Supplementary Materials for:

A closed-loop simulation framework and indicator approach for evaluating impacts of retrospective patterns in stock assessments

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A. Description of the Stock Reduction Analysis age-structured model

A.1. Dynamics equations

The population abundance $N_{y,a}$ of age a at the beginning of year y is

$$N_{y,a} = \begin{cases} R_y & a = 1 \\ N_{y-1,a-1}\exp(-Z_{y-1,a-1}) & a = 2,..,A-1 \\ N_{y-1,A-1}\exp(-Z_{y-1,A-1}) + N_{y-1,A}\exp(-Z_{y-1,A}) & a = A \end{cases}, \quad (A.1)$$

where R_y is the recruitment of age 1, $Z_{y,a} = \sum_f v_{y,a,f} F_{y,f} + M_{y,a}$ is the total mortality rate from fishing mortality $F_{y,f}$ from all fleets f and natural mortality $M_{y,a}$.

The selectivity at age $v_{a,f}$, assuming a logistic function, is

$$v_{a,f} = \left\{1 + \exp\left[-\ln(19) \times \left(\frac{a - a_{50(f)}}{a_{95(f)} - a_{50(f)}}\right)\right]\right\}^{-1}, \quad (A.2)$$

where a_{50} and a_{95} are the ages of 50% and 95% vulnerability, respectively. The selectivity at age is, assuming a double-Gaussian (dome-shape) function, is

$$v_{a,f} = \begin{cases} \exp\left[-0.5\left(\frac{a-\mu_f}{\omega_f^{asc}}\right)^2\right], & a \leq \mu_f \\ \exp\left[-0.5\left(\frac{a-\mu_f}{\omega_f^{des}}\right)^2\right], & a > \mu_f \end{cases}, \quad (A.3)$$

where μ_f is the age of full selectivity, and ω_f^{asc} and ω_f^{des} are parameters that control the width of the ascending and descending limbs (referenced by superscript asc and des, respectively) of the selectivity at age. Selectivity can also be independent parameters with age. Selectivity can be year-specific by time-block by specifying the change points of each time block.

The catch-at-age $C^A_{y,a,f}$ is

$$C^A_{y,a,f} = \frac{v_{y,a,f} F_{y,f}}{Z_{y,a}}(1 - \exp[-Z_{y,a}])N_{y,a}, \quad (A.4)$$

and the catch $C^W_{y,f}$ (in weight) is

$$C^W_{y,f} = \sum_a w_{y,a} C^A_{y,a,f}, \quad (A.5)$$

where $w_{y,a}$ is the weight-at-age schedule.

With a Beverton-Holt stock-recruit function, the recruitment (at age-1) in year y is

$$R_y = \frac{\alpha B^S_{y-1}}{1+\beta B^S_{y-1}} \exp(\delta_y - 0.5\tau^2), \tag{A.6}$$

where δ_y are normally-distributed deviates with standard deviation τ, spawning biomass B^S_y is calculated as

$$B^S_y = \sum_a m_{y,a} w_{y,a} N_{y,a}, \tag{A.7}$$

and $m_{y,a}$ is the maturity-at-age schedule. Stock recruit parameters are defined as:

$$\alpha = \frac{4h}{(1-h)\phi_{0,y=1}} \tag{A.8a}$$

$$\beta = \frac{5h-1}{(1-h)R_0\phi_{0,y=1}}, \tag{A.8b}$$

where R_0 and h are the unfished recruitment and steepness, respectively, parameters corresponding to unfished recruits per spawner calculated from biological parameters in the first year of the model ($\phi_{0,y=1}$).

The age composition observed from an index of abundance is

$$I^A_{y,a,s} = q_s v_{a,s} N_{y,a}, \tag{A.9}$$

where s indexes the survey, q is the catchability coefficient, and $v_{a,s}$ is the survey selectivity parameterized similarly to the fleet selectivity. The annual value from the aggregate index is

$$I_{y,s} = \sum_a I^A_{y,a,s}. \tag{A.10}$$

The model estimates R_0, selectivity parameters, and recruitment deviates, with steepness and biological parameters fixed. The fishing mortality $F_{y,f}$ is solved iteratively such that predicted catches ($\widehat{C^W_{y,f}}$) match observed values.

A.2. Likelihoods

The log-likelihood L^I of the observed indices $I_{y,s}^{\mathrm{obs}}$ (after omitting constants) is

$$L^I = \sum_s \left[\sum_y - \ln(\sigma_{y,s}) - 0.5 \sum_y \left(\frac{\ln[I_{y,s}^{\mathrm{obs}}] - \ln[\hat{I}_{y,s}]}{\sigma_{y,s}} \right)^2 \right], \tag{A.11}$$

where $\sigma_{y,s}$ is the standard deviation of the index, and the circumflex [^] denotes an estimate.

The log-likelihood L^{CA} of the catch at age compositions $C_{y,a,f}^{A}$ is

$$L^{CA} = \sum_f \sum_y \sum_a O_{y,f}\, p_{y,a,f}^{\mathrm{obs}} \ln[\hat{p}_{y,a,f}], \tag{A.12}$$

where $O_{y,f}$ is the assumed sample size of the age composition, $\hat{p}_{y,a,f} = \hat{C}_{y,a,f}^{A} / \sum_a \hat{C}_{y,a,f}^{A}$ is the estimated catch-at-age proportion. Similarly, the log-likelihood L^{IA} for the index at age is

$$L^{IA} = \sum_s \sum_y \sum_a O_{y,s}\, p_{y,a,s}^{\mathrm{obs}} \ln[\hat{p}_{y,a,s}], \tag{A.13}$$

where $\hat{p}_{y,a,s} = \hat{I}_{y,a,s}^{A} / \sum_a \hat{I}_{y,a,s}^{A}$ is the estimated survey-at-age proportion.

The log-likelihood L^{δ} of annual recruitment deviates $\hat{\delta}_y$, estimated as penalized parameters, is

$$L^{\delta} = -\sum_y \ln \tau - \frac{1}{2\tau^2} \sum_y \hat{\delta}_y^{\;2}. \tag{A.14}$$

where τ is the standard deviation of recruitment deviates.

The total log-likelihood Λ of the model is

$$\Lambda = L^I + L^{CA} + L^{IA} + L^{\delta}. \tag{A.15}$$

B. Simulated data observations in the projection period

Once the SRA conditioning model is used to set up the historical period of the operating model, the operating model is then projected forward following the catch advice prescribed by the management procedure. For the application of the management procedures, future projected data are simulated as follows.

The observed catch in weight is

$$\tilde{C}^{W}_{i,m,y,f} = C^{W}_{i,m,y,f}\ \omega^{C}\ \exp(\delta^{C}_{i,y,f}), \tag{B.1}$$

where i indexes simulation, m indexes the management procedure, y indexes year, and f indexes fleet, the tilde (~) denotes a simulated observation of the underlying variable, ω is the ratio between the simulated observation and true value in the operating model, i.e., the catch reporting rate, and δ is the simulated observation error generated from a normal distribution,

$$\delta^{C}_{i,y,f} \sim N(0, [\sigma^{C}]^{2}), \tag{B.2}$$

with standard deviation σ^{C} (Table B.1).

The observed age compositions from the fleet $\tilde{C}^{A}_{i,m,y,f}$ and survey $\tilde{I}^{A}_{i,m,y,s}$ are sampled annually from a multinomial distribution,

$$\tilde{C}^{A}_{i,m,y,f} \sim \text{Multinomial}\ (O_{y=y_H,f}\ , p^{A}_{i,m,y,f}), \tag{B.3}$$

$$\tilde{I}^{A}_{i,m,y,s} \sim \text{Multinomial}\ (O_{y=y_H,s}\ , p^{A}_{i,m,y,s}), \tag{B.4}$$

where the sample size $O_{y=y_H}$ is the value used in the terminal year of the conditioning model (y_H), and annual proportions p^{A} are calculated from the operating model.

The observed index is

$$\tilde{I}_{i,m,y,s} = I_{i,m,y,s}\ \exp(\varepsilon_{i,y,s}), \tag{B.5}$$

where s indexes survey, $\varepsilon_{i,y,s}$ is the simulated observation error sampled with autocorrelation:

$$\varepsilon_{i,y,s} = \rho_s \varepsilon_{i,y-1,s} + \delta^I_{i,y,s}\sqrt{1-\rho_s^2} \tag{B.6}$$

$$\delta^I_{i,y,s} \sim N\left(-0.5[\sigma^I_s]^2 \times \frac{1-\rho_s}{\sqrt{1-\rho_s^2}}\ ,\ [\sigma^I_s]^2\right) \tag{B.7}$$

The standard deviation σ^I_s and lag-1 autocorrelation coefficient ρ_s are calculated from the residuals in the conditioning model. The mean of $\delta^I_{i,y,s}$ is bias-adjusted so that $E\left[\exp(\delta^I_{i,y,s})\right] = 1$ (Thorson et al. 2016).

Specification of the observation error parameters in the cod and pollock operating models are provided in Tables B.1-B.2.

Table B.1. Observation error parameters for the Gulf of Maine cod operating models. For survey parameters, three values are presented corresponding to the NEFSC spring, NEFSC fall, and Massachusetts bottom trawl surveys.

		Operating model		
Parameter	**Description**	**MC**	**IM**	**MCIM**
ω^C	Bias in observed catch	2.25	1.00	1.25
σ^C	Standard deviation of observed catch	0.05	0.05	0.05
$O_{y=y_H,f}$	Multinomial sample size of fishery age composition	80	80	80
$O_{y=y_H,s}$	Multinomial sample size of survey age composition	15, 15, 9	15, 15, 9	15, 15, 9
σ_s^I	Standard deviation of survey	0.44, 0.42, 0.51	0.44, 0.42, 0.51	0.44, 0.42, 0.51
ρ_s	Autocorrelation of survey	0.26, 0.26, 0.54	0.29, 0.16, 0.43	0.26, 0.16, 0.44

Table B.2. Observation error parameters for the New England pollock operating models. For fishery parameters, two values are presented corresponding to the commercial and recreational fleets. For survey parameters, two values are presented corresponding to the NEFSC spring and NEFSC fall bottom trawl surveys.

Parameter	**Description**	**Operating model**		
		SS	**SWB**	**SWF**
ω^C	Bias in observed catch	1, 1	1, 1	1, 1
σ^C	Standard deviation of observed catch	0.05, 0.05	0.05, 0.05	0.05, 0.05
$O_{y=y_H,f}$	Multinomial sample size of fishery age composition	75, 60	75, 60	75, 60
$O_{y=y_H,s}$	Multinomial sample size of survey age composition	30, 30	30, 30	30, 30
σ_s^I	Standard deviation of survey	0.67, 0.21	0.67, 0.21	0.67, 0.21
ρ_s	Autocorrelation of survey	0.22, 0.22	0.10, 0.22	0.08, 0.25

C. Supplementary Figures

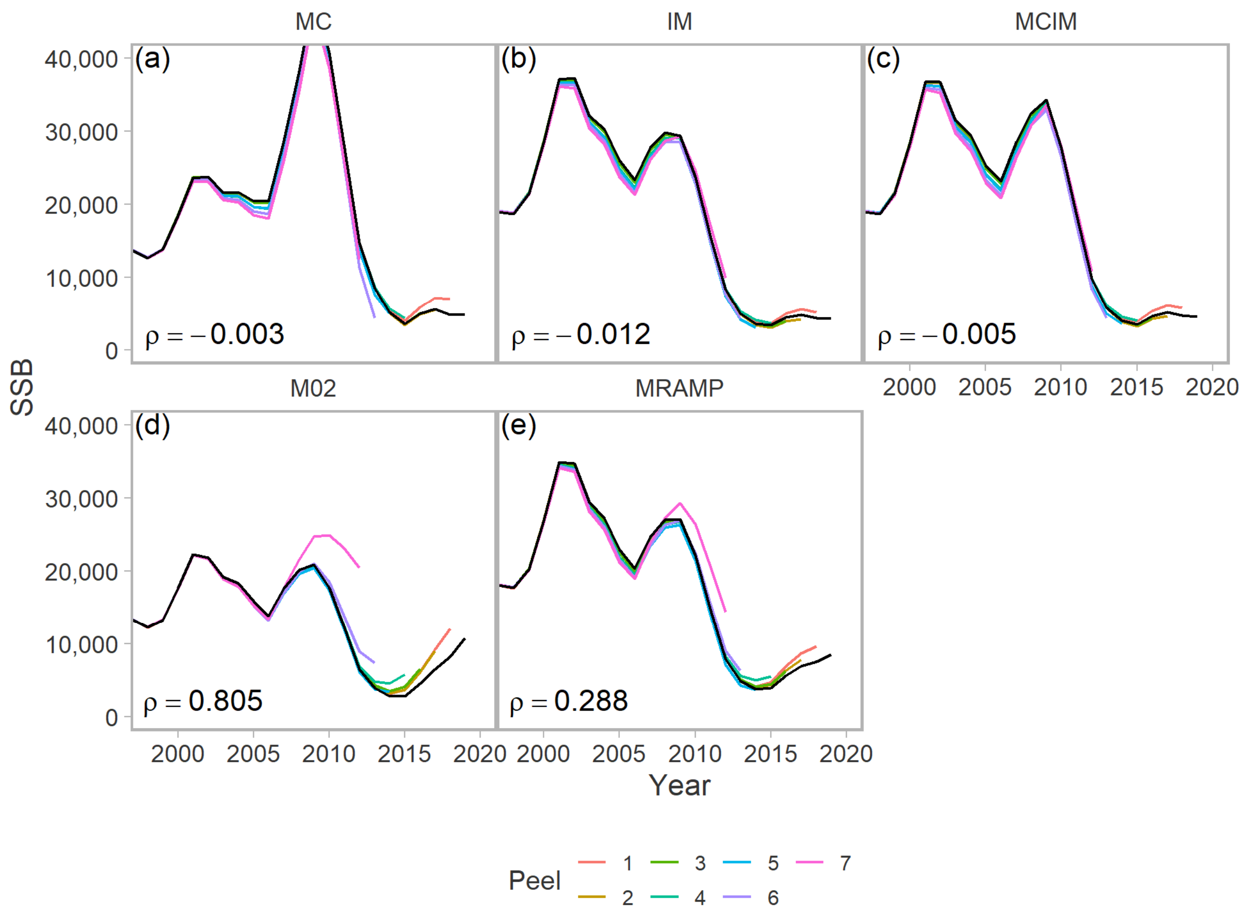

Figure C.1. Retrospective SSB estimates for cod in the SRA models used to condition the operating models (MC, IM, and MCIM) and assessment models (M02 and MRAMP). Black lines indicate the full model and peels indicate the number of years of data removed from the end of the time series.

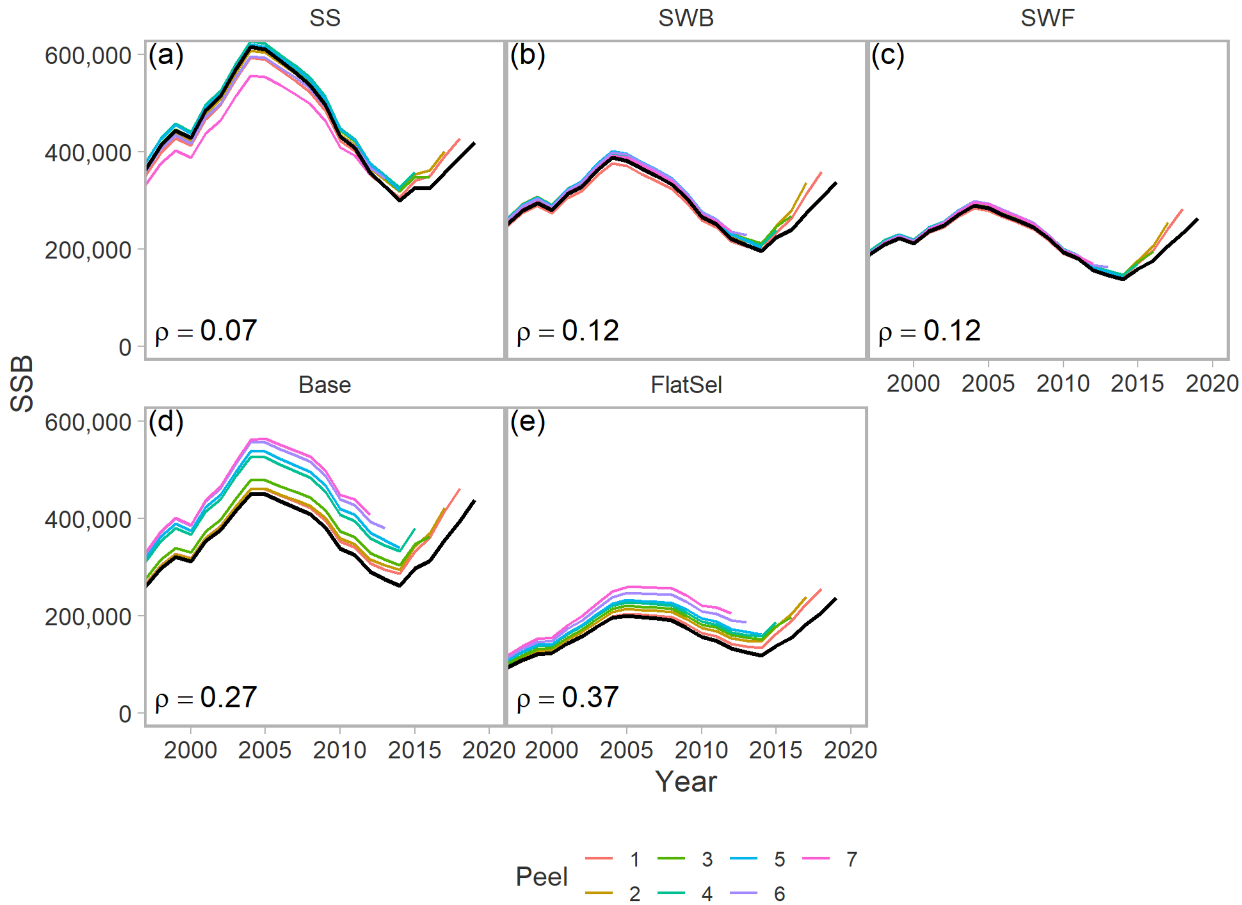

Figure C.2. Retrospective SSB estimates for pollock in the SRA models used to condition the operating models (SS, SWB, and SWF) and assessment models (Base and FlatSel). Black lines indicate the full model and peels indicate the number of years of data removed from the end of the time series.

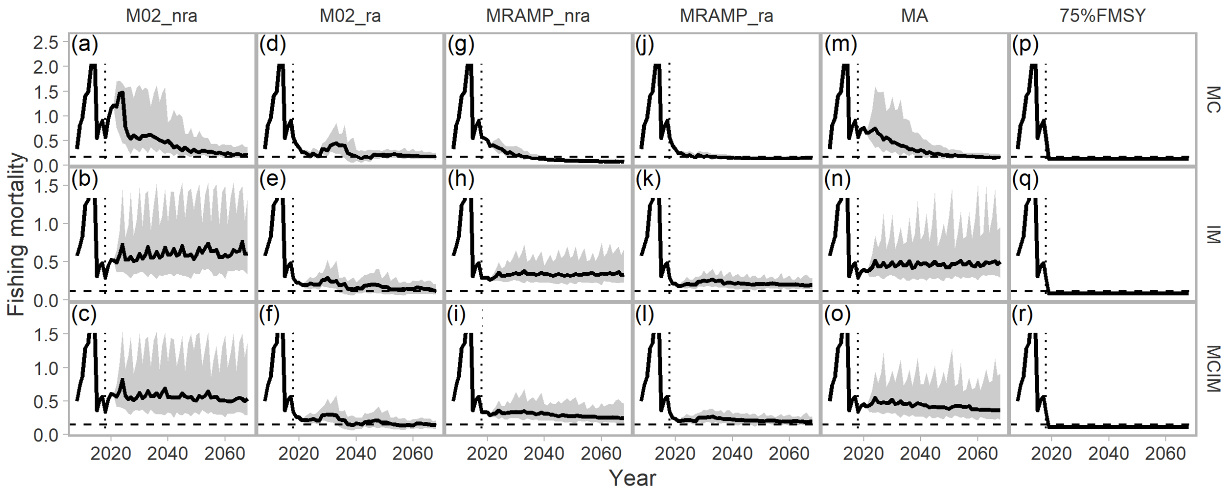

Figure C.3. Projected fishing mortality for the cod operating models (rows) under each MP (column). Solid lines indicate the median and the grey region the 90% confidence interval among 100 simulations. Dashed, horizontal lines indicate F_{MSY} (see Table 2 of the main text). Dotted, vertical lines indicate the start of the projection period.

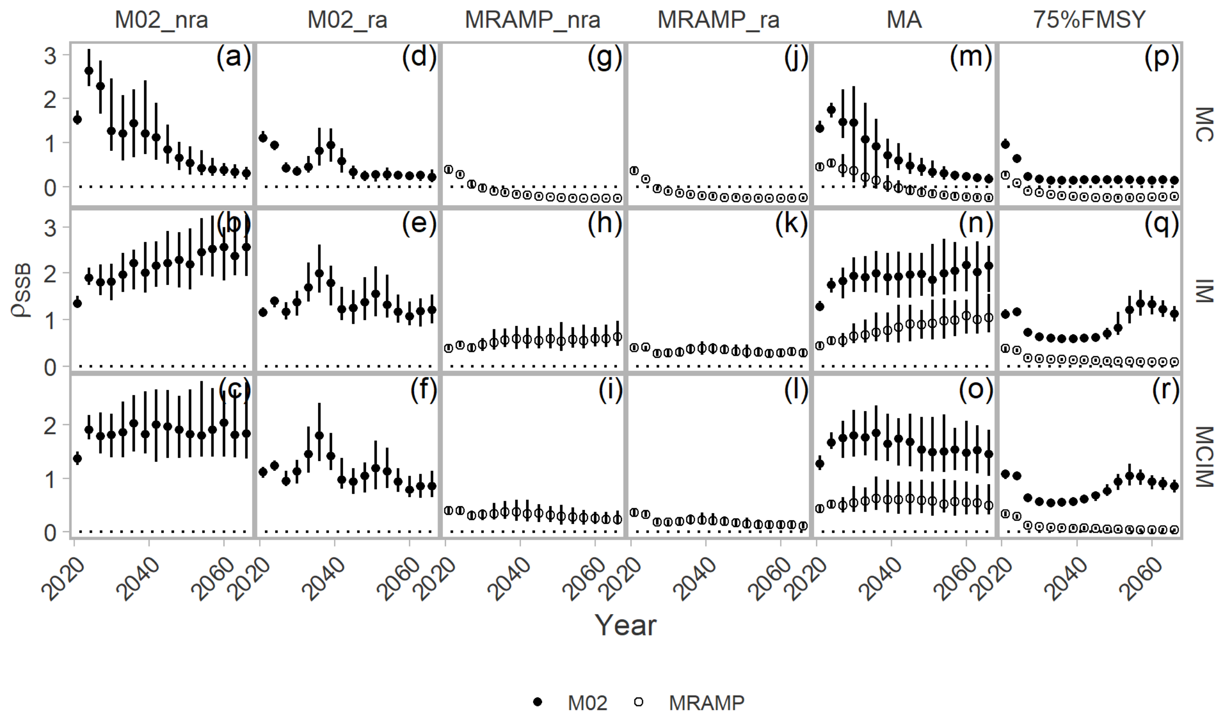

Figure C.4. Mohn's rho for the assessment model (AM) in the cod operating models (rows) and MPs (columns). Points and lines indicate the median and interquartile range, respectively. Both AMs were fitted for 75%FMSY reference MP but not used in the management procedure.

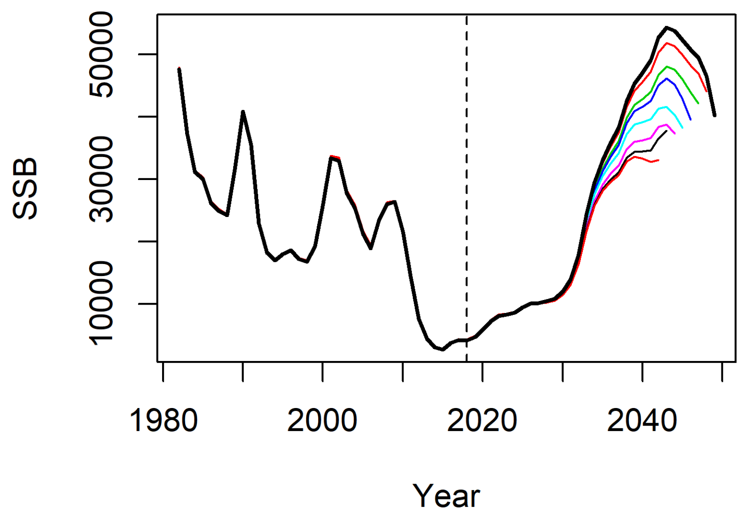

Figure C.5. An example of a negative Mohn's rho in the cod case study from a fitted model inside the MRAMP MP during the closed-loop simulation of the MC (missing catch) operating model. The retrospective pattern shown is from an assessment (simulation #1 out of 100) conducted in year 31 (2048) of the projection period. The Mohn's rho is -0.24. The dashed vertical line indicates the start of the projection period.

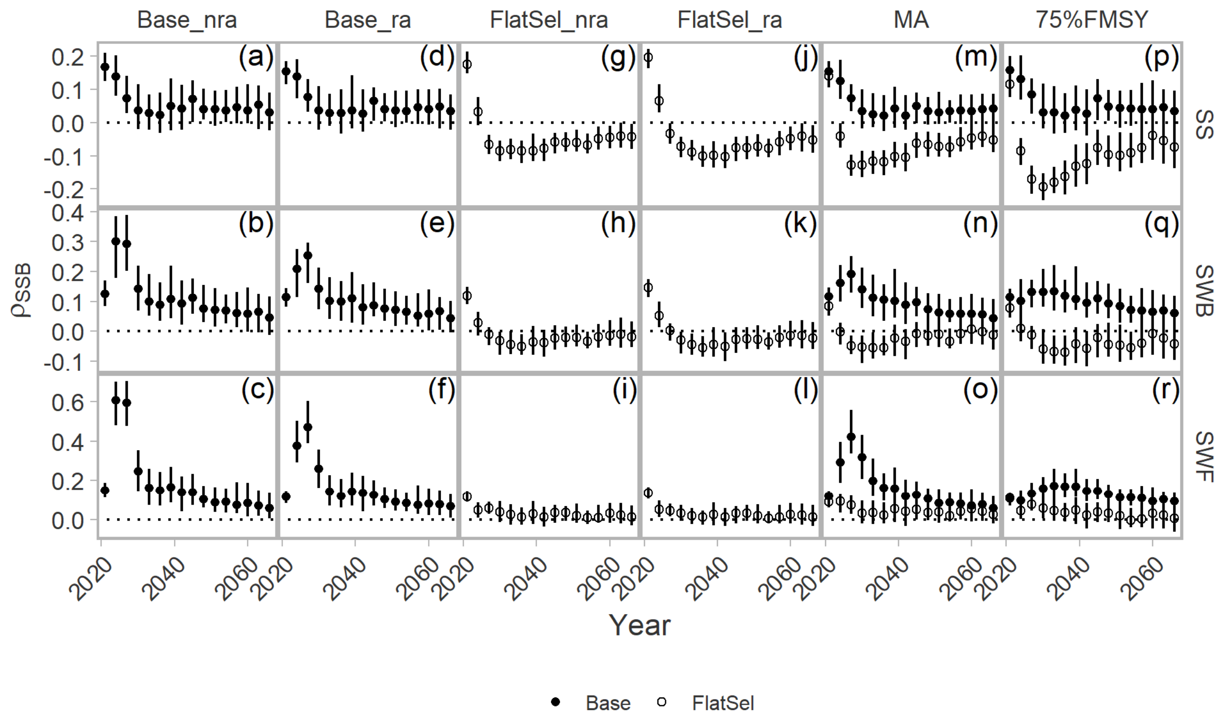

Figure C.6. Mohn's rho for the assessment model (AM) in the pollock operating models (rows) and MPs (columns). Points and lines indicate the median and interquartile range, respectively. Both AMs were fitted for 75%FMSY reference MP but not used in the management procedure.

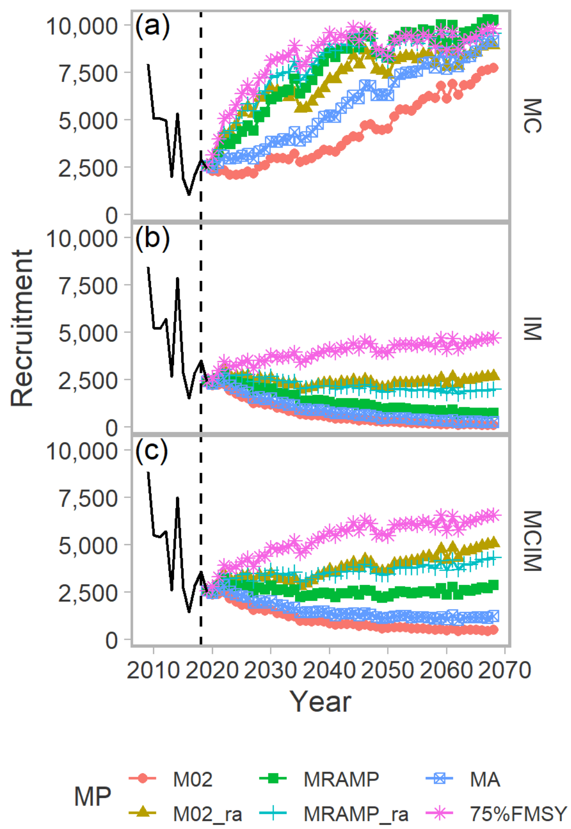

Figure C.7. Mean recruitment during the projection period (in color) for the cod operating models. In black is the historical recruitment. Dashed, vertical lines indicate the start of the projection period.

References

Thorson et al. 2016. Corrigendum: How variable is recruitment for exploited marine fishes? A hierarchical model for testing life history theory. Canadian Journal of Fisheries and Aquatic Sciences 73: 1014.