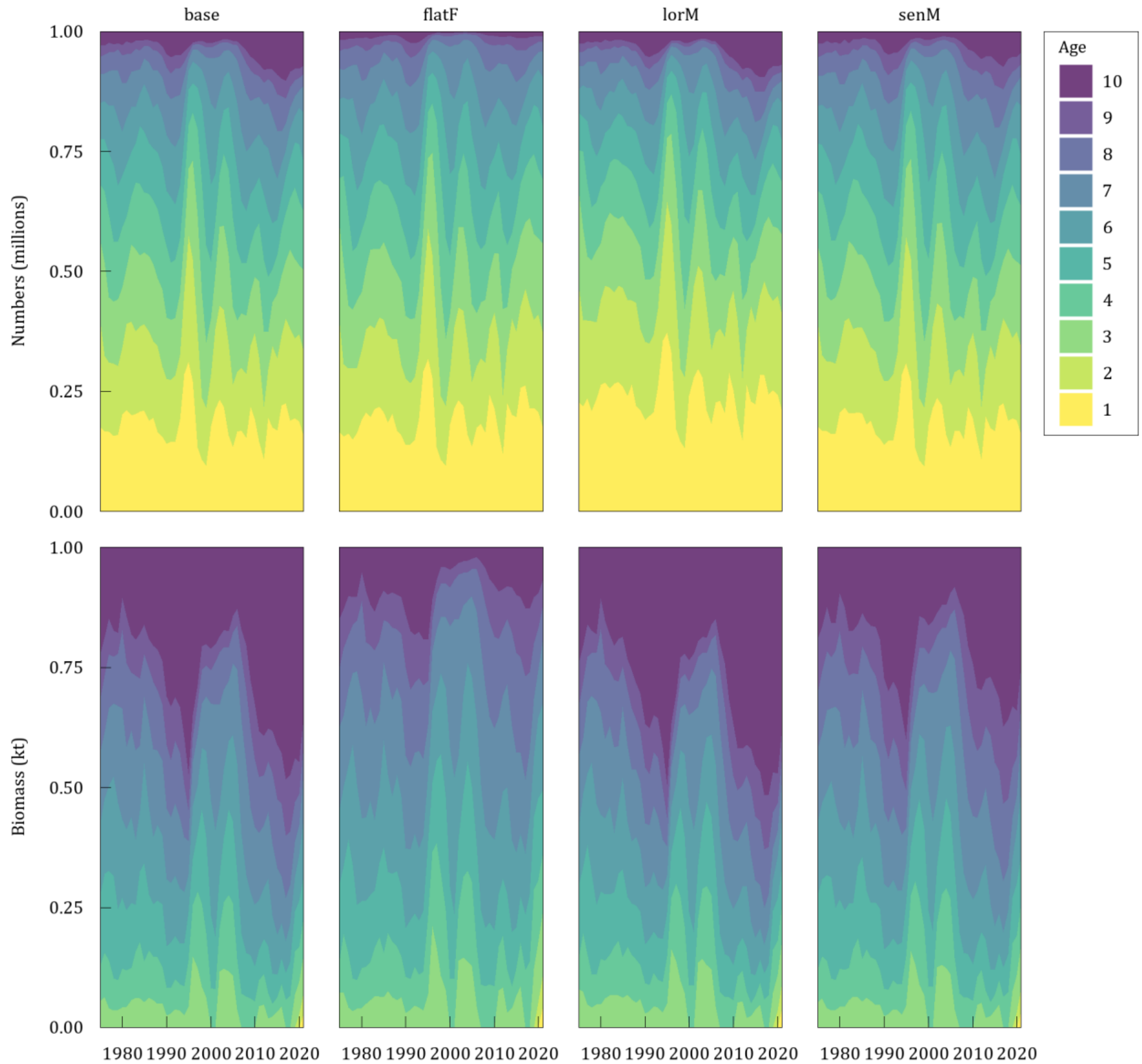

Figure 21. Stock abundance and biomass proportion at age.

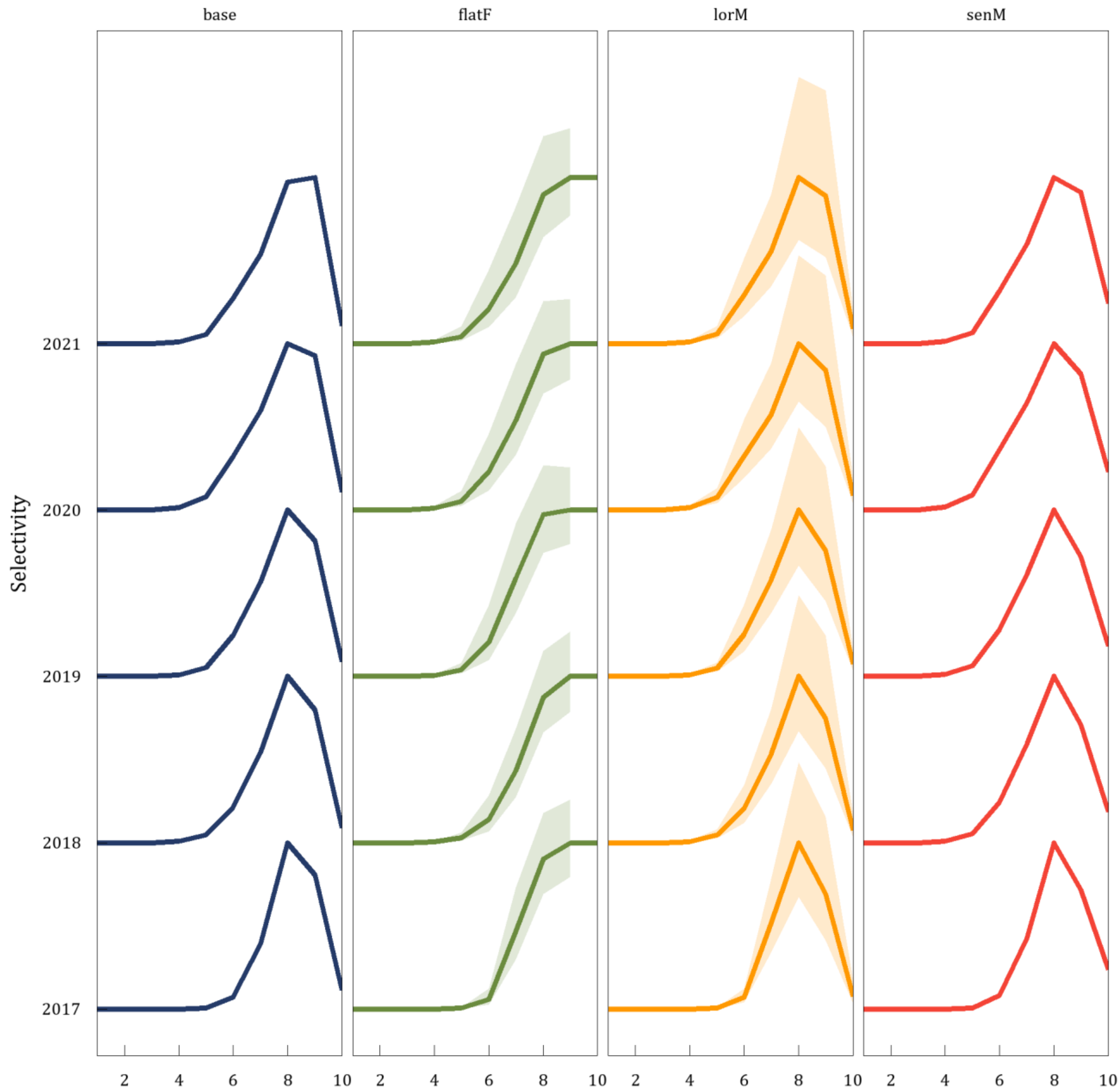

Figure 22. Selectivity curves from the most recent five years.

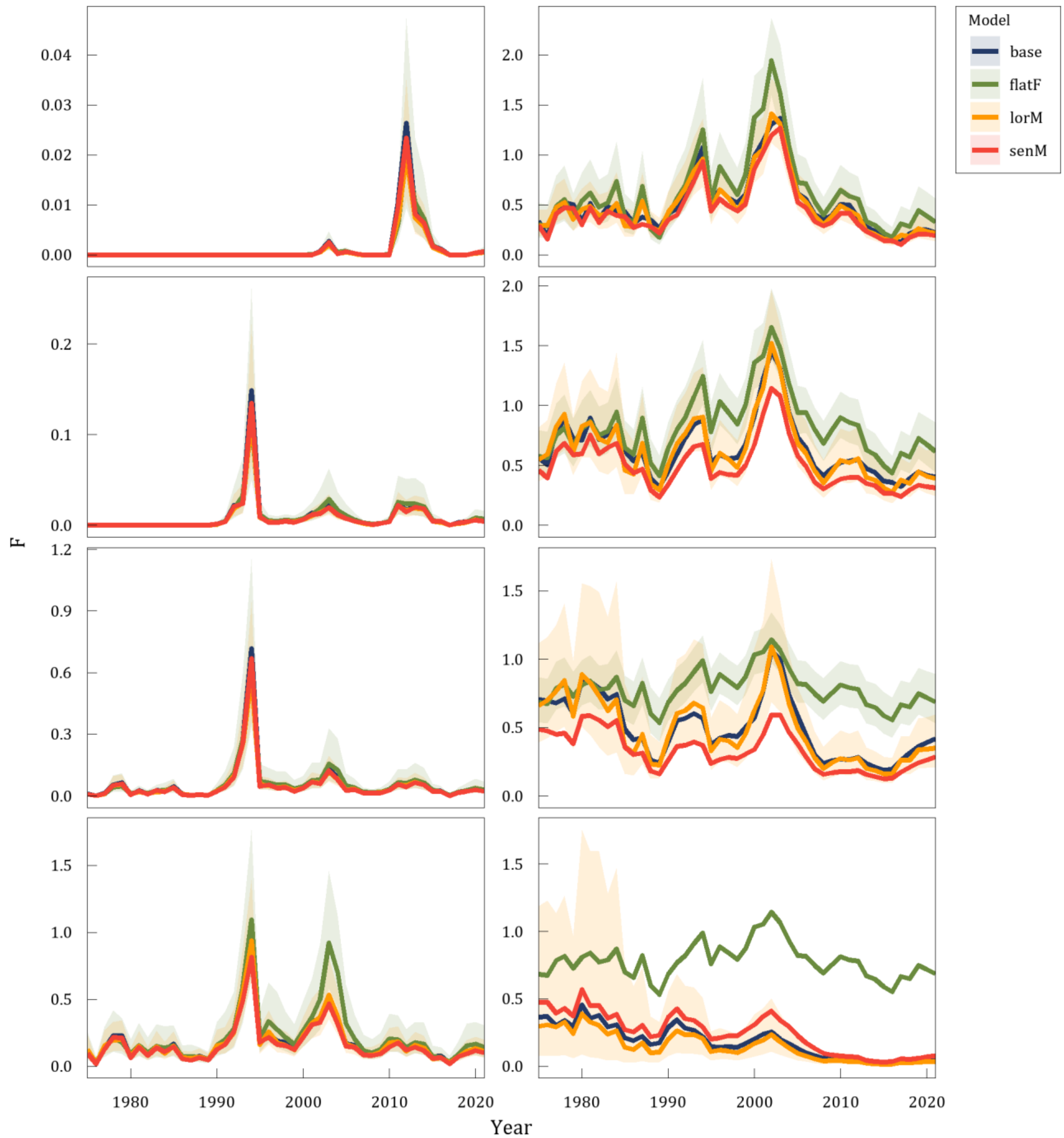

Figure 23. Fishing mortality at age.

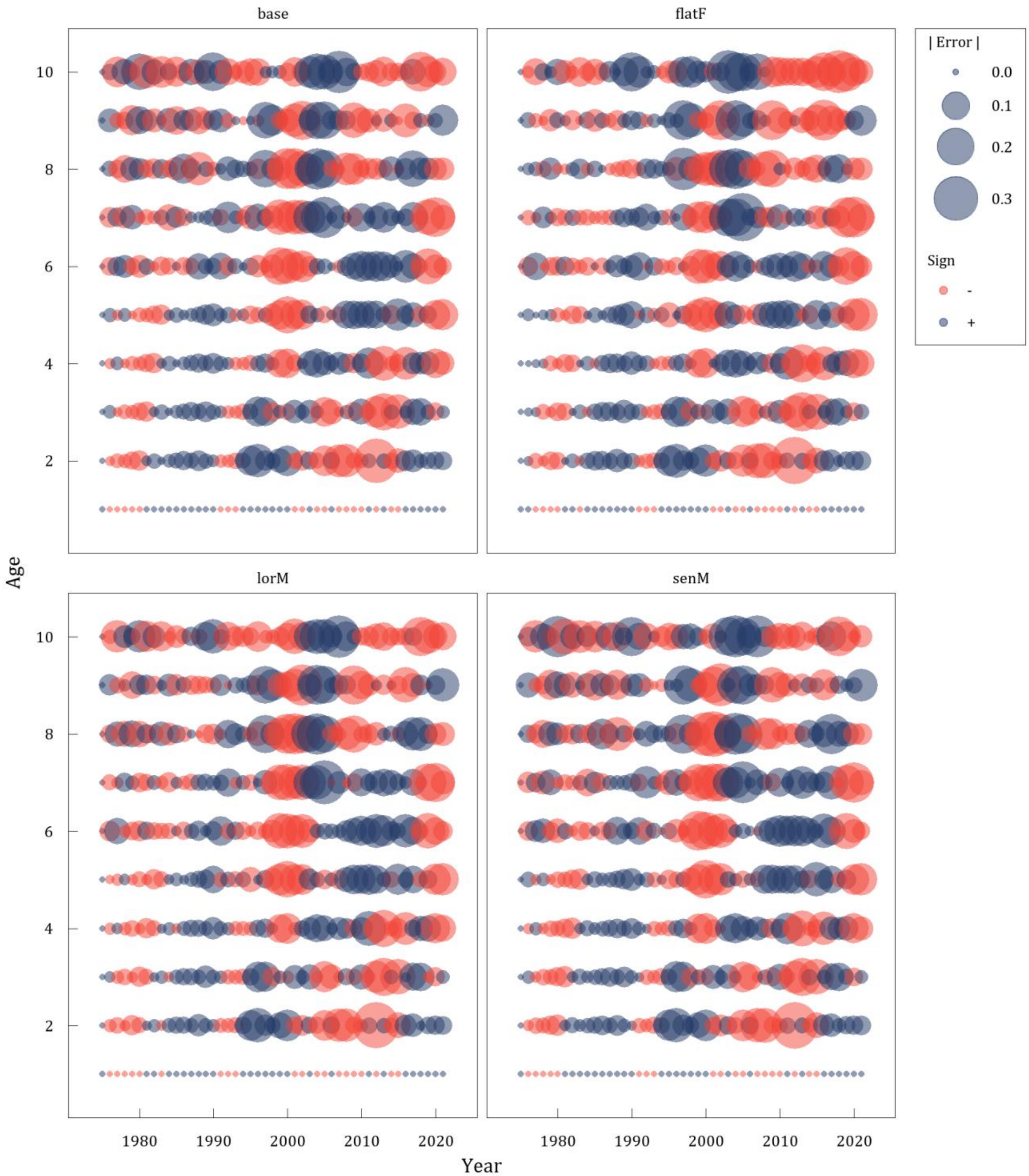

Figure 24. Matrix plot of predicted process errors.

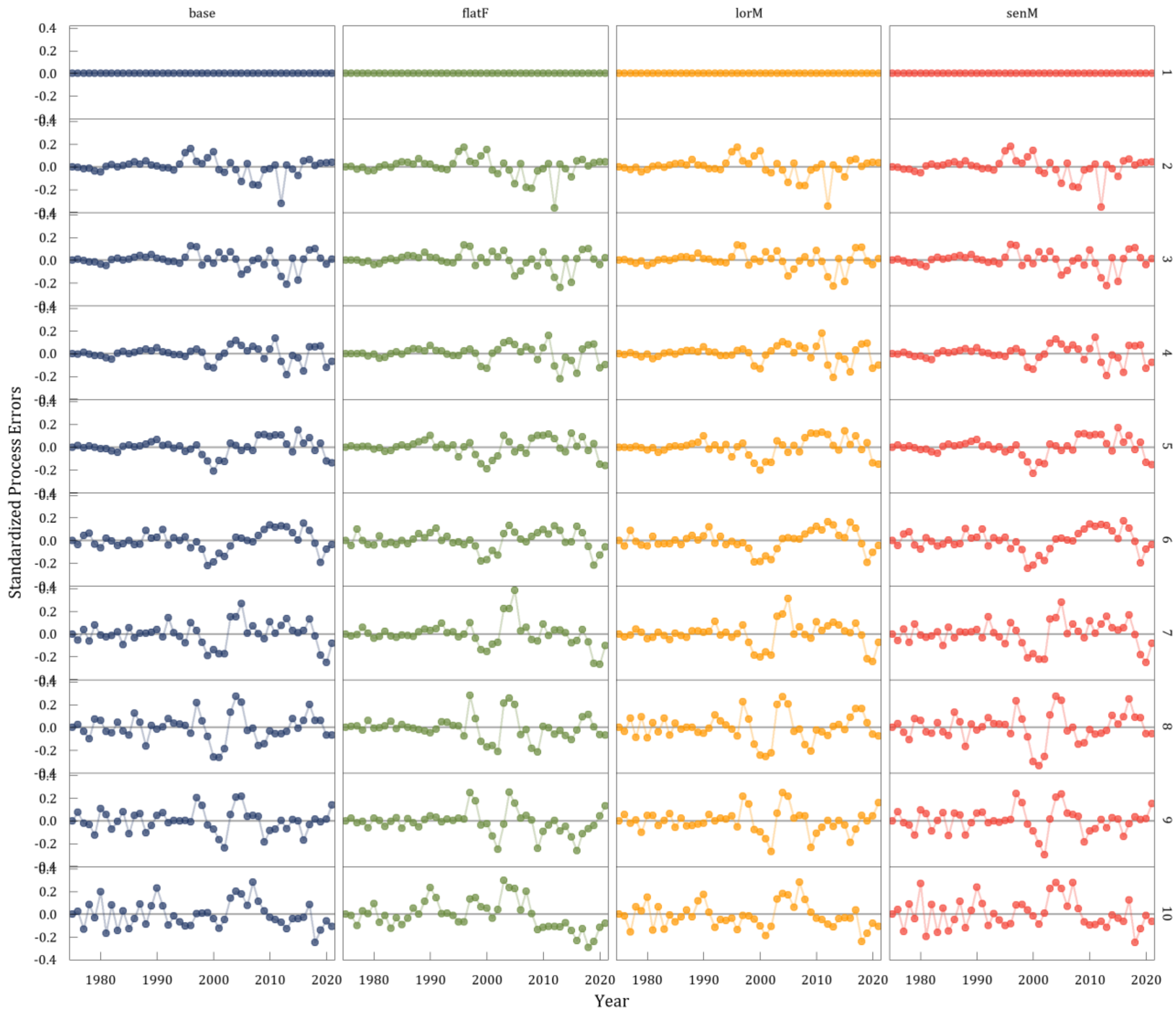

Figure 25. Predicted process error at age.

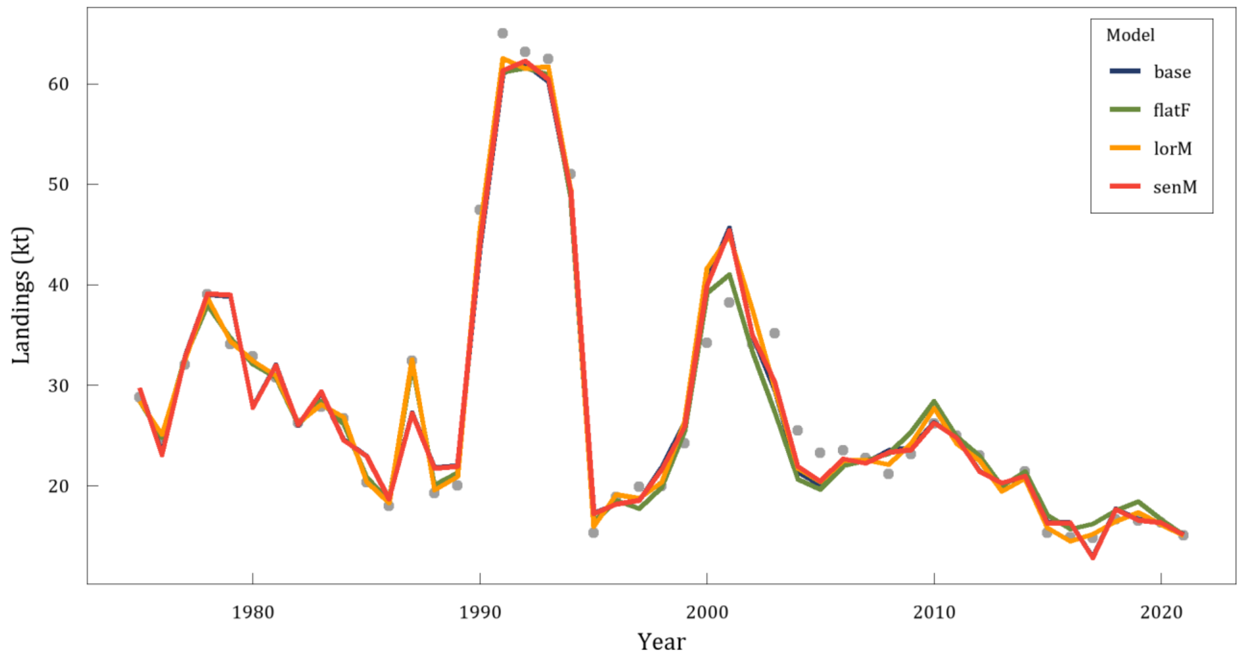

Figure 26. Observed and predicted landings (kt).

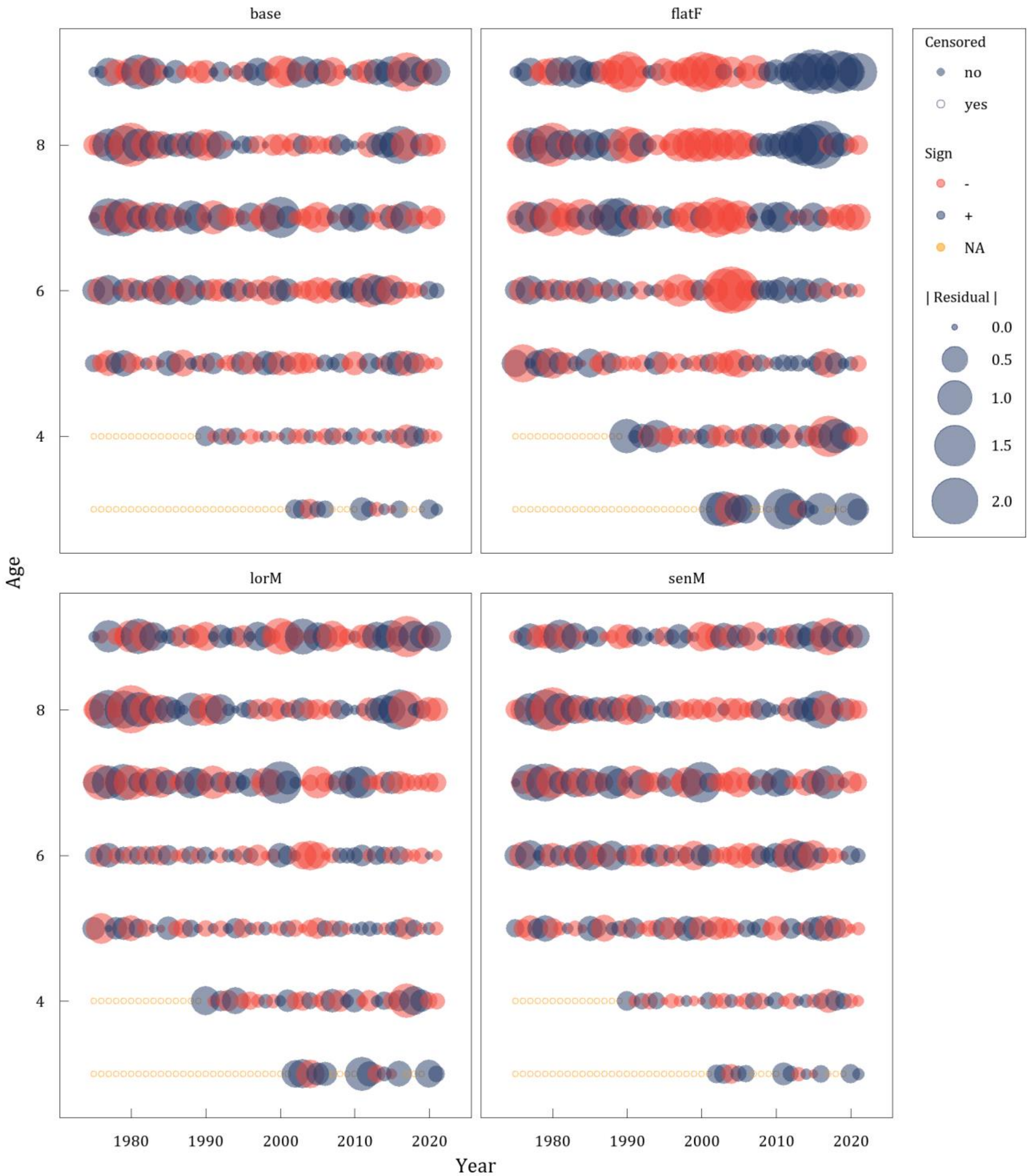

Figure 27. Matrix plot of standardized residuals for catch at age continuation ratio logits (observed minus predicted).

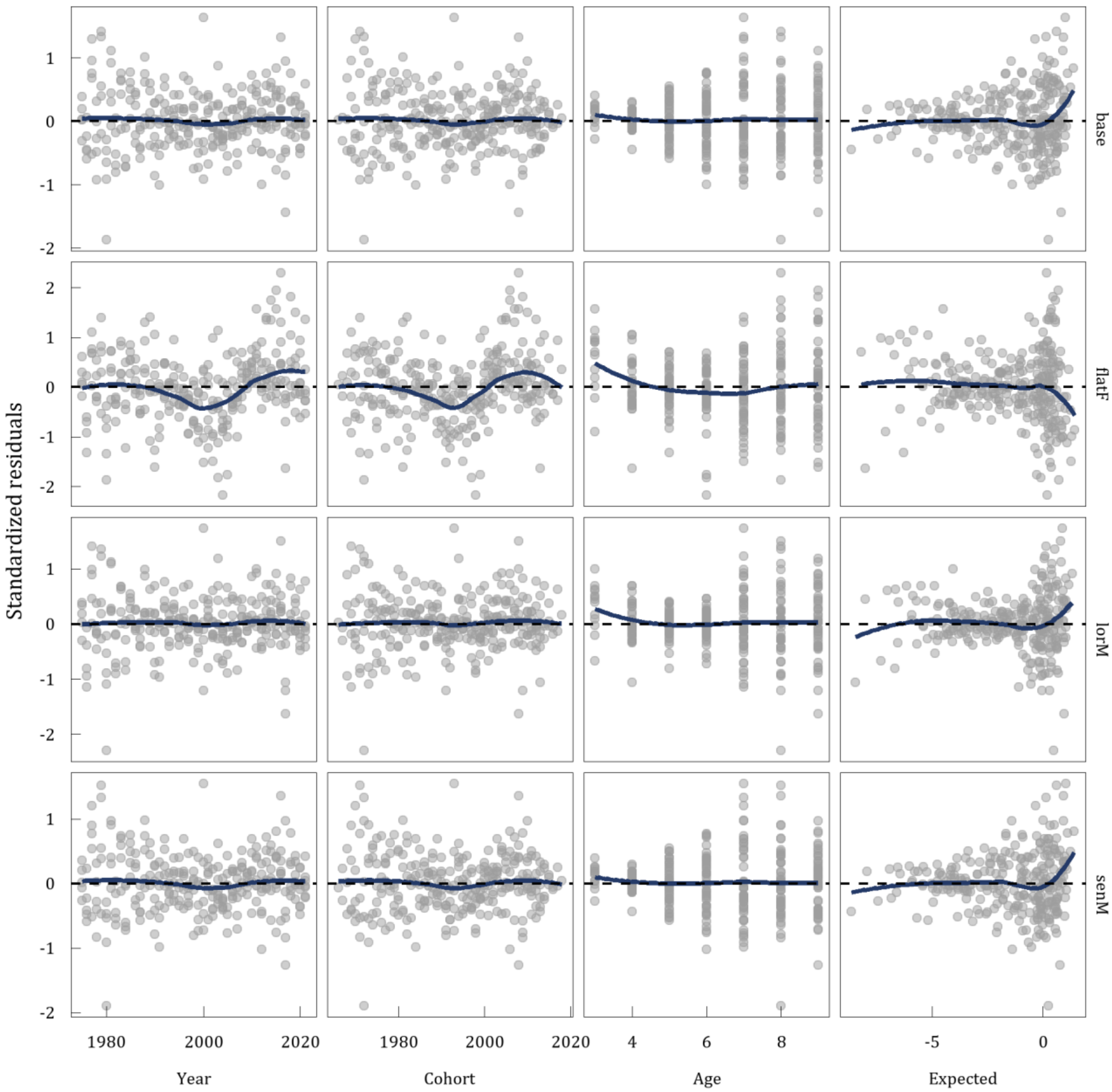

Figure 28. Standardized residuals for catch at age continuation ratio logits versus year, cohort, age, and predicted value.

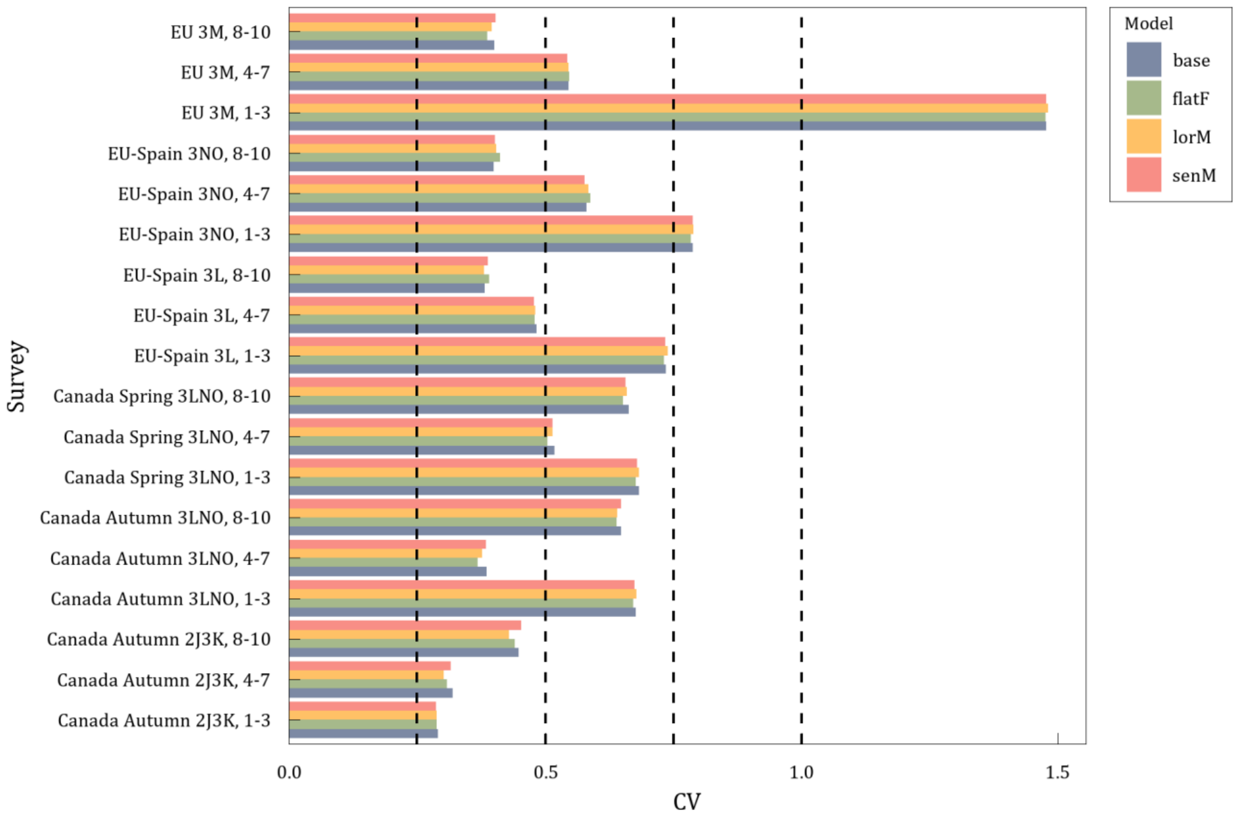

Figure 29. Estimates of survey CV. Age ranges follow the survey name.

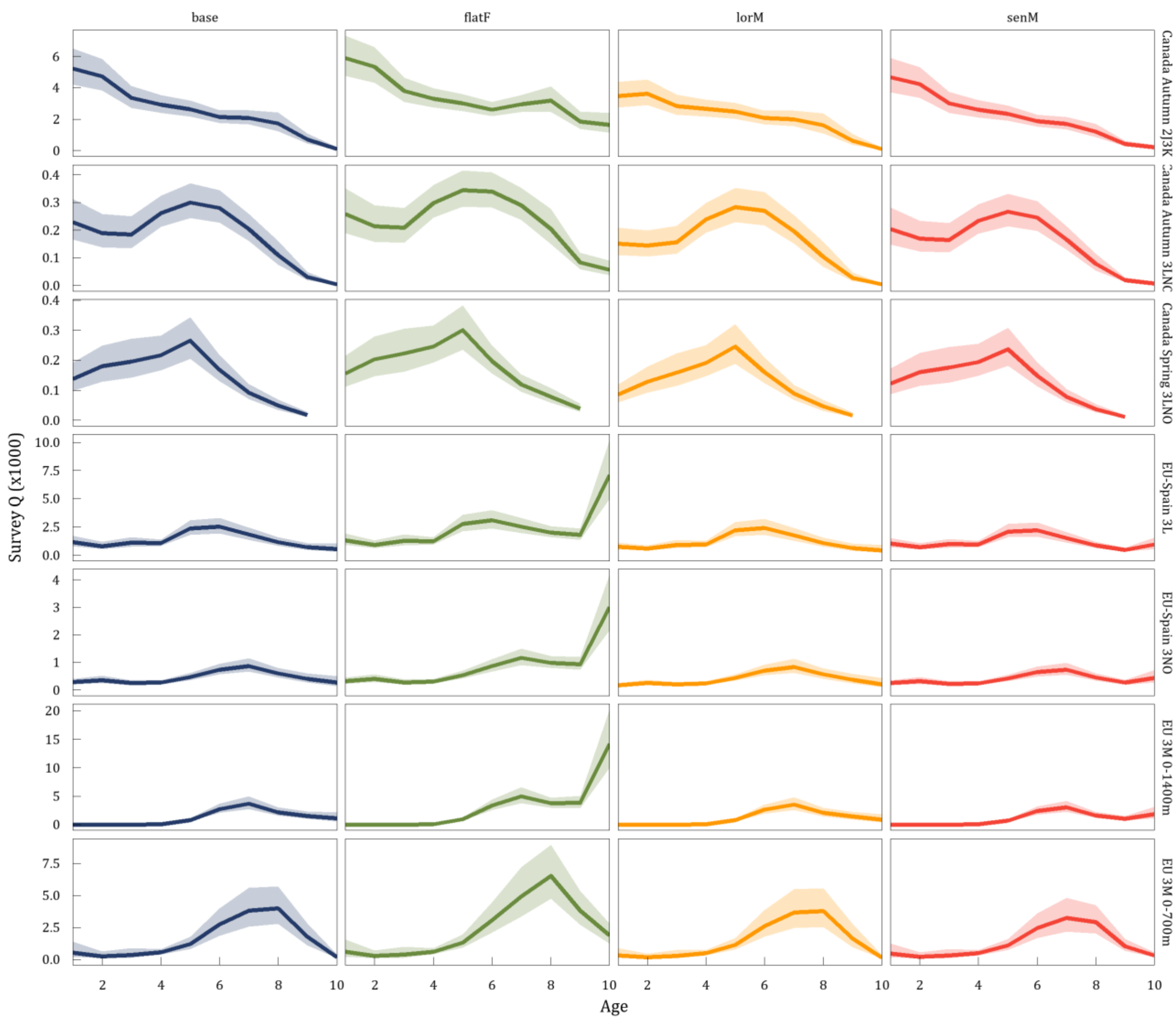

Figure 30. Age patterns in survey catchability parameters, with 95% confidence intervals.

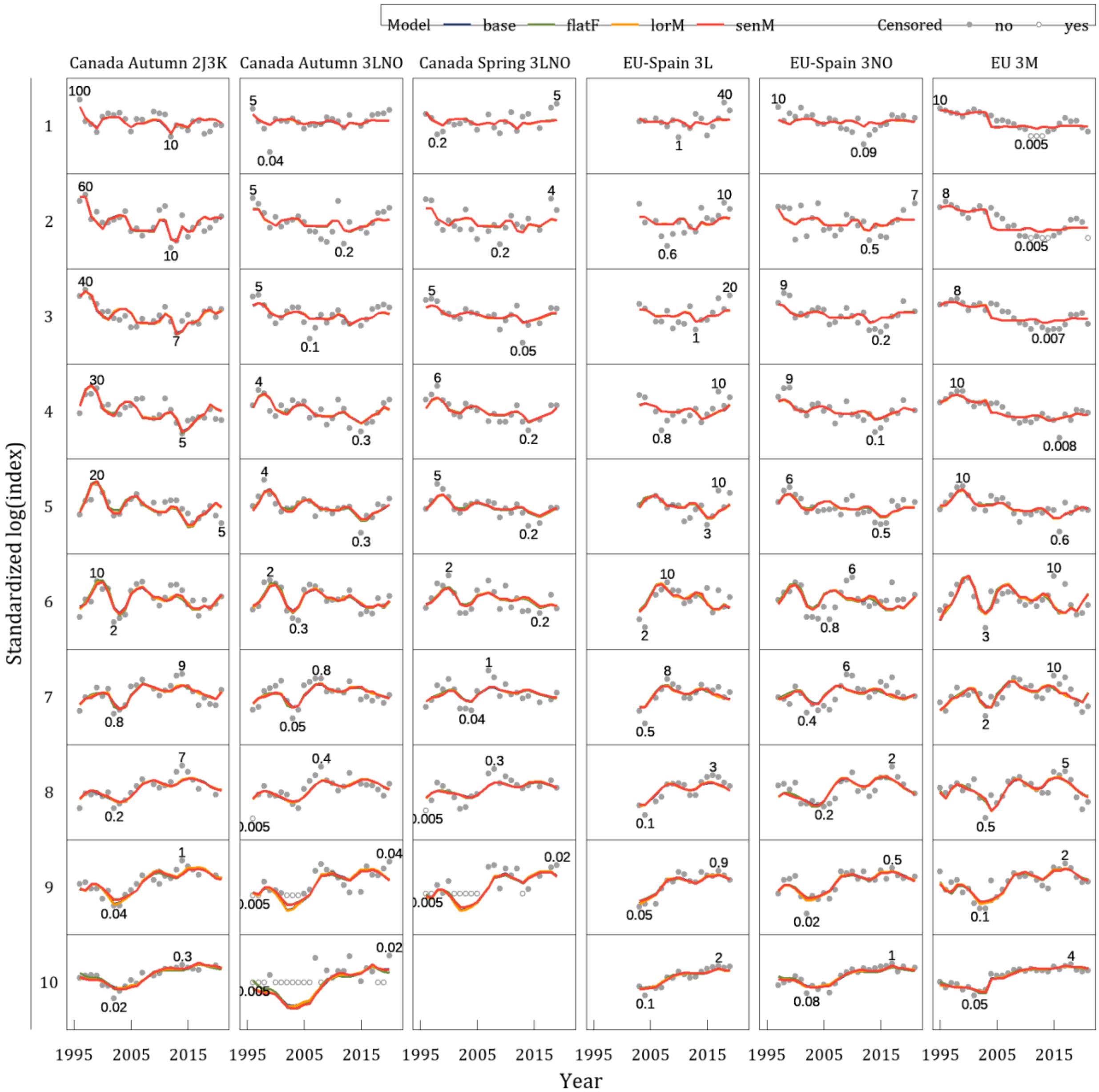

Figure 31. Observed and predicted survey indices at age. Log(index) standardized by survey and age. Min and max observed index values are indicated.

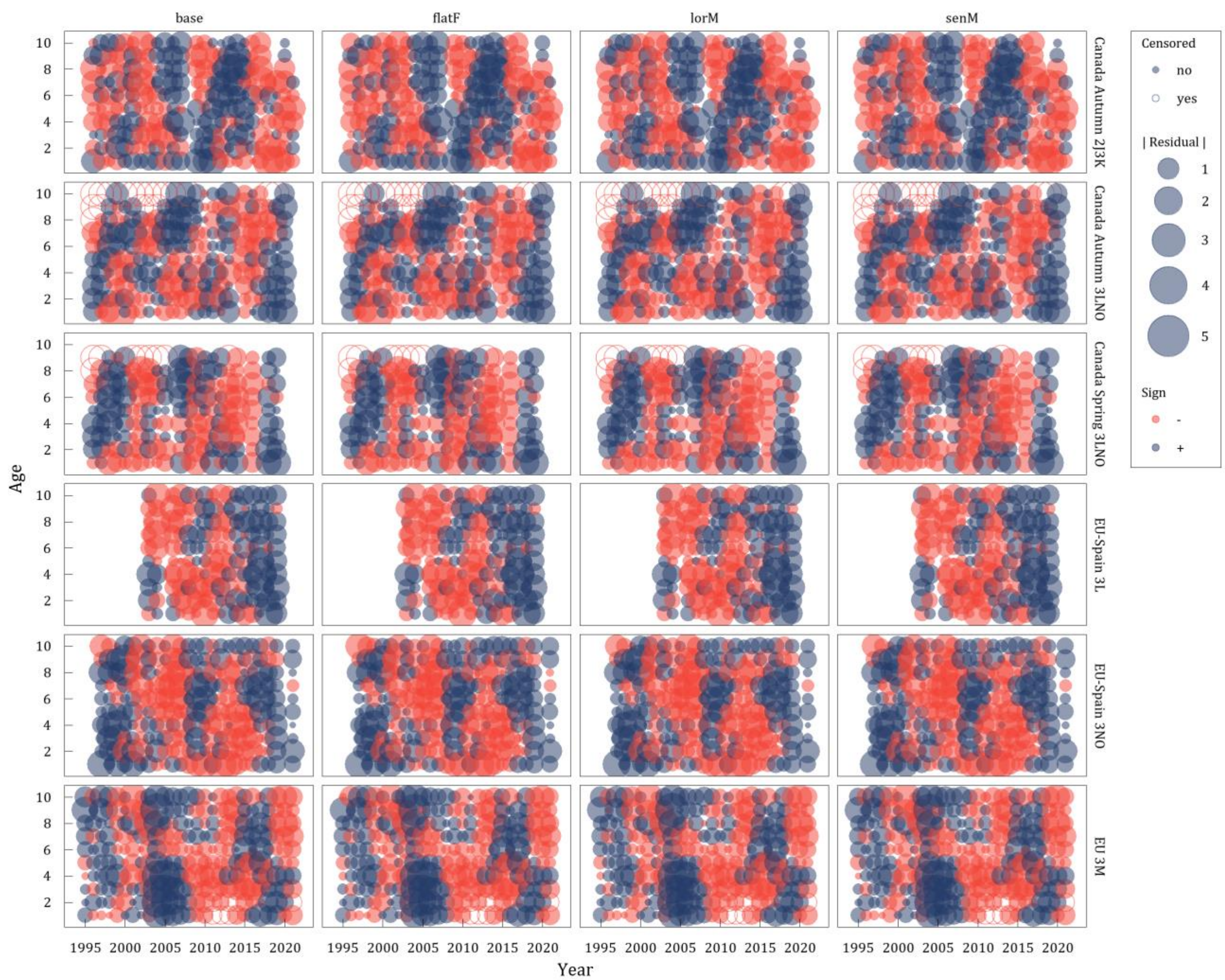

Figure 32. Matrix plot of standardized residuals for index at age by survey.

Colophon

This version of the document was generated on 2024-04-10 21:05:34.508572 using the R markdown template for SCR documents from **NAFOdown**.

The computational environment that was used to generate this version is as follows:

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#>    promises              1.2.0.1    2021-02-11 [1] CRAN (R 4.3.1)
#>    ps                    1.7.5      2023-04-18 [1] CRAN (R 4.3.1)
#>    purrr               * 1.0.1      2023-01-10 [1] CRAN (R 4.3.1)
#>    R6                    2.5.1      2021-08-19 [1] CRAN (R 4.3.1)
#>    ragg                  1.2.5      2023-01-12 [1] CRAN (R 4.3.1)
#>    Rcpp                  1.0.11     2023-07-06 [1] CRAN (R 4.3.1)
#>    RcppEigen           * 0.3.3.9.4  2023-11-02 [1] CRAN (R 4.3.2)
#>    readr               * 2.1.4      2023-02-10 [1] CRAN (R 4.3.1)
#>    remotes               2.4.2.1    2023-07-18 [1] CRAN (R 4.3.2)
#>    rlang                 1.1.1      2023-04-28 [1] CRAN (R 4.3.1)
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#>    rmarkdown          2.23       2023-07-01 [1] CRAN (R 4.3.1)
#>    rprojroot          2.0.3      2022-04-02 [1] CRAN (R 4.3.1)
#>    rstudioapi         0.15.0     2023-07-07 [1] CRAN (R 4.3.1)
#>    scales             1.2.1      2022-08-20 [1] CRAN (R 4.3.1)
#>    sessioninfo        1.2.2      2021-12-06 [1] CRAN (R 4.3.1)
#>    shiny              1.7.4.1    2023-07-06 [1] CRAN (R 4.3.1)
#>    showtext           0.9-6      2023-05-03 [1] CRAN (R 4.3.1)
#>    showtextdb         3.0        2020-06-04 [1] CRAN (R 4.3.1)
#>    stringi            1.7.12     2023-01-11 [1] CRAN (R 4.3.0)
#>    stringr          * 1.5.0      2022-12-02 [1] CRAN (R 4.3.1)
#>    sysfonts           0.8.8      2022-03-13 [1] CRAN (R 4.3.1)
#>    systemfonts        1.0.4      2022-02-11 [1] CRAN (R 4.3.1)
#>    textshaping        0.3.6      2021-10-13 [1] CRAN (R 4.3.1)
#>    tibble           * 3.2.1      2023-03-20 [1] CRAN (R 4.3.1)
#>    tidyr            * 1.3.0      2023-01-24 [1] CRAN (R 4.3.1)
#>    tidyselect         1.2.0      2022-10-10 [1] CRAN (R 4.3.1)
#>    tidyverse        * 2.0.0      2023-02-22 [1] CRAN (R 4.3.1)
#>    timechange         0.2.0      2023-01-11 [1] CRAN (R 4.3.1)
#>  D TMB              * 1.9.10     2023-12-12 [1] CRAN (R 4.3.2)
#>    tzdb               0.4.0      2023-05-12 [1] CRAN (R 4.3.1)
#>    urlchecker         1.0.1      2021-11-30 [1] CRAN (R 4.3.1)
#>    usethis            2.2.2      2023-07-06 [1] CRAN (R 4.3.1)
#>    utf8               1.2.3      2023-01-31 [1] CRAN (R 4.3.1)
#>    uuid               1.1-0      2022-04-19 [1] CRAN (R 4.3.0)
#>    V8                 4.3.3      2023-07-18 [1] CRAN (R 4.3.1)
#>    vctrs              0.6.3      2023-06-14 [1] CRAN (R 4.3.1)
#>    viridisLite        0.4.2      2023-05-02 [1] CRAN (R 4.3.1)
#>    withr              2.5.0      2022-03-03 [1] CRAN (R 4.3.1)
#>    xfun               0.39       2023-04-20 [1] CRAN (R 4.3.1)
#>    xml2               1.3.5      2023-07-06 [1] CRAN (R 4.3.1)
#>    xslt               1.4.4      2023-02-21 [1] CRAN (R 4.3.1)
#>    xtable             1.8-4      2019-04-21 [1] CRAN (R 4.3.1)
#>    yaml               2.3.7      2023-01-23 [1] CRAN (R 4.3.0)
#>    zip                2.3.0      2023-04-17 [1] CRAN (R 4.3.1)
#>    zoo                1.8-12     2023-04-13 [1] CRAN (R 4.3.1)
#>
#>  [1] C:/Users/RegularP/AppData/Local/R/win-library/4.3
#>  [2] C:/Program Files/R/R-4.3.0/library
#>
#>  D ── DLL MD5 mismatch, broken installation.
#>
#> ──────────────────────────────────────────────────────────────────────────
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