Results of the management strategy evaluation for plaice (*Pleuronectes platessa*) in Division 7.e (western English Channel – ple.27.7e) – Working document for WKBPLAICE 2024

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1 Introduction

This working document describes the results of the management strategy evaluation (MSE) conducted for plaice (*Pleuronectes platessa*) in Division 7.e (western English Channel – ple.27.7e) as part of the ICES WKBPLAICE benchmark in 2024. The term MSE is used here in the context of a closed-loop simulations.

The data for this plaice stock is described in detail in a working document (https://github.com/shfischer/WKBPLAICE2024_ple.27.7e_data/blob/WKBPLAICE/WKBPLAICE2024_data.pdf).

Table 1 summarises the operating models. For details, see the dedicated working document (https://github.com/shfischer/WKBPLAICE2024_ple.27.7e_MSE/blob/WKBPLAICE2024/WKBPLAICE2024_ple.27.7e_OM.pdf).

Table 1: Operating models.

#	Category	ID	Difference	SAM refit?	Operating model type
1	Baseline	*Baseline*	–	–	Baseline
2	Catch	*Catch: no discards*	No discards (100% survival)	Yes	Reference
3		*Catch: 100% discards*	All discards die (0% survival)	Yes	Reference
4		*Catch: +10%*	Catch always 10% above TAC	No	Robustness
5		*Catch: -10%*	Catch always 10% below TAC	No	Robustness
6		*Catch: no migration*	Catch from 7.d excluded	Yes	Reference
7	Natural mortality (M)	*M: -50%*	M 50% below *baseline*	Yes	Reference
8		*M: +50%*	M 50% above *baseline*	Yes	Reference
9		*M: Gislason*	Age-dependent M following Gislason et al. (2010)	Yes	Reference
10	Recruitment	*R: no AC*	No auto-correlation (AC) in recruitment resiudals	No	Reference
11		*R: failure*	Recruitment failure in years 2025–2029	No	Robustness
12		*R: +20%*	Recruitment always 20% higher	No	Robustness
13		*R: -20%*	Recruitment always 20% lower	No	Robustness
14	Uncertainty	*CV: index*	Higher uncertainty (observation error) for index	No	Robustness

The complete source code of the operating models and MSE simulations and summarised results are available on GitHub at https://github.com/shfischer/WKBPLAICE2024_ple.27.7e_MSE/tree/WKBPLAICE2024. The exact versions of R and R packages were recorded with `renv` (https://rstudio.github.io/renv/articles/renv.html). Furthermore, random numbers were generated before the simulations. This makes the entire simulation and its results reproducible.

2 Management procedures

Following the conclusions of Fischer et al. (2023), the focus of this MSE was on the ICES data-limited category 3 "chr" rule and this method was tuned with a stock-specific MSE to optimise its management performance. For comparison, the previously used default ICES category 3 method ("rfb" rule) and the category 1 data-rich approach (MSY rule) were also tested but not tuned.

All management procedures were implemented for 20 years (2025–2044).

2.1 The chr rule

The chr rule (Fischer et al., 2022; ICES, 2022) is a relative constant harvest rate rule. The chr rule sets the catch advice by targeting a relative harvest rate (catch divided by a biomass index):

$$A_{y+1} = I\ H\ b\ x \tag{1}$$

where A_{y+1} is the new catch advice for year $y+1$, I the biomass index value, H the (relative) target harvest rate, b the biomass safeguard, and x a multiplier. The elements of the chr rule are defined as:

$$I = \sum_{i=y-n_0-n_1+1}^{y-n_0} (I_i/n_1) \tag{2}$$

$$H = C_{\text{ref}}/I_{\text{ref}} \tag{3}$$

$$b = \min\left(1, \frac{I}{I_{\text{trigger}}}\right) \tag{4}$$

where I is the biomass index, n_0 the offset between last biomass index year and assessment year (default $n_0 = 1$), n_1 the number of biomass index years used in I (default $n_1 = 1$), C the realised catch, $C_{\text{ref}}/I_{\text{ref}}$ the harvest rate from a reference period, and I_{trigger} an index trigger value calculated from the lowest observed index value I_{loss} via an index trigger multiplier w ($I_{\text{trigger}} = wI_{\text{loss}}$, default $w = 1.4$). The multiplier x essentially adjusts the harvest rate target H.

The default advice interval is annual ($v = 1$) and changes in catch advice are limited with an uncertainty cap to an increase of +20% ($u_u = 1.2$) and decrease of −30% ($u_l = 0.7$) but the application of the cap is conditional on $I \geq I_{\text{trigger}}$.

The chr rule is the default ICES method to calculate the advice for ICES category 3 stocks with moderate individual growth (ICES, 2022), defined with the von Bertalanffy parameter k ($0.2\text{year}^{-1} \leq k < 0.32\text{year}^{-1}$).

According to the ICES technical guidelines (ICES, 2022), the generic target harvest rate H

is calculated by using catch length data to find reference years in which the mean catch length is above an MSY proxy length ($L_{F=M}$). The harvest rate is then calculated for these reference years, and an MSY proxy harvest rate ($F_{\text{MSY,proxy}}$) is calculated as the average of these values. The generic application of the chr rule then uses a multiplier of $x = 0.5$, based on generic simulations (ICES, 2020; Fischer et al., 2022), to reduce the MSY proxy harvest rate.

The ICES definition of the generic harvest rate target was not applicable for ple.27.7e because the mean catch length was below the MSY proxy length in all years for which data were available. Instead, a reference harvest rate was calculated as the average harvest rate of all available years, separately for the two biomass indices (Figure 1).

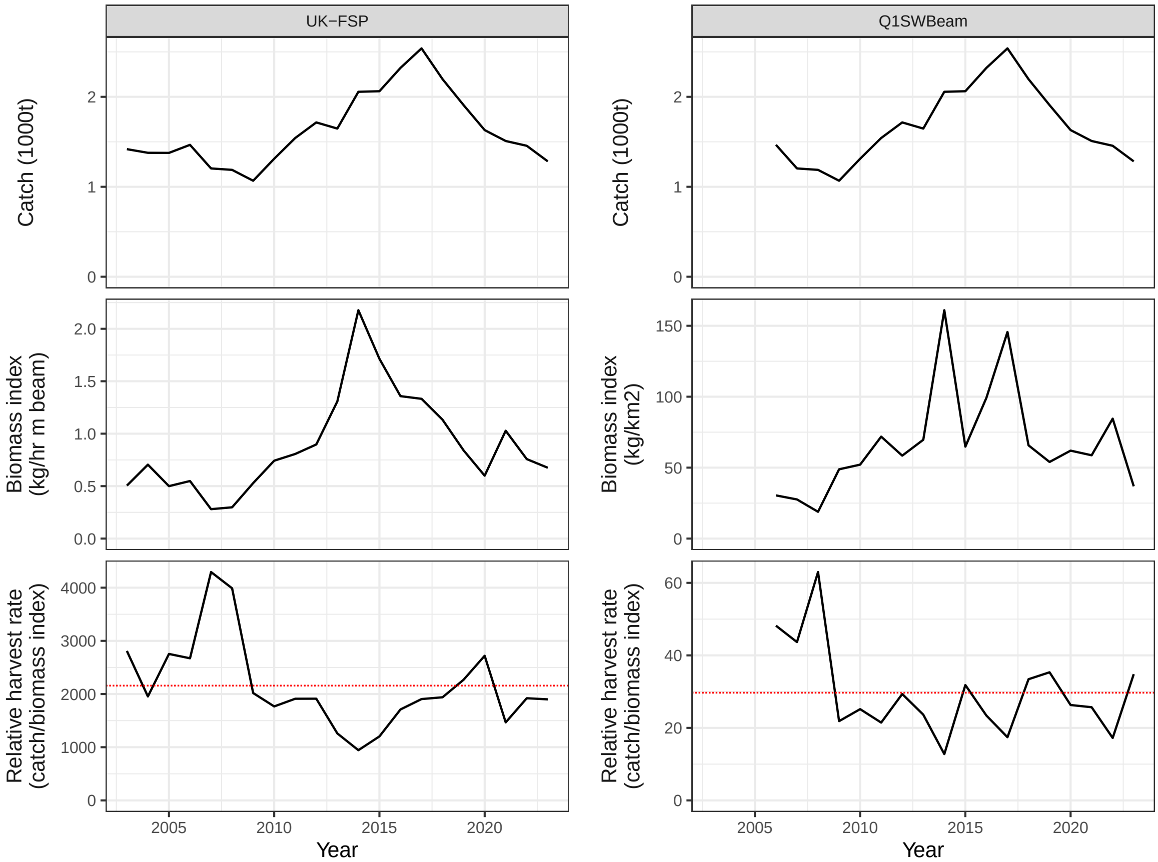

Figure 1: Relative harvest rates for the two survey indices. The red horizontal line indicates the average (arithmetic mean) over all data years.

The parameters of the chr rule that were included in the tuning were (1) the multiplier adjusting the harvest rate (x), (2) the parameter linking I_{trigger} to I_{loss} (w), the number of years in the biomass index (n_1), and the advice interval (v). The time lag between the assessment (intermediate) year was fixed to $n_0 = 1$ because more recent survey data are not typically available for this stock. This means the chr rule used in the tuning was:

$$A_{y+1} = \sum_{i=y-n_1}^{y-1} (I_i/n_1) \;\; H \; \min\left(1, \frac{\sum_{i=y-n_1}^{y-1} (I_i/n_1)}{w \; I_{\text{loss}}}\right) \; x \tag{5}$$

The (conditional) uncertainty cap limiting advice changes to +20% and −30% was also kept for consistency with other ICES category 3 stocks.

The management reference values (I_{loss} and H) are defined in Table 2.

Table 2: Management reference points for the chr rule.

Reference point	Index	Value	Basis
I_{loss}	UK-FSP	0.280337	Lowest observed index value in year 2007
I_{loss}	Q1SWBeam	18.8653	Lowest observed index value in year 2008
H	UK-FSP	2158.17	Average harvest rate 2003–2023
H	Q1SWBeam	29.6972	Average harvest rate 2006–2023

2.2 The rfb rule

The rfb rule (ICES, 2022, 2020; Fischer et al., 2020, 2021a,b), which is currently used to provide ICES advice for ple.27.7e, was also tested for comparison. This method was only tested with its default parameterisation following ICES guidelines but without optimising it. The default rfb rule is defined as

$$A_{y+1} = A_y \; r \; f \; b \; x \tag{6}$$

with the new catch advice A_{y+1}, previous catch advice A_y, biomass index trend r, fishing proxy f, and biomass safeguard b:

$$r = \frac{\sum_{i=y-2}^{y-1}(I_i/2)}{\sum_{i=y-5}^{y-3}(I_i/3)} \tag{7}$$

$$f = \frac{\bar{L}_{y-1}}{L_{F=M}} \tag{8}$$

$$b = \min\left\{1, \frac{I_{y-1}}{I_{\text{trigger}}}\right\} \tag{9}$$

$$x = 0.95 \tag{10}$$

where I is the biomass index, $\bar{L}$ the mean catch length above length of first capture L_c, $L_{F=M}$ an MSY proxy reference length, I_{trigger} an index trigger value calculated from the lowest observed index value I_{loss} via an index trigger buffer w ($I_{\text{trigger}} = wI_{\text{loss}}$, default $w = 1.4$), and x a multiplier for scaling the advice (default $x = 0.95$ for stocks with von Bertalanffy $k < 0.2$ year^{-1}, $x = 0.9$ for stocks with $0.2 \leq k < 0.32$ year^{-1}).

The default advice interval is biennial ($v = 2$) and changes in catch advice are limited with an uncertainty cap to an increase of +20% ($u_u = 1.2$) and decrease of −30% ($u_l = 0.7$) but the application of the cap is conditional on $I_{y-1} \geq I_{\text{trigger}}$.

2.3 ICES MSY rule

For comparison with the category 3 data-limited methods, a category 1 data-rich management procedure was also tested with the MSE framework. The ICES MSY rule, as defined by ICES (2019), was used:

$$F_{y+1} = F_{\text{target}} \; \min\left(1, B_{y+1}/B_{\text{trigger}}\right) \tag{11}$$

where F_{y+1} is the fishing mortality targeted in the advice year, F_{target} and B_{trigger} the management target (F_{MSY}) and trigger (MSYB_{trigger}), respectively, defined by ICES, B_{y+1} the SSB at the beginning of the advice year. This method relies on fitting a SAM model and conducting a short-term forecast with it (to get SSB estimates in the advice year and convert the target F into a catch value). For the short-term forecast, typical settings used in ICES were used (entire time series used to sample recruitment, biological and fishery parameters from the last five years, F status quo assumption in the intermediate year.

Management reference points for use in the SAM short-term forecast were estimated from the baseline operating model with standard ICES software EqSim (http://github.com/ices-tools-prod/msy) and following ICES guidelines (ICES, 2021). This stock would be classified as stock type 5 with no clear relationship between stock and recruitment and so B_{lim} was based on the lowest observed SSB ($B_{\text{loss}} = 2333$ tonnes), and $B_{\text{pa}} = 1.4B_{\text{lim}} = 3266$ tonnes. F_{MSY} is then calculated by projecting with a mix of stock-recruitment models (Rickers, hockey stick, Beverton and Holt) and without B_{trigger}. This led to $F_{\text{MSY}} = 0.211$, which was below $F_{p0.5}$. F in recent years was above F_{MSY}, so MSYB_{trigger} was set to MSY$B_{\text{trigger}} = B_{\text{pa}}$. These management reference points were estimated with the observed data from the baseline operating model and also used in the other operating models.

Fitting SAM is a computing-intensive process. In the MSE loop, SAM was sped up following (ICES, 2019) by providing initial parameter values from the previous years' model fit, relaxing the convergence criterion (relative tolerance relaxed from 10^{-10} to 10^{-3}), and removing the Newton steps. Nevertheless, running one MSE simulation with 20 years and 1,000 simulation replicates took around 35 hours, much more than for the category 3 empirical methods, which only a few minutes.

2.4 Performance statistics

The management performance of the MPs was evaluated through three main metrics:

- Depletion risk – $P_{B_{\text{lim}}}$

  The proportion of simulation replicates for which the stock is below the biomass limit reference point B_{lim})

- Catch – C/MSY

  The catch (C) relative to MSY

- Stock size – SSB/B_{MSY}

  The spawning stock biomass (SSB) relative to its MSY value

- ICV (inter-annual catch variability)

  The average (absolute) change in the catch, defined as ICV $= |(C_y - C_{y-v})/C_{y-v}|$, where C_y is the catch in year y and v advice interval.

The metrics allowed a summary of the management performance of the MPs, including both biological (stock size, depletion risk) and economic (catch) quantities. Three time periods were defined for the 20-year projection in the MSE:

- *long term*: last 10 years (2035–2044)
- *short term*: first 10 years (2025–2034)
- *all*: all 20 years (2025–2044)

For catch, stock size, and ICV, medians of the respective time period and the 1000 simulation replicates as well as the distribution of the values were considered.

ICES defines three types of risks or probabilities (ICES, 2013, 2018):

- Risk 1 is the average probability that SSB is below B_{lim} over a number of years (i.e. the average of the annual probabilities)
- Risk 2 is the probability that SSB is below B_{lim} at least once during a number of years.
- Risk 3 is the maximum probability that SSB is below B_{lim} (i.e. the maximum of the annual probabilities).

In general, management procedures in ICES are evaluated based on risk 3. In this MSE, the risk ($P_{B_{\text{lim}}}$) was defined as the maximum annual risk (i.e. ICES risk 3) over the respective time period. However, the average risk of the annual values and their distribution were also considered.

2.5 Tuning of management procedures

Tuning of a management procedure is the process of changing its parameters to find the set of parameters that best meet the management objectives.

The usual approach of ICES in providing advice on fishing opportunities is to follow the ICES interpretation of the maximum sustainable yield (MSY) and the precautionary approach to fisheries (ICES, 2023). The MSY approach refers to fishing at F_{MSY}, i.e. at the fishing mortality that leads to the highest long-term catch. For not-short-lived species, the typical ICES interpretation of the precautionary approach is to limit the risk of the stock falling below the biomass limit reference point (B_{lim}) to 5%.

This approach was also adopted here with catch and risk as defined in the previous section. The tuning was performed on the long-term management performance (the last 10 years of the 20-year projection, i.e. 2035–2044). This is the typical approach in ICES because the short-term performance is crucially dependent on the initial state of the stock. For example, in the operating model reference set, the B_{lim} risk was 12.7% at the beginning of the simulation. This meant that if the initial period was included in the tuning, no management procedure (including zero fishing) would have been precautionary.

The parameters of the chr rule included in the tuning are listed in Table 3.

Table 3: Parameters of the chr rule included in the tuning. See Equation 5 for details.

Parameter	**Minimum**	**Maximum**	**Step**	**Description**
v	1	2	1	Advice interval (annual or biennial)
n_1	1	2	1	Number of years used in the biomass index
x	0	5	0.01	Multiplier adjusting the harvest rate target
w	0	5	0.01	Multiplier linking I_{trigger} to I_{loss}

The MSE framework of Fischer et al. (2023) allowed the automatic optimisation of management procedures by using a genetic algorithm. However, the tuning of the chr rule in this exercise was fairly simple with only four parameters (of which two, v and n_1, had just two possible values). Consequently, the resulting grid search for x and w was conducted manually.

The first explorations were conducted using only the baseline operating model. For this purpose, full grids of x and w in steps of 0.01 were explored.

The advice interval was restricted to annual (every year) or biennial (every second year) because ICES currently provides advice for category 3 stocks with either interval. Longer advice intervals were not considered because it seemed unrealistic that advice would be given triennially or less frequently and because previous simulation work (e.g. Fischer et al., 2021a)

The final tuning was conducted with the operating model reference set, which included seven different operating models (Table 1). This set of operating models was treated as one large ensemble operating model, essentially giving each of the individual operating models the same weight, but where stock dynamics and operating model reference points differed between the individual operating models. Ultimately, the reference set operating model consisted of 7,000 thousand simulation replicates (1,000 for each of the individual operating models) which were simulated for 20 years. The tuning of the chr rule then had to satisfy the precautionary criterion (B_{lim} risk not exceeding 5%) over this reference set. The reference set tuning was consequently computationally more complex and it was infeasible to run full grids. The tuning was done by firstly searching over the entire search space with a low resolution (steps of 0.1 for x and w) and then increasing the resolution (steps of 0.01) to delineate the boundary between precautionary and non-precautionary management (defined by the strict 5% B_{lim} risk limit) and to find the area with the maximum catch.

One 20-year projection of the reference set operating model took less than 5 minutes on a single CPU core. However, tens of thousands of parameter combinations were needed, increasing the computational complexity. This required the use of high-performance computing resources. The simulations were run on the high-performance computing system of the Imperial College Research Computing Service (www.doi.org/10.14469/hpc/2232).

3 Baseline explorations

The first explorations of the chr rule were conducted with the baseline operating model only and the "FSP-UK" survey was chosen as the biomass index.

First, the multiplier (x in Equation 1) was optimised and with values tested from 0 to 2 with steps of 0.01 (i.e. 201 values in total. The highest catch was observed for a multiplier of $x = 0.63$ (Figure 2) and was before the B_{lim} risk reached 5%. Figure 3 shows the MSE trajectories corresponding to the optimised multiplier.

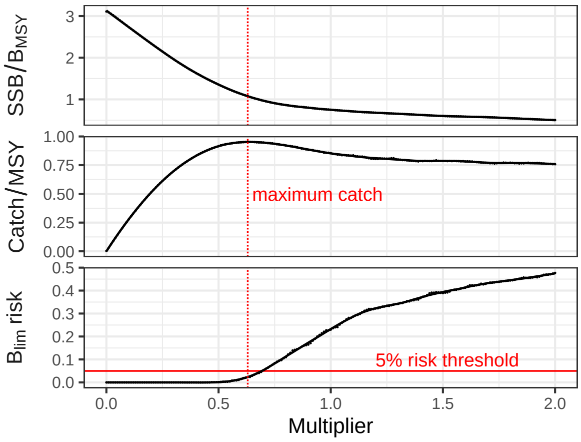

Figure 2: Baseline operating model. The impact of the multiplier of the chr rule. Each point represents the result of one MSE simulation with 1,000 simulation replicates and a loess smoother is fitted to obtain a smoother curve. The performance statistics are shown for the last 10 years of a 20-year simulation.

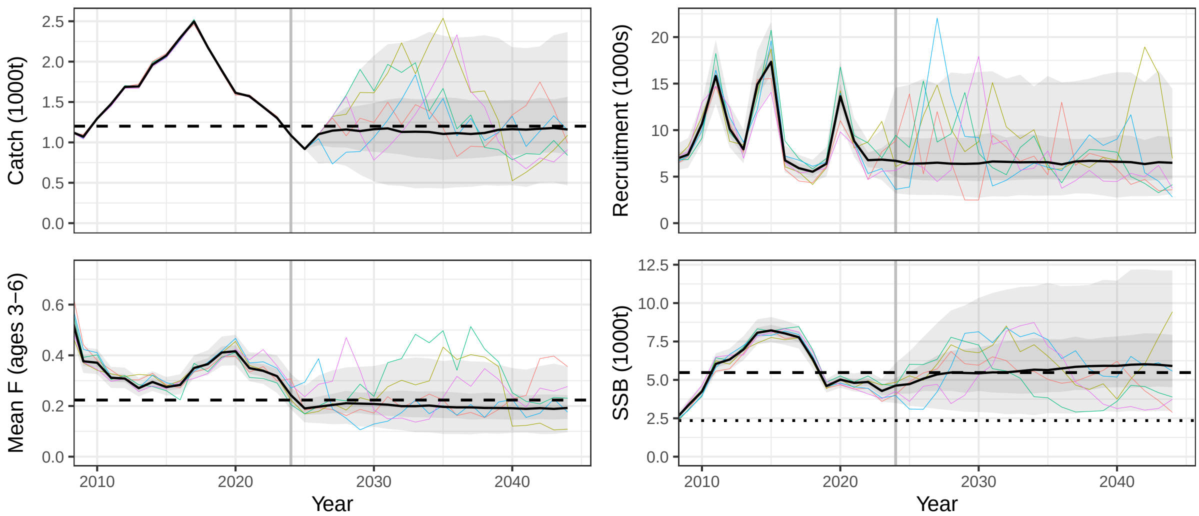

Figure 3: Baseline operating model. MSE trajectory corresponding to the optimum solution from Figure 2. The black curves shows the medians of the simulation are surrounded by 50 and 95% confidence intervals. The coloured curved represent the first 5 of the 1,000 simulation replicates. The vertical grey line indicates the start of the implementation of the chr rule. Horizontal black dashed lines show MSY levels and the dotted line B_{lim}.

Secondly, the biomass index trigger multiplier (w) was added to the optimisation. The default value is $w = 1.4$ and values from 0 to 2, with steps of 0.01 (i.e. 201 values) were tested in combination with the multiplier x (also 201 values, 40401 possible combinations in total). The results of this grid search are shown in Figures 4 and 5 and the MSE trajectory of the optimum combination in Figure 6.

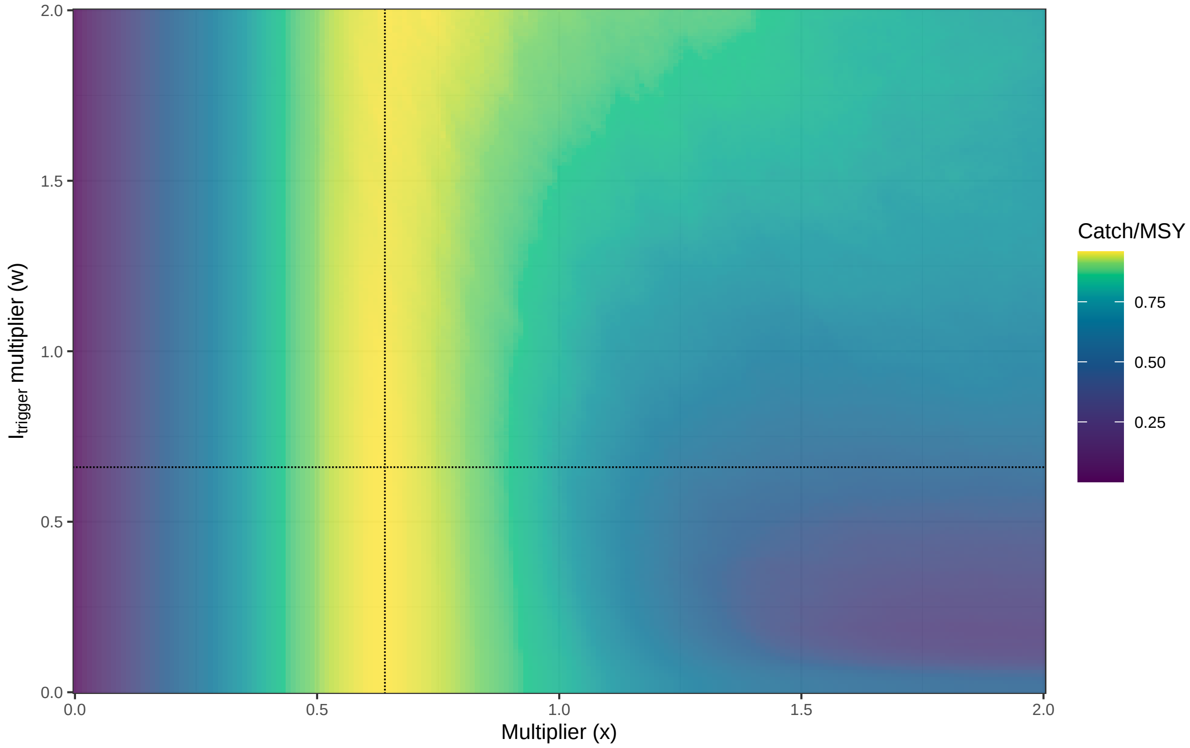

Figure 4: Baseline operating model. The impact of the multiplier x and the biomass index trigger multiplier w on the catch of the chr rule. Each cell (40401 in total) represents the result of one MSE simulation. The cell highlighted by the vertical and horizontal lines is the combination with the highest catch.

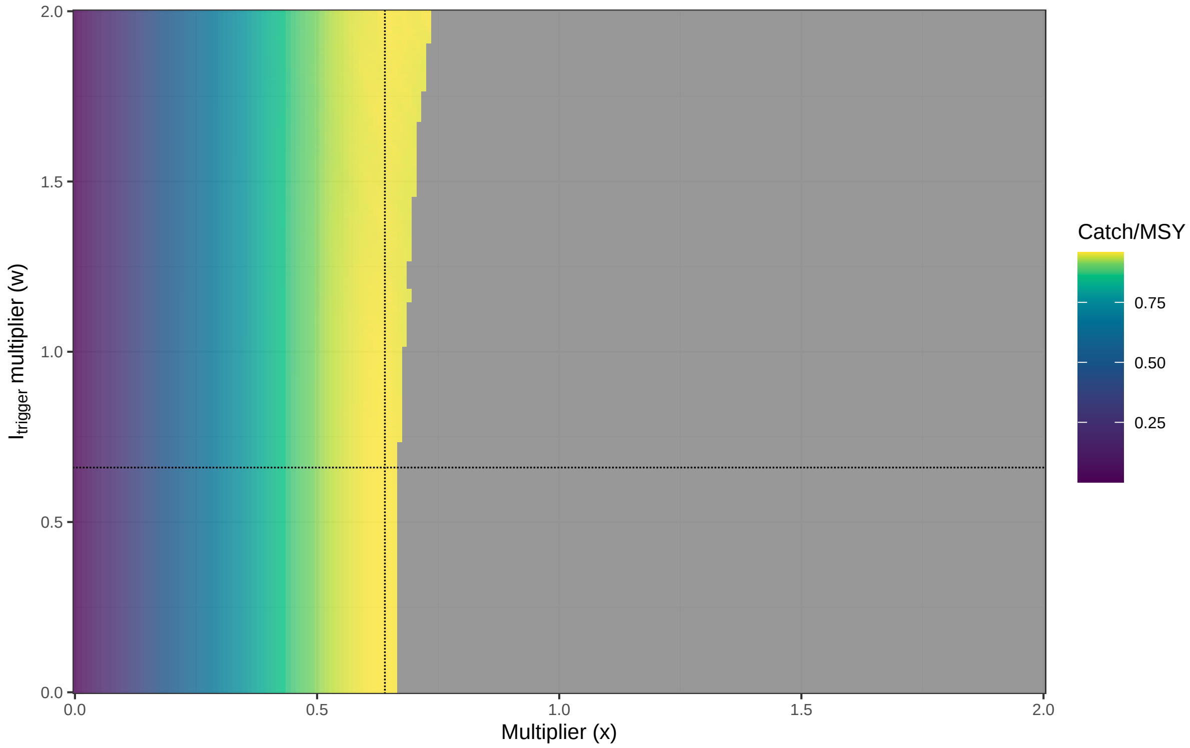

Figure 5: Baseline operating model. The same results as in Figure 4 but the cells where B_{lim} exceeds 5% are shaded grey.

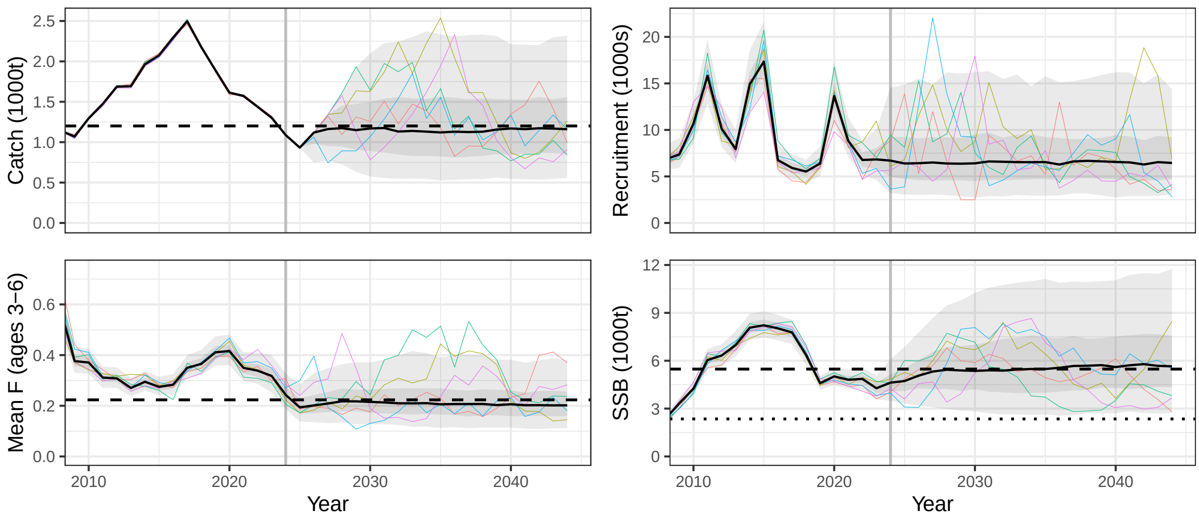

Figure 6: Baseline operating model. MSE trajectory corresponding to the optimum solution from Figure 5. See Figure 3 for details.

Finally, the advice interval (v, default $v = 1$, i.e. annual advice) and the number of years in the biomass index (n_1, default $n_1 = 1$) were included in the optimisation. This led to three additional grid searches and a total of 161604 cells, each corresponding to one parameterisation of the chr rule (Figure 7) and the performance statistics of the optimised chr parameterisations are shown in Figure 8.

The outcomes of the different optimised chr parameterisation was fairly similar in terms of risk, catch, SSB, and catch variability (Figure 8). Consequently, for the subsequent tuning with the reference set operating model, only one version of annual advice (with $v = 1$ and $n_1 = 1$) and biennial advice (with $v = 2$ and $n_1 = 2$) was tuned.

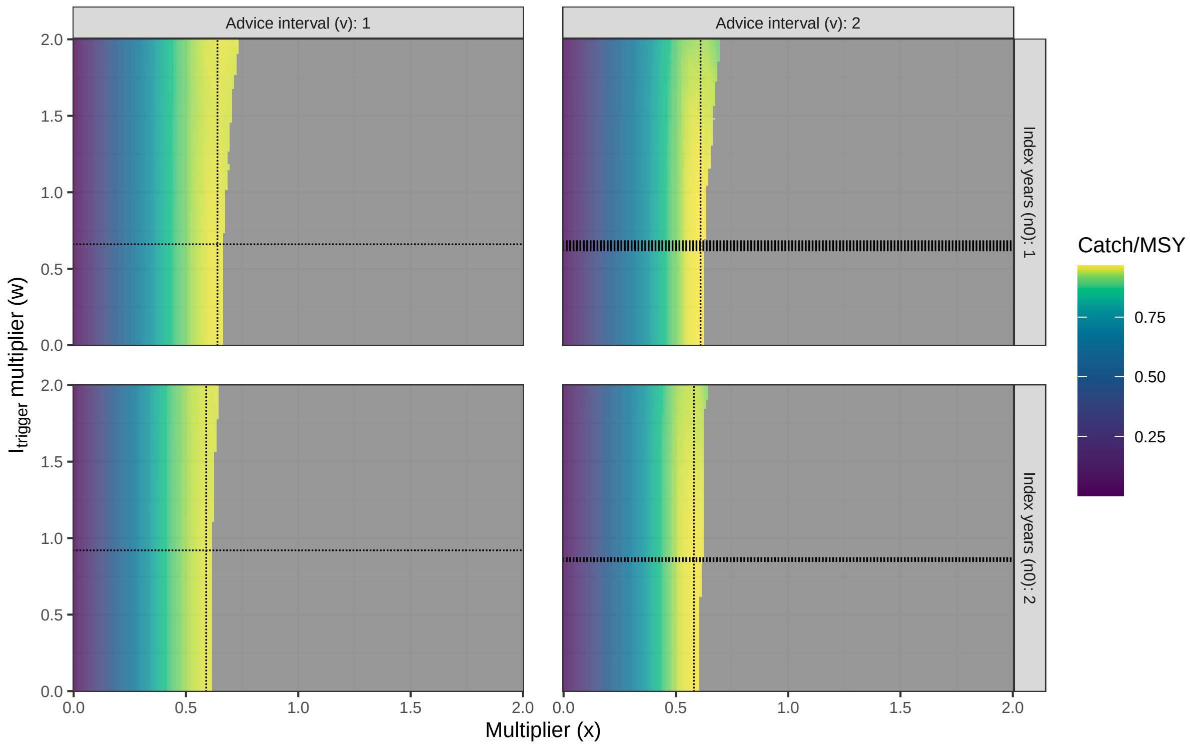

Figure 7: Baseline operating model. Optimisation of x, w, n_1, and v (see Table 3 for details of the parameters). Grey cells indicate combinations where B_{lim} risk exceeds 5%. Horizontal and vertical lines highlight the cells with the highest (precautionary) catch. For the biennial advice (right column), there are several values of w that lead to identical catch values.

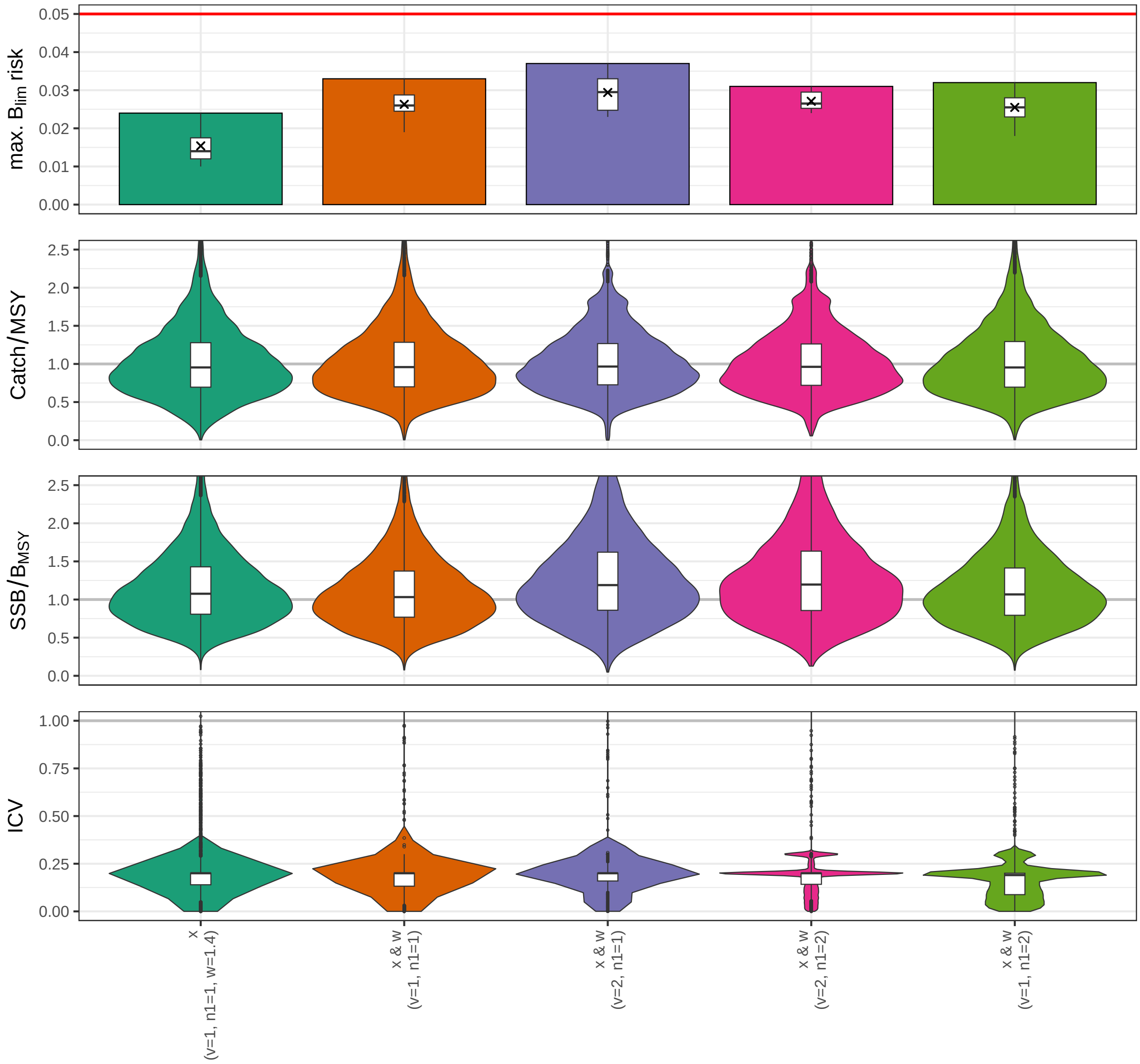

Figure 8: Baseline operating model. Performance statistics corresponding to the optimised chr rules from Figures 2 and 7. For catch, SSB, and ICV (inter-annual catch variability), the distribution shown corresponds to the values over 10 years and 1,000 simulation replicates. The risk (top row) shows the distribution of the annual values over the years, the bar is the maximum of these 10 values (ICES risk 3), and the "x" is the average over the 10 years (ICES risk 1).

Table 4: Final optimised parameters of the chr rule. See Table 3 and Equation 3 for a definition of the parameters. The summary statistics are shown for the long-term (2035–2044).

ID	**Tuning**	**Index**	**Optimum**	n_1	v	x	w	$B_{\mathbf{lim}}$ **risk**	**Catch/MSY**	**SSB/$B_{\mathbf{MSY}}$**
MP1	x	UK-FSP	Global	1	1	0.59	1.40	0.047	0.922	1.223
MP2	x & w	UK-FSP	Local	1	1	0.59	0.90	0.050	0.926	1.203
MP3	x & w	UK-FSP	Global	1	1	0.68	3.12	0.049	0.943	1.216
MP4	x & w	UK-FSP	Local	2	2	0.58	1.02	0.050	0.934	1.271
MP5	x & w	UK-FSP	Global	2	2	0.66	3.70	0.030	0.982	1.397
MP6	x	Q1SWBeam	Global	1	1	0.75	1.40	0.046	0.936	1.213
MP7	x & w	Q1SWBeam	Local	1	1	0.75	1.05	0.050	0.938	1.194
MP8	x & w	Q1SWBeam	Global	1	1	0.84	2.81	0.050	0.967	1.239
MP9	x & w	Q1SWBeam	Local	2	2	0.67	0.89	0.050	0.872	1.357
MP10	x & w	Q1SWBeam	Global	2	2	0.88	4.03	0.048	0.941	1.359

4 Final tuning with the reference set operating models

The final tuning of the chr rule was performed for several versions of the chr rule (Table 4) with the operating model reference set (i.e. seven operating models combined, Table 1). Both survey indices (UK-FSP and Q1SWBeam) were considered independently and the chr rule was tuned with (1) the multiplier x, (2) x and the I_{trigger} multiplier w with an annual advice, and (3) x and w with a biennial advice.

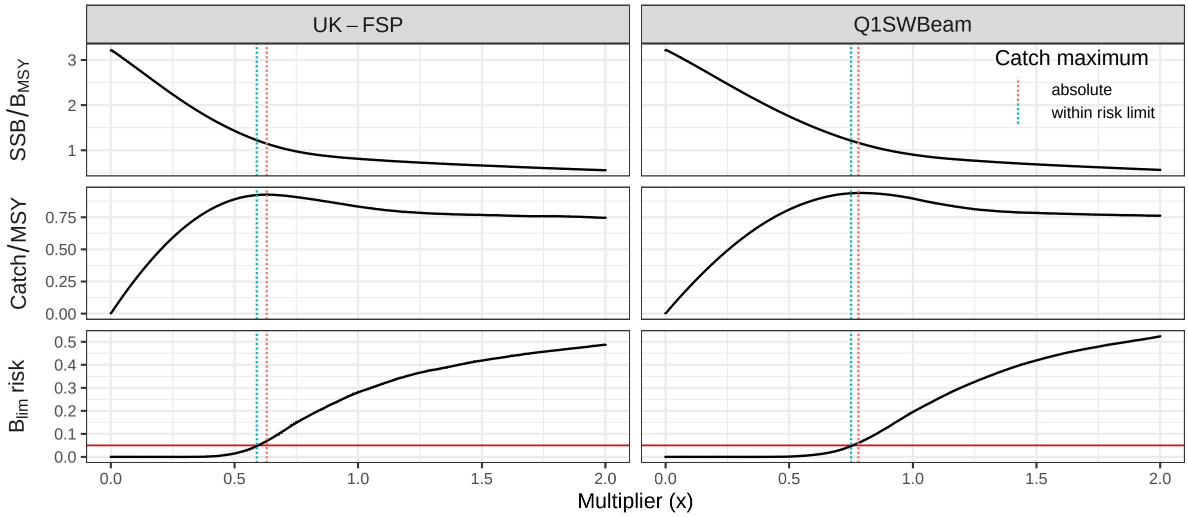

Figure 9: Reference set. Optimisation of the chr rule with x.

Figure 9 illustrates the optimisation with the multiplier x. For both surveys, a catch maximum was found. However, this catch maximum was not precautionary (B_{lim}risk $> 5\%$), and so x had to be reduced to meet the precautionary criterion (MP1 and MP6 in Table 4).

Figures 10 and 12 show the performance statistics and Figures 11 and 13 the MSE projections for these optimised chr rules.

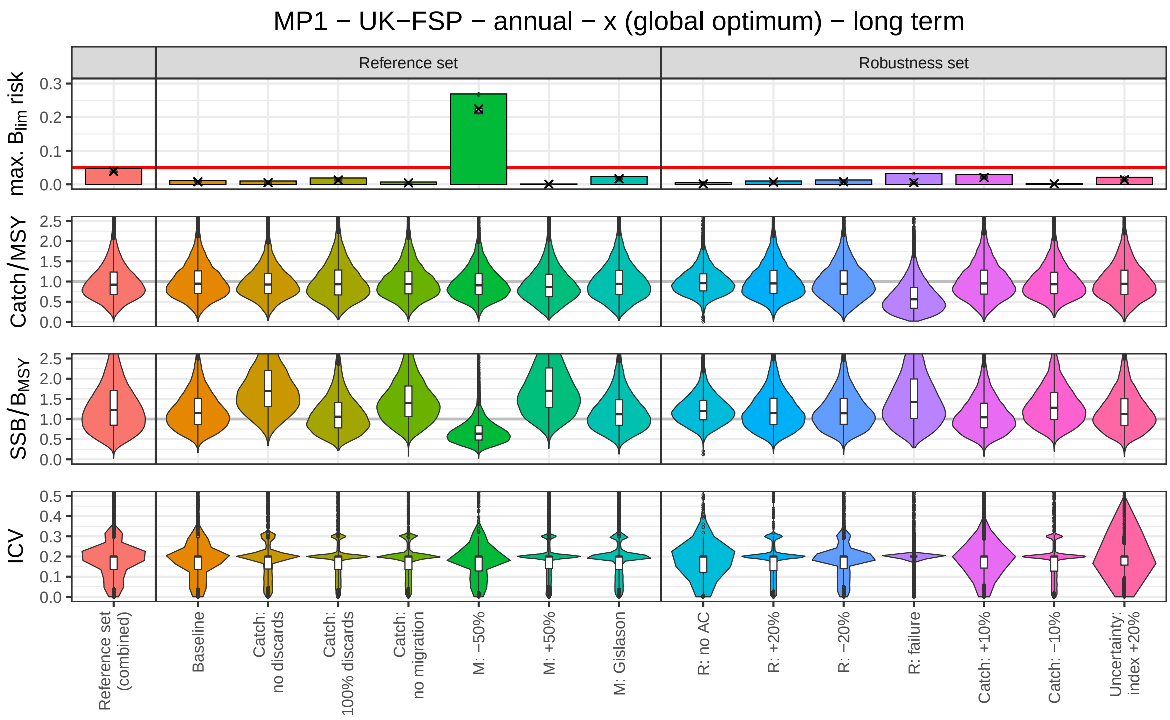

Figure 10: Reference set. Long-term performance statistics corresponding to the chr rule optimised with the multiplier x from Figure 9 for the UK-FSP survey (MP1 in Table 4. For catch, SSB, and ICV (inter-annual catch variability), the distribution shown corresponds to the values over 10 years and 7,000 simulation replicates (1,000 for each of the 7 operating models). The risk (top row) shows the distribution of the annual values over the years, the bar is the maximum of these 10 values (ICES risk 3), and the "x" is the average over the 10 years (ICES risk 1).

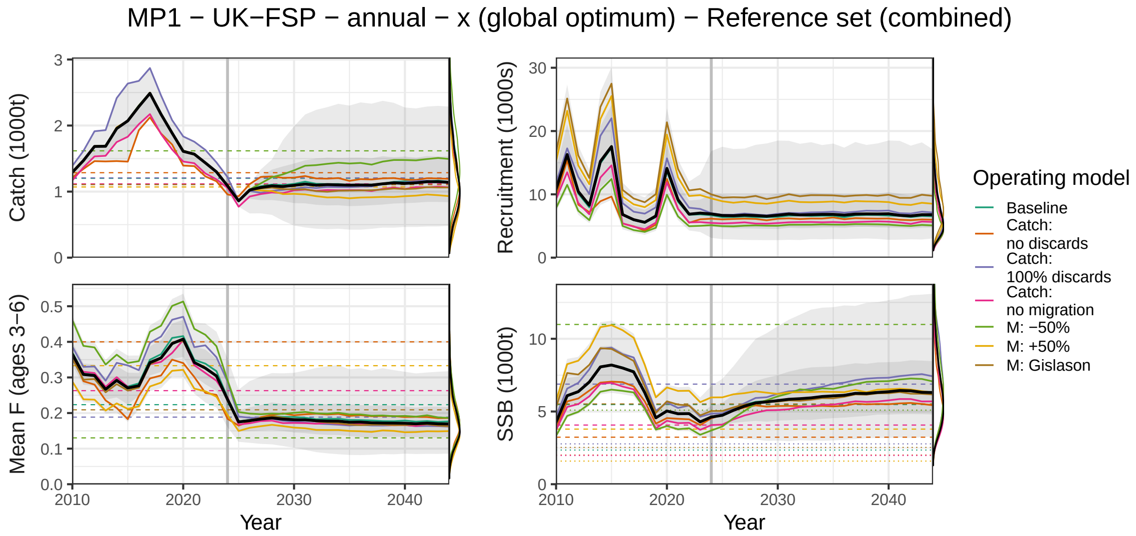

Figure 11: Reference set. MSE trajectories corresponding to the chr rule optimised with the multiplier x from Figure 9 for the UK-FSP survey (MP1 in Table 4. The black curves are the medians of all simulations replicates over all operating models, surrounded by 50% and 95% confidence intervals shaded in grey. The coloured curves correspond to the medians of the individual operating models. Dashed horizontal lines are MSY reference values and dotted lines B_{lim} values by operating model. Each panel in the figure includes a density plot of the distribution in the last simulation year (2044) on the right.

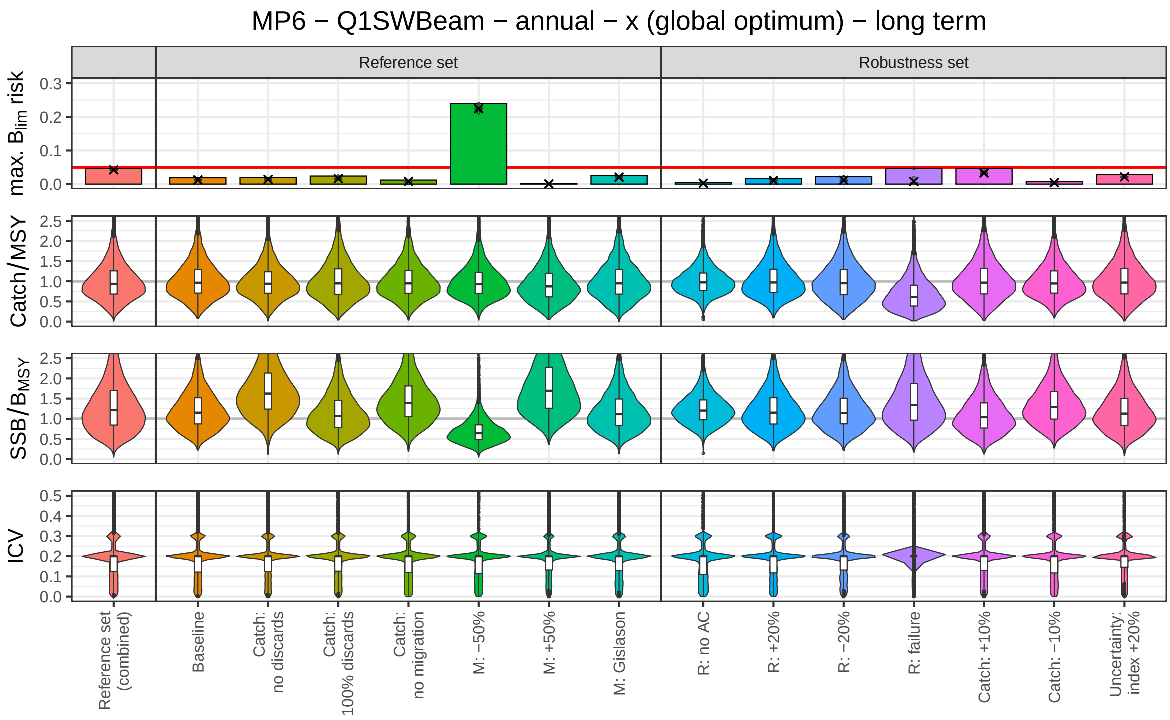

Figure 12: Reference set. Long-term performance statistics corresponding to the chr rule optimised with the multiplier x from Figure 9 for the Q1SWBeam survey (MP1 in Table 4). See Figure 10 for details.

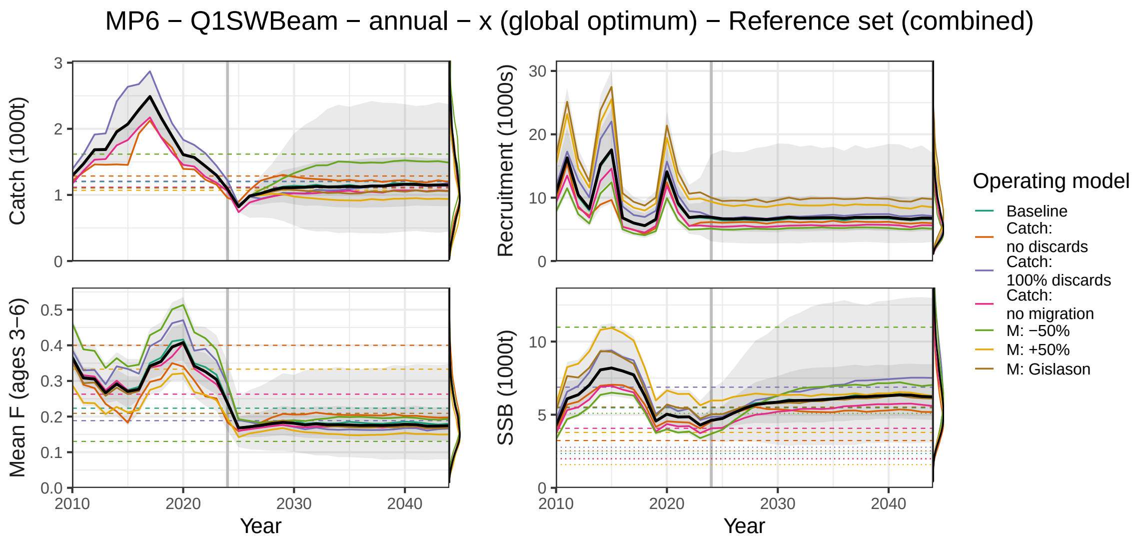

Figure 13: Reference set. MSE trajectories corresponding to the chr rule optimised with the multiplier x from Figure 9 for the Q1SWBeam survey (MP1 in Table 4). See Figure 11 for details.

Figures 14 and 15 show the results of the grid search for x and w with the operating model reference set. A total of around 24,000 different parameterisations of the chr rule were run.

Initially, a precautionary catch maximum was found for all versions of the chr rule with relatively low values of w (indicated by blue lines in Figures 14 and 15 and called MP2, MP4, MP7, and MP9 in Table 4). For the annual versions (MP2 and MP6), the multipliers x stayed exactly the same as when x was tuned on its own ($x = 0.59$ for UK-FSP, $x = 0.75$ for Q1SWBeam), but w was reduced (from $w = 1.4$ to $w = 0.90$ for UK-FSP and $w = 1.05$ for Q1SWBeam). The improvement in performance statistics was negligible (for UK FSP, the catch increased from 92.2% to 92.6% of MSY, and from 93.3% to 93.8% for Q1SWBeam).

However, when the search space was extended, these solutions turned out to be just local optima in the grid search. Subsequently, global optima were found for higher values of w (indicated by red lines in Figures 14 and 15 and called MP3, MP5, MP8, and MP10 in Table 4).

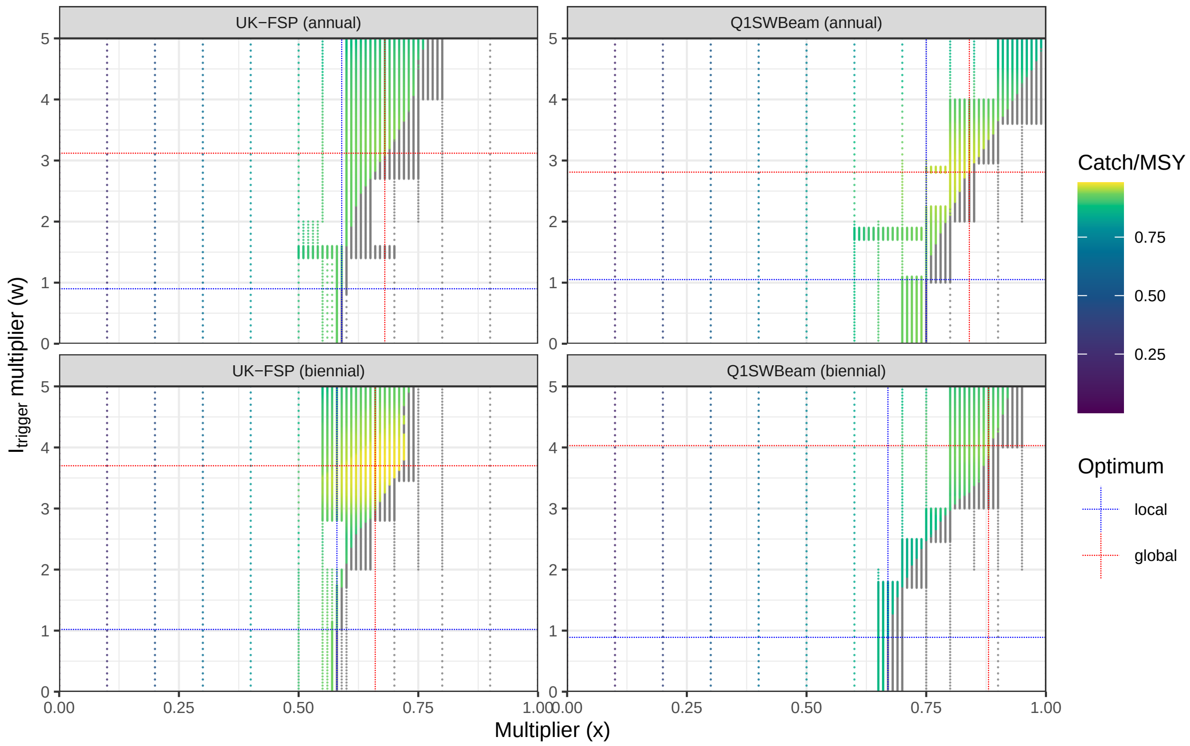

Figure 14: Reference set. Optimisation of the chr rule with x and w, for annual and biennial advice. Each point in the figure corresponds to one MSE projection. Points shaded grey indicate non-precautionary solutions.

Figure 16 summarises the performance statics for the 10 versions of the optimised chr rule. The performance between the chr rule version was fairly similar, resulting in catches just below MSY and SSB slightly above B_{MSY}, but the global optima (MP3, MP5, MP8, and MP10) resulted in a wider spread of SSB and catch values in the long term. The performance statistics for all operating models are shown in Figures S1–S30. Plots with trajectories of the optimised chr rule versions for the reference set operating models are shown in Figures S31–S40. Individual plots for all operating models are available online (see Table S1 for links).

Increasing the observation error for the index increased the B_{lim} risk for all versions of the

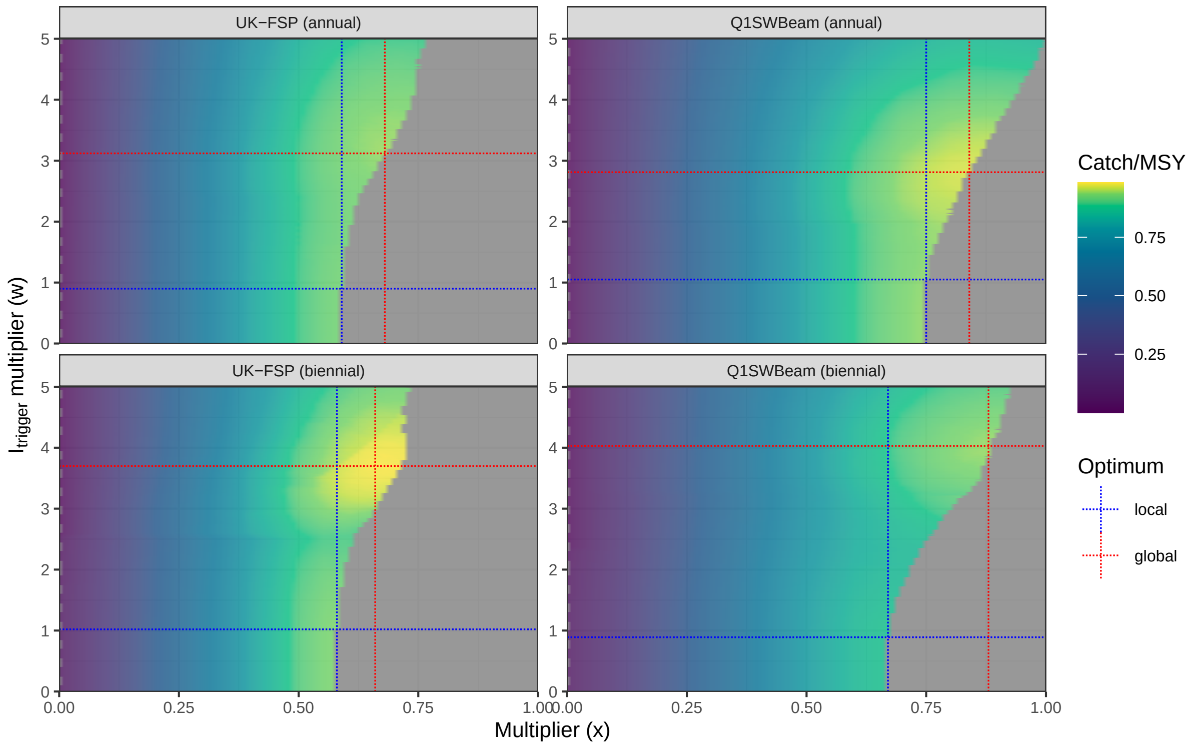

Figure 15: Reference set. Optimisation of the chr rule with x and w, for annual and biennial advice. The same results as in Figure 14 are shown but for plotting purposes the space between points is interpolated.

chr rule (Figure 17). The increases were largest for the chr rules with a biennial catch advice (MP4–MP5 and MP9–MP10). The change in the average catch was relatively small, even when the observation error was doubled.

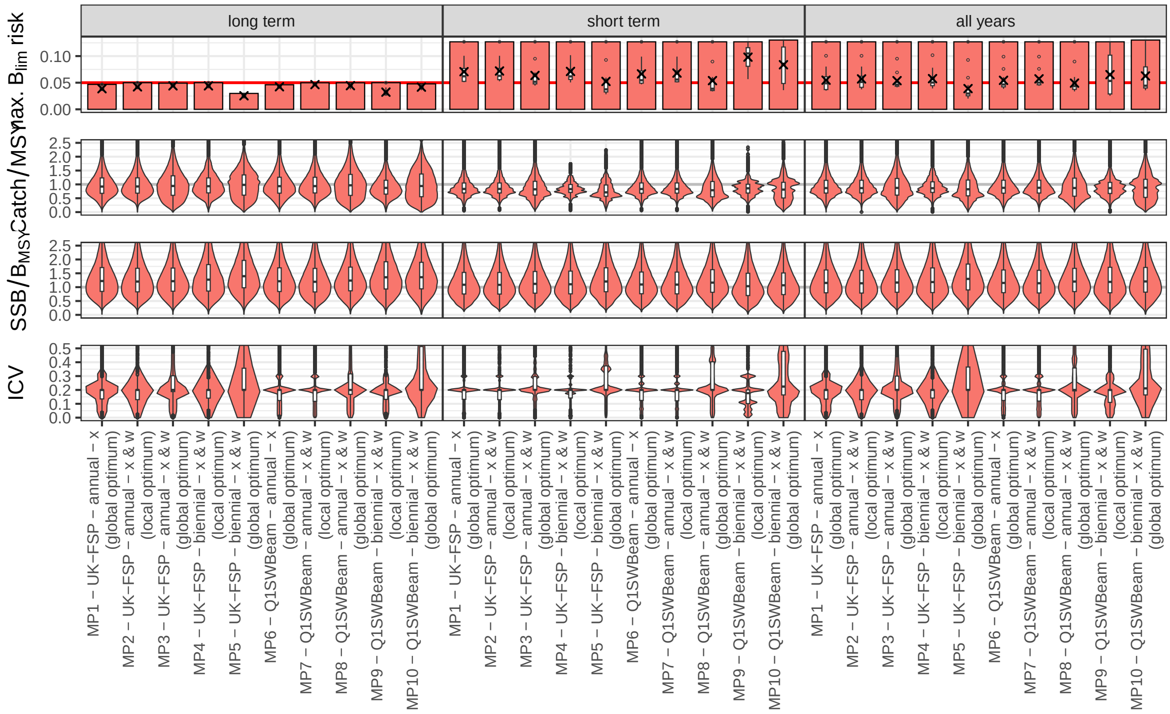

Figure 16: Reference set. Comparison of the performance statistics for the 10 versions of the optimised chr rule. The versions of the chr rule correspond to MP1–MP10 of Table 4 from left to right in each panel.

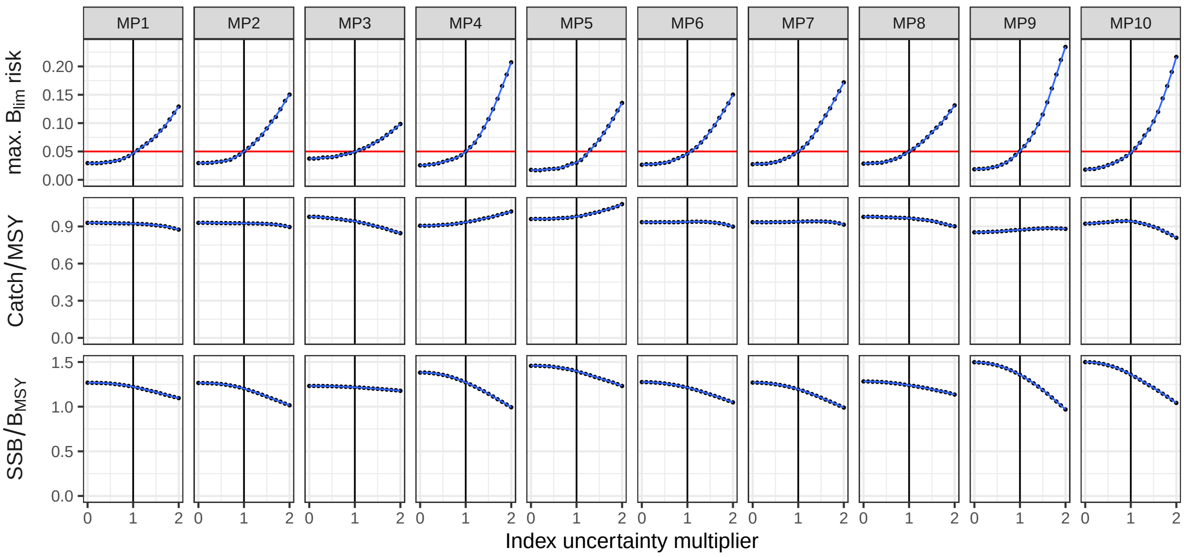

Figure 17: Reference set. Impact of the observation error of the index on the long-term performance statistics on the combined operating model reference set. The vertical lines indicate the default observation error.

5 Alternative management procedures

The two alternative management procedures (rfb rule and ICES MSY rule) were only run with their default parameterisation but tested with all operating models. Their performance is summarised in Table 5 and Figures 18 and 20 show the long-term performance statistics (short-term and all years statistics are available in Figures S41–S44). Figures 19 and 21 show the projections for the reference set operating models.

Table 5: Summary statistics of the alternative management procedures for the reference set operating model.

MP	Period	B_{lim} risk	Catch/MSY	SSB/B_{MSY}	ICV
ICES MSY	long term	0.063	0.967	1.079	0.106
ICES MSY	short term	0.127	0.864	1.058	0.114
ICES MSY	all years	0.127	0.910	1.068	0.110
rfb	long term	0.009	0.633	1.801	<0.001
rfb	short term	0.127	0.694	1.195	<0.001
rfb	all years	0.127	0.673	1.451	<0.001

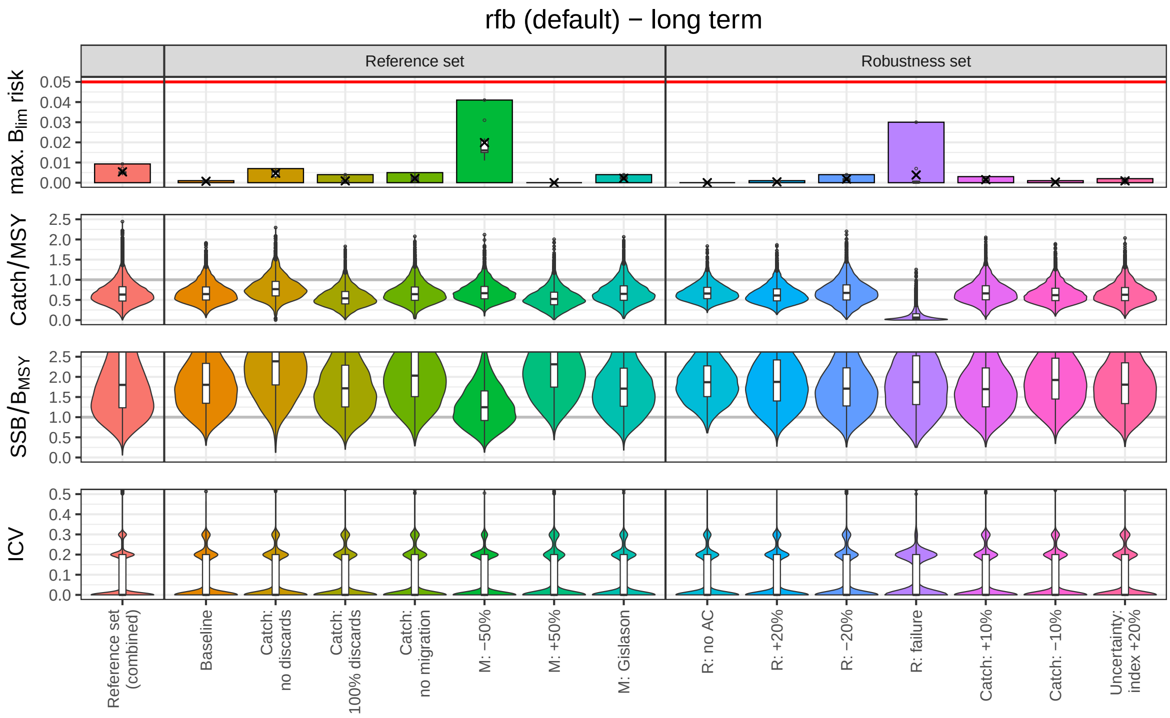

Figure 18: rfb rule. Long-term performance statistics for all operating models. See Figure 10 for details.

The rfb rule was precautionary in the long term with the reference set operating model but led to relatively low catches. The catches were still slightly decreasing and SSB increasing at the end of the 20-year projection. On the other hand, the ICES MSY rule was not precautionary in the long term but led to fairly stable stock dynamics after around five years.

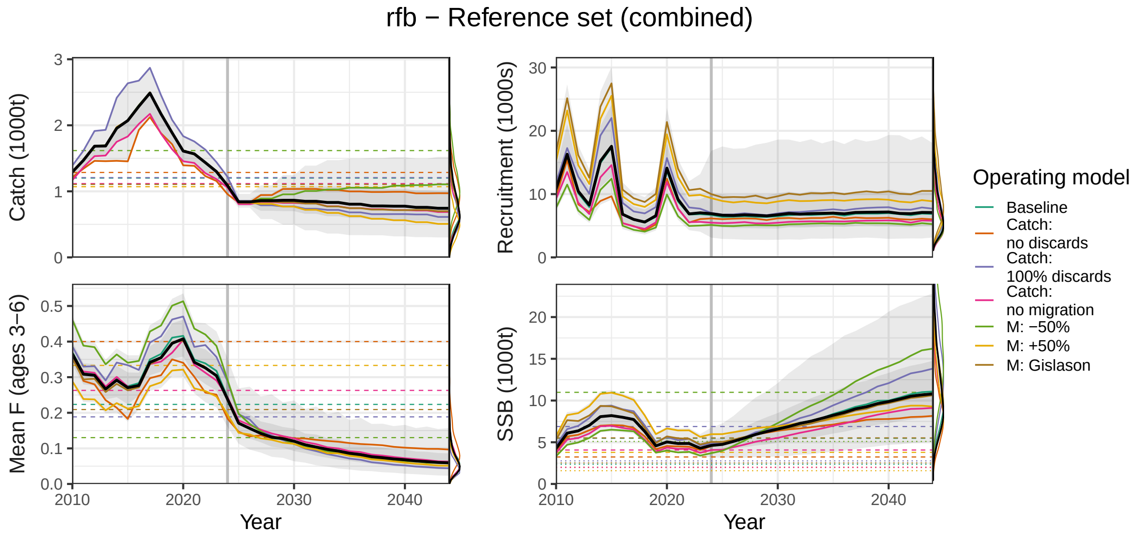

Figure 19: rfb rule. MSE trajectories for the reference set operating models. See Figure 11 for details.

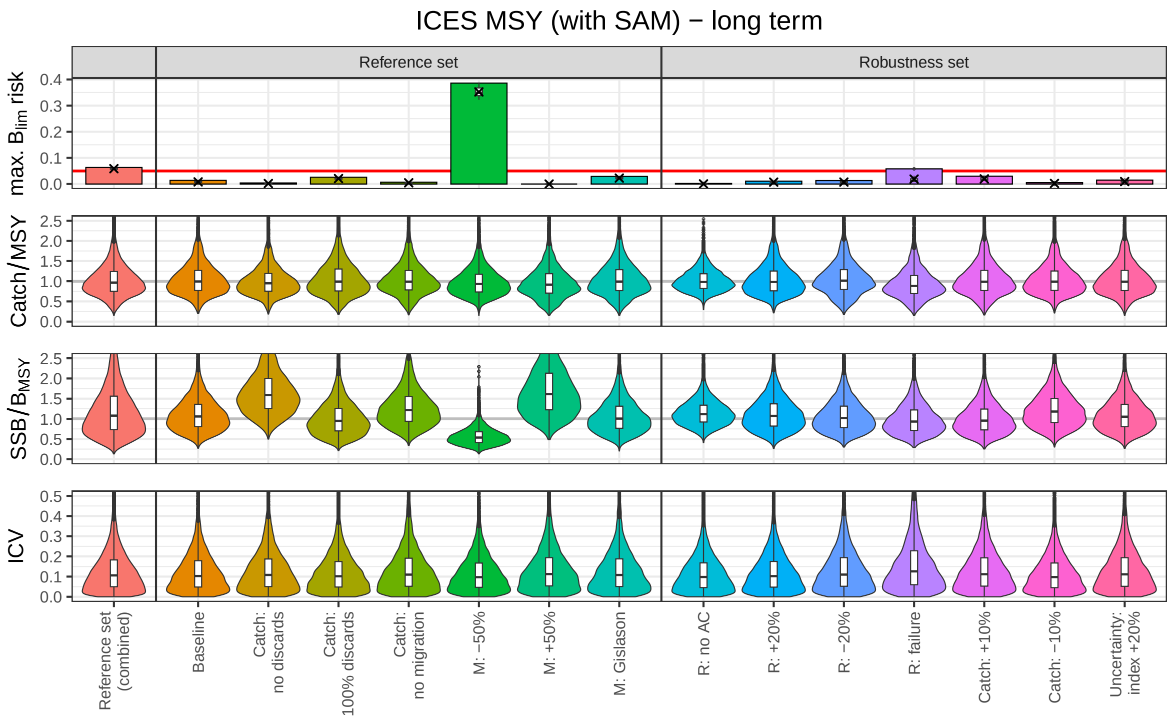

Figure 20: ICES MSY rule. Long-term performance statistics for all operating models.

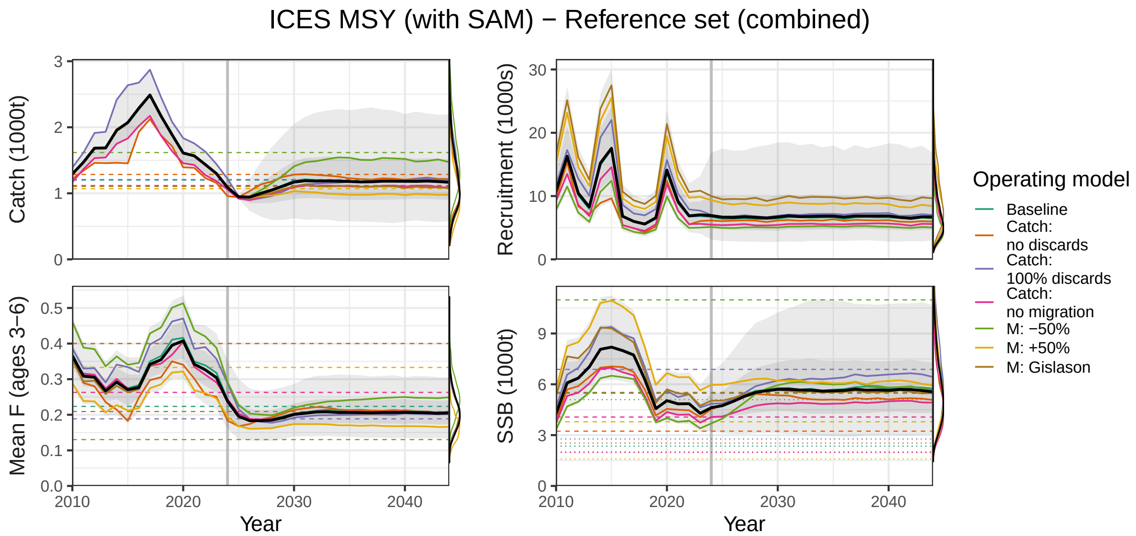

Figure 21: ICES MSY rule. MSE trajectories for the reference set operating models. See Figure 11 for details.

6 Discussion

All versions of the chr shown in Section 4 were precautionary in the long term and could be implemented by ICES. Furthermore, all were an improvement compared to the currently used rfb rule and provided a higher long-term catch (87–98% of MSY, 63% for the rfb rule).

In general, including more parameters of the chr rule in the optimisation resulted in higher long-term catches but the difference was only a few percentage points. If simplicity is wanted, the chr rule tuned only with the multiplier x could be the preferred option (MP1 with the UK-FSP index or MP6 with the Q1SWBeam index).

The highest catches were observed when the multiplier x and the I_{trigger} multiplier w were included with the global tuning (MP3, MP5, MP8, MP10). However, with these parameterisations, w was high (2.81–4.03), which means that I_{trigger} was also high. This has the effect that the biomass safeguard of the chr rule (which reduces the target harvest rate when the biomass index is below I_{trigger}) is frequently applied and changes in the catch advice from year to year are larger because the harvest is not constant. Furthermore, the stability clause of the chr rule (limiting changes to +20% and −30%) is turned off when the biomass safeguard is active, which means that larger changes in the catch are allowed. The effect of this was that the inter-annual catch variability (ICV) was higher. Additionally, the spread of catch and SSB values was higher. These two features (higher inter-annual changes, wider spread) are generally undesirable features in fisheries management and MP3, MP5, MP8, and MP10 should be avoided unless maximising catch is the only criterion.

All versions of the chr rule were generally robust as tested with the robustness set of operating models and B_{lim} risk was frequently below 5%. The only substantial exception is the recruitment failure scenario, which led to higher B_{lim} risks for MP4 and MP9 (optimisation with x and w, biennial advice, for both surveys).

When looking at the short term or the all years combined, B_{lim} risk was always above 5% because it was already above 5% at the beginning of the projection. This meant that short-term risk did not provide additional information on which to base the selection of a version of the chr rule.

7 Conclusion

All tuned versions of the chr rule were precautionary in the long term and an improvement compared to the currently used rfb rule. The choice of chr rule parameterisation depends on the choice of management objectives and their trade-offs. If simplicity is wanted, MP1 and MP6 are ideal.

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S1 Supplementary figures

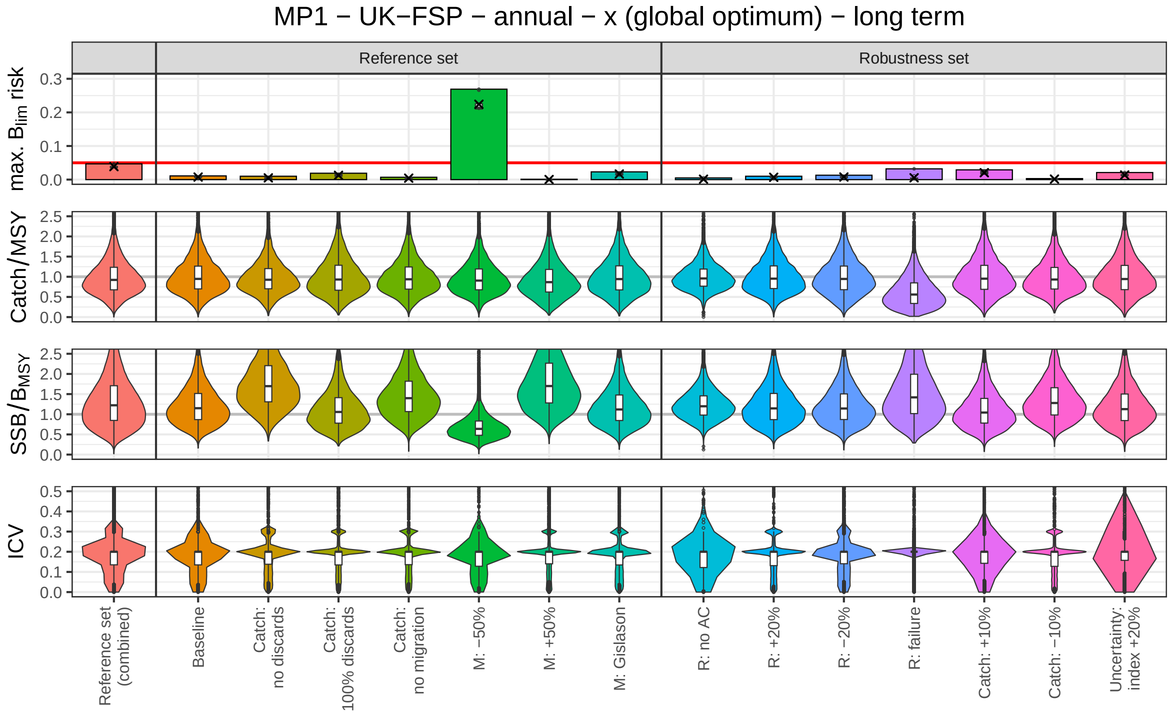


Figure S1: Long-term performance statistics for MP1 of Table 4 for all operating models.

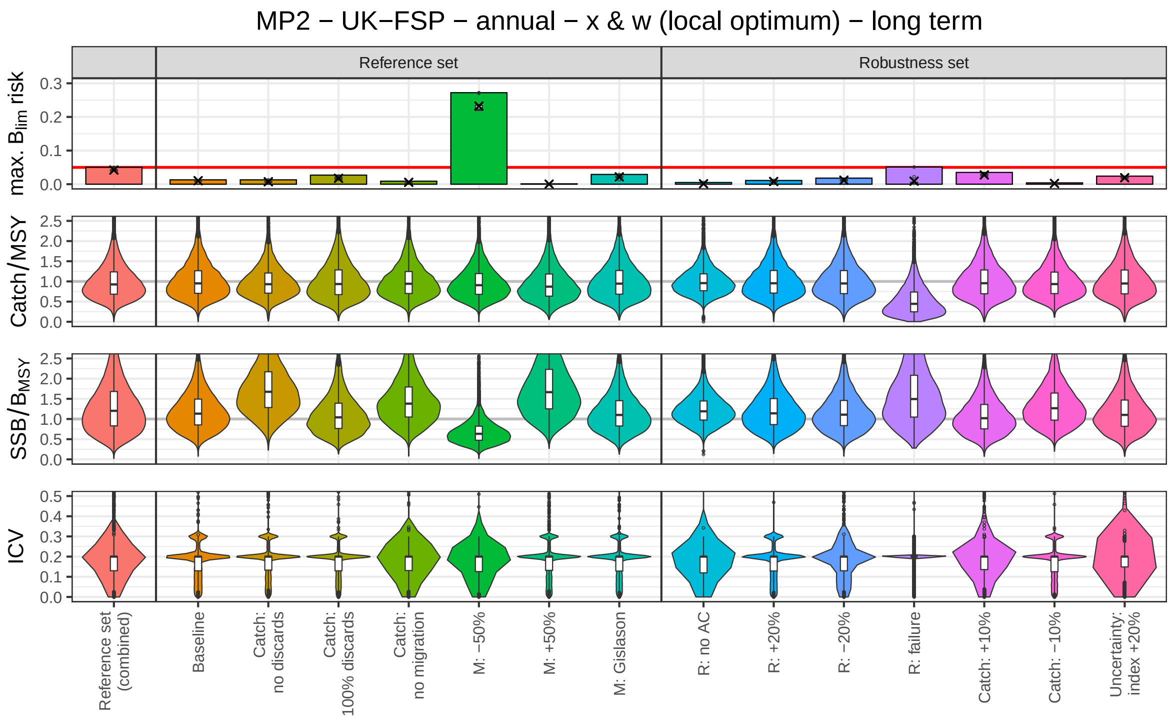


Figure S2: Long-term performance statistics for MP2 of Table 4 for all operating models.

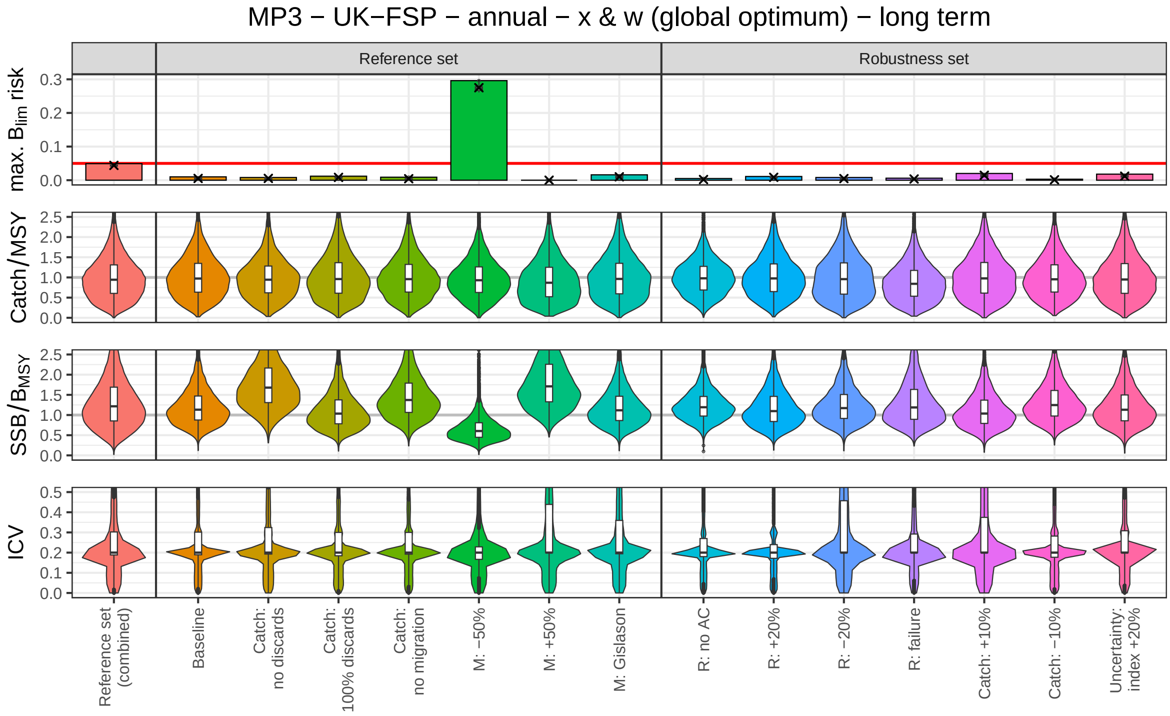


Figure S3: Long-term performance statistics for MP3 of Table 4 for all operating models.

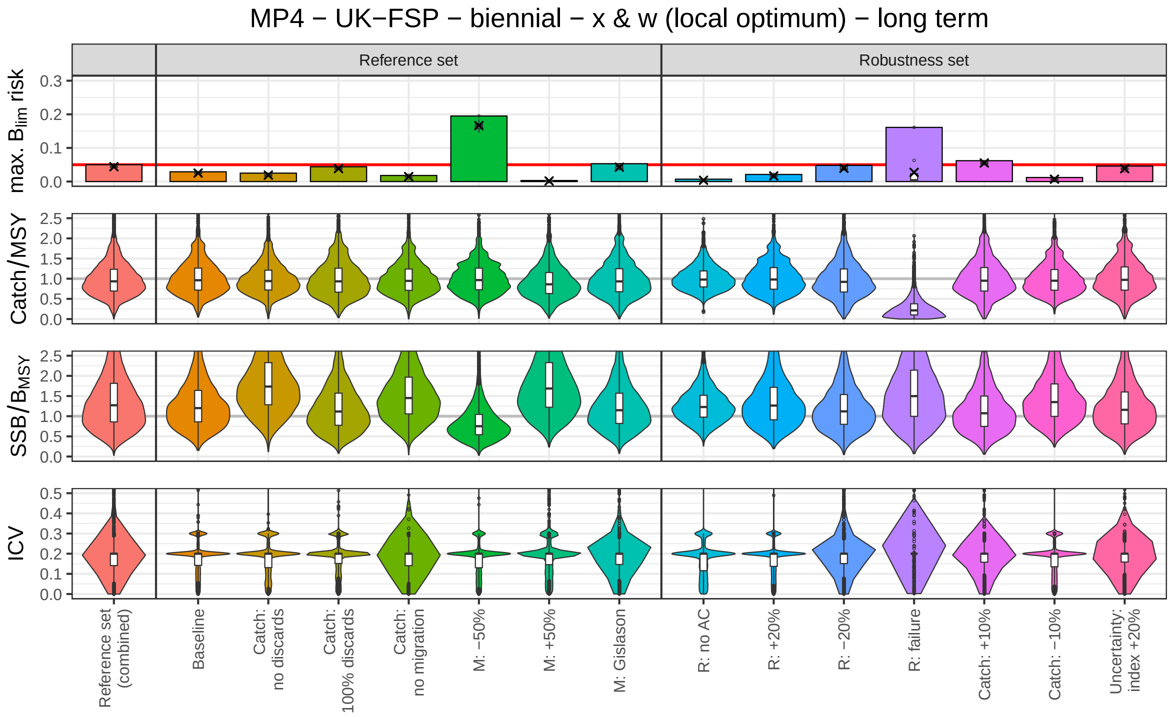


Figure S4: Long-term performance statistics for MP4 of Table 4 for all operating models.

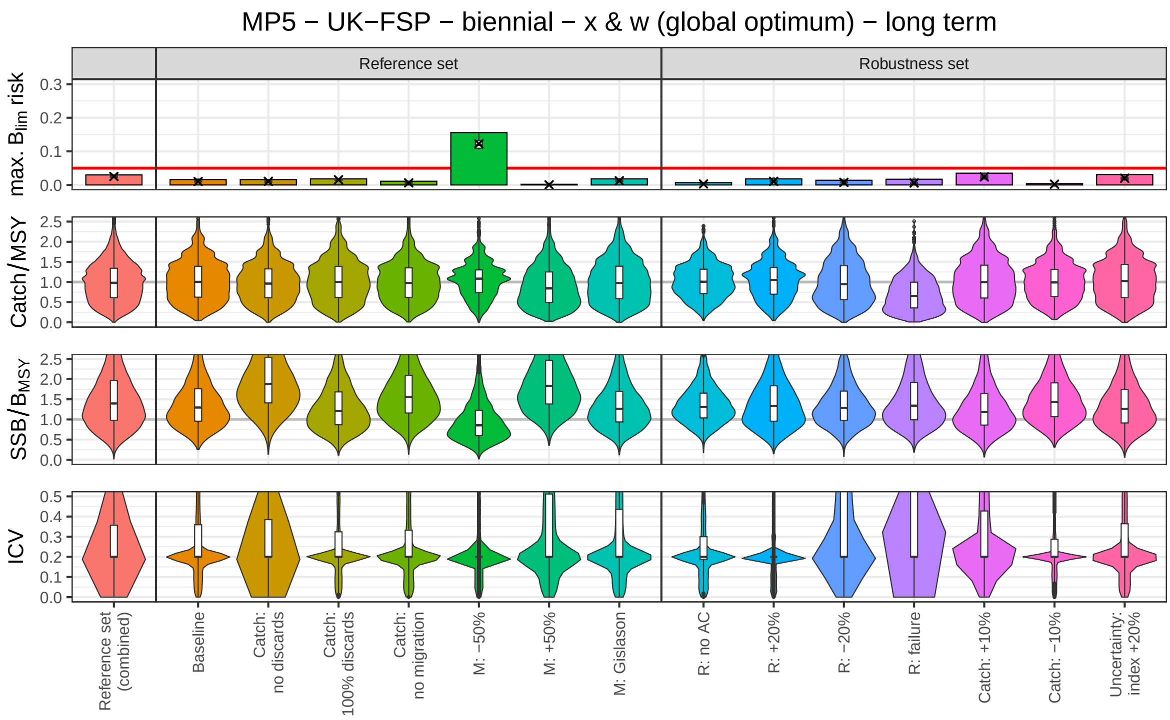


Figure S5: Long-term performance statistics for MP5 of Table 4 for all operating models.

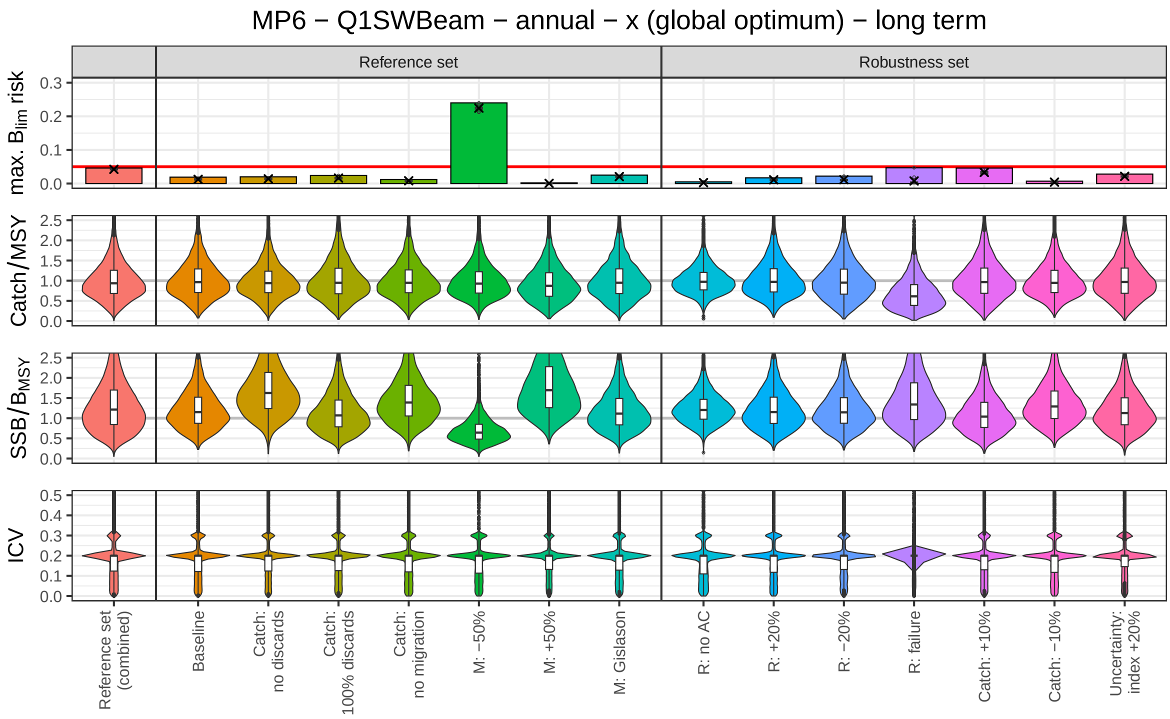


Figure S6: Long-term performance statistics for MP6 of Table 4 for all operating models.

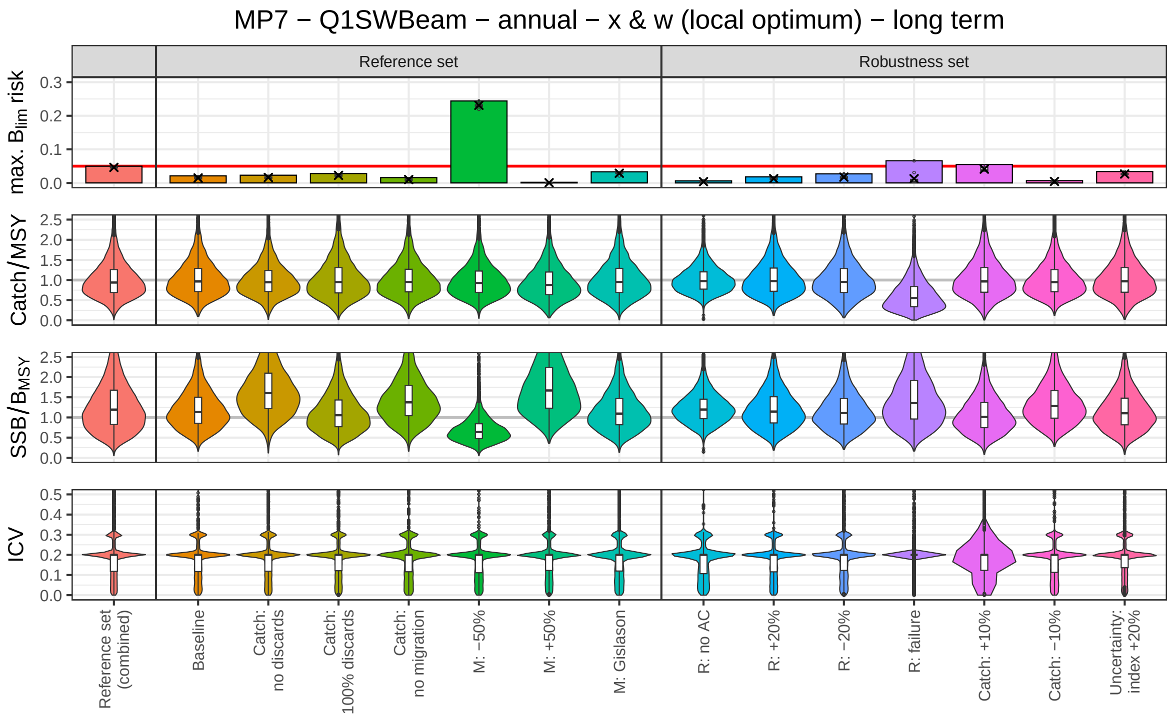


Figure S7: Long-term performance statistics for MP7 of Table 4 for all operating models.

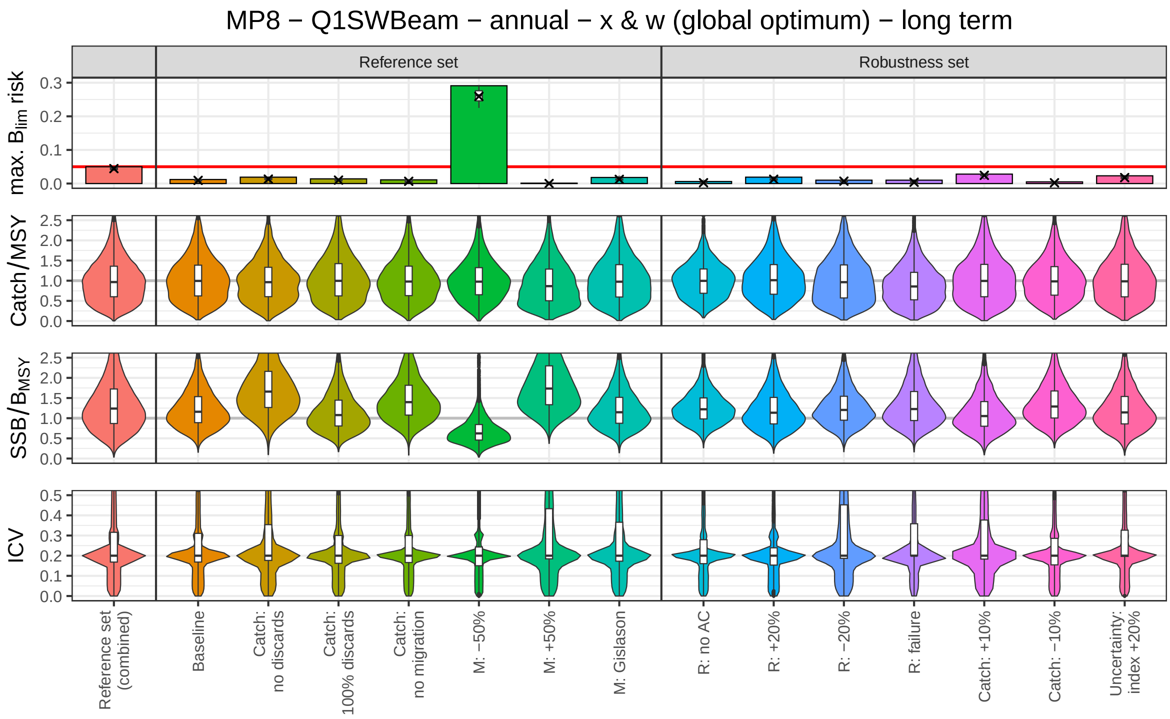


Figure S8: Long-term performance statistics for MP8 of Table 4 for all operating models.

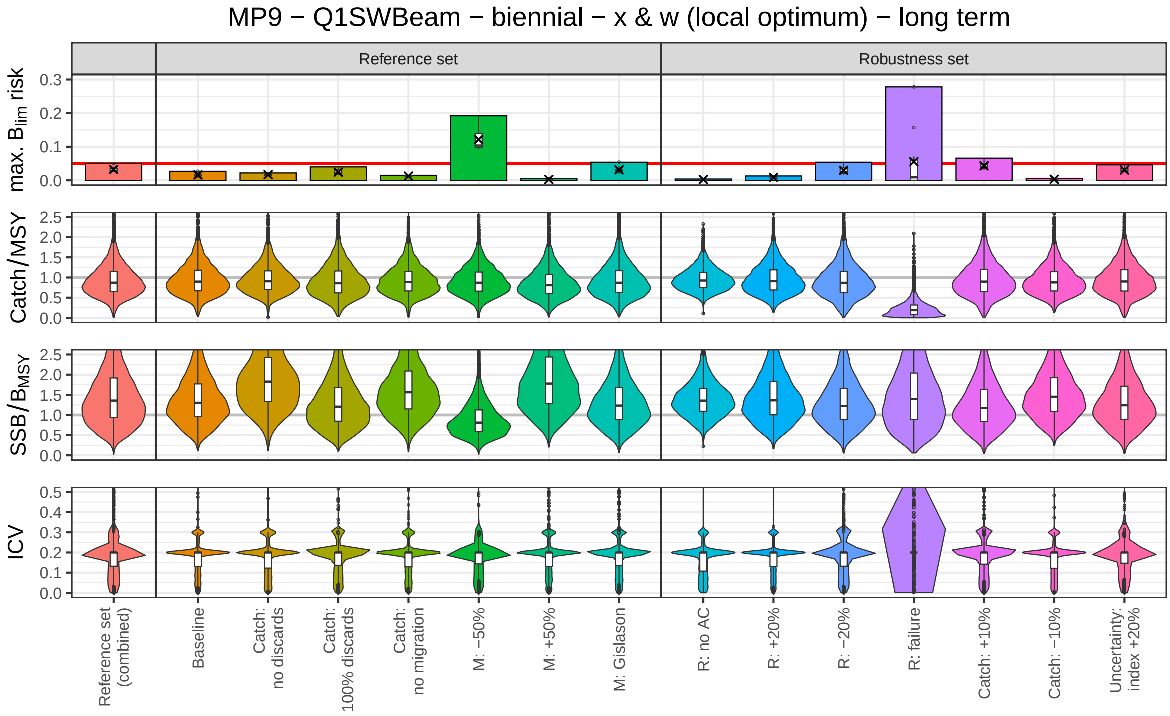


Figure S9: Long-term performance statistics for MP9 of Table 4 for all operating models.

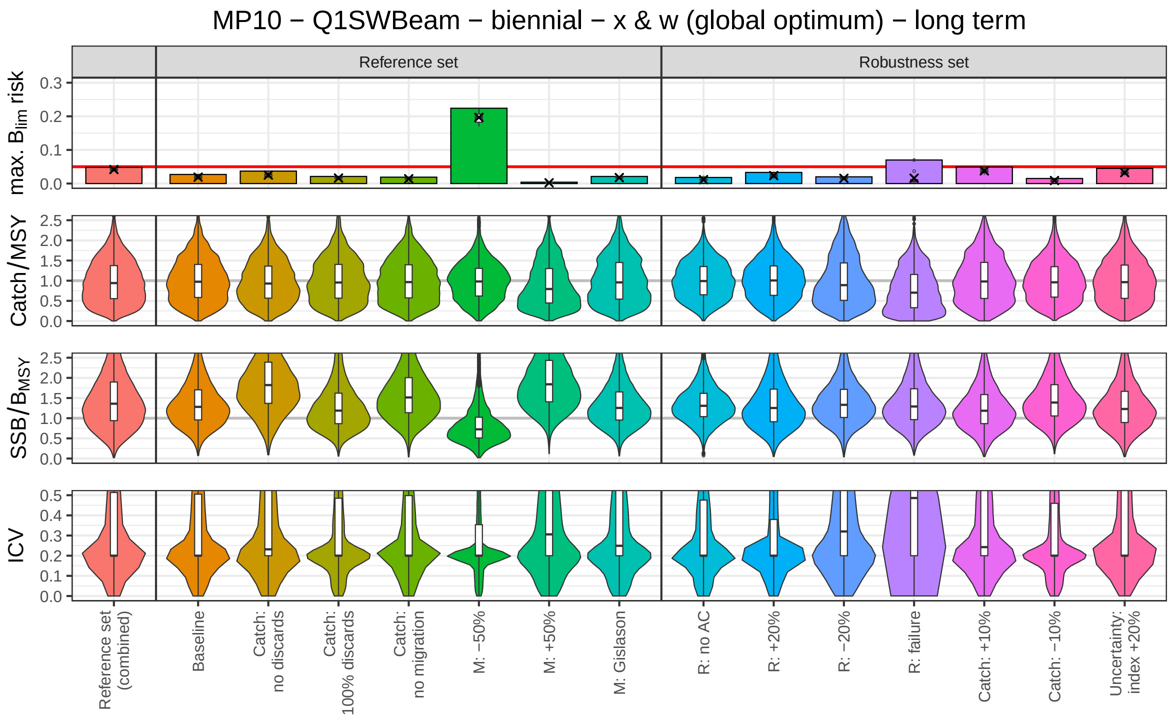


Figure S10: Long-term performance statistics for MP10 of Table 4 for all operating models.

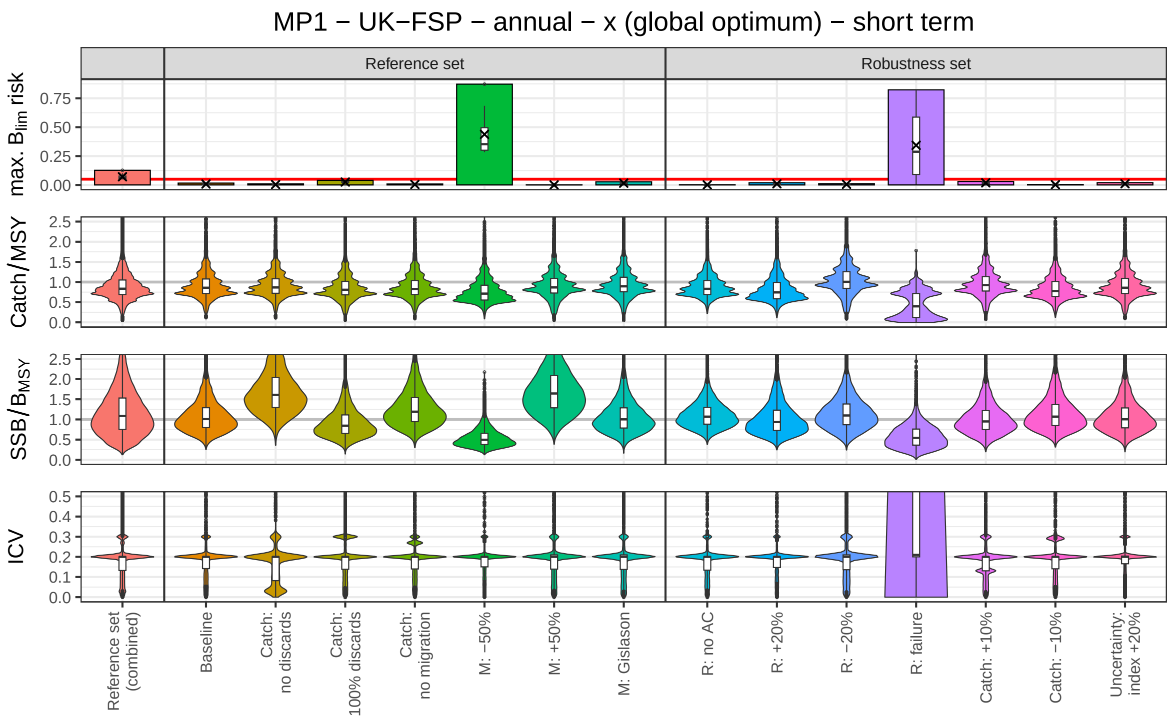


Figure S11: Short-term performance statistics for MP1 of Table 4 for all operating models.

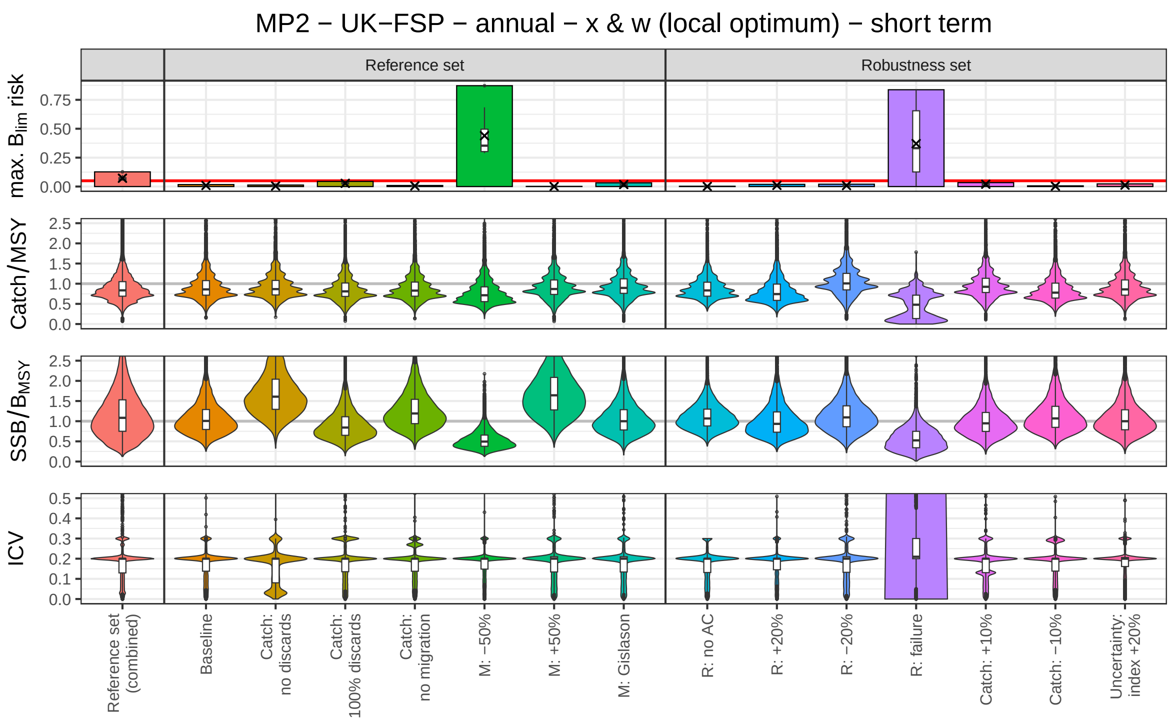


Figure S12: Short-term performance statistics for MP2 of Table 4 for all operating models.

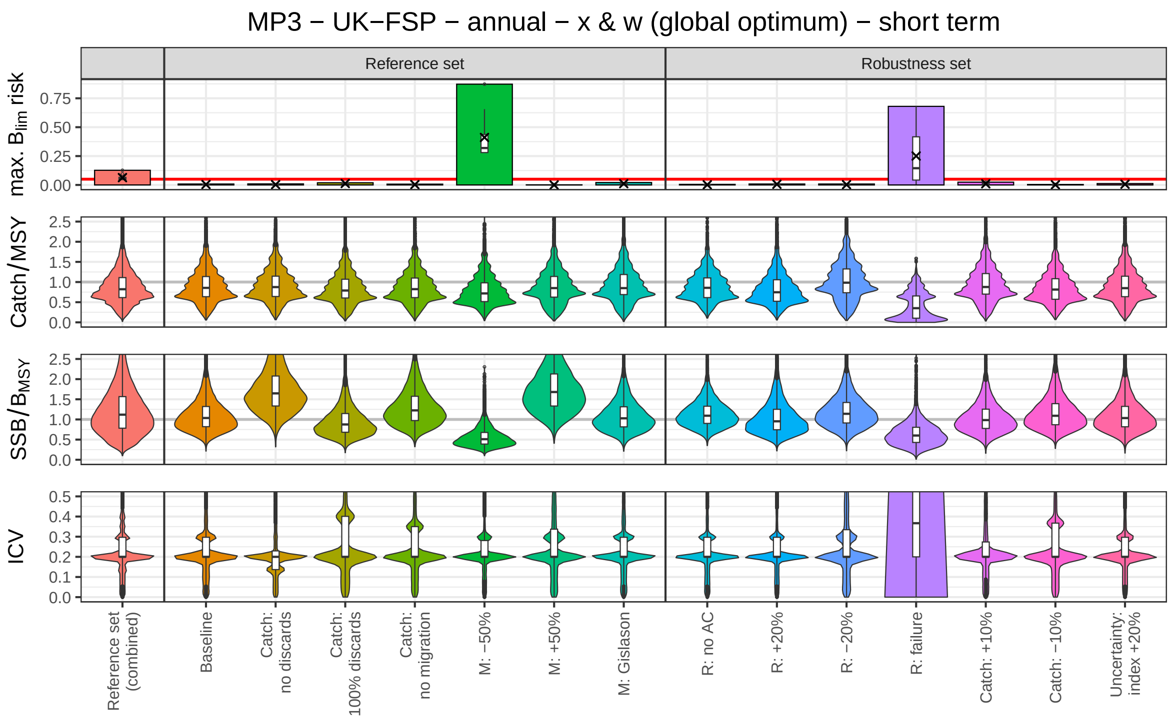


Figure S13: Short-term performance statistics for MP3 of Table 4 for all operating models.

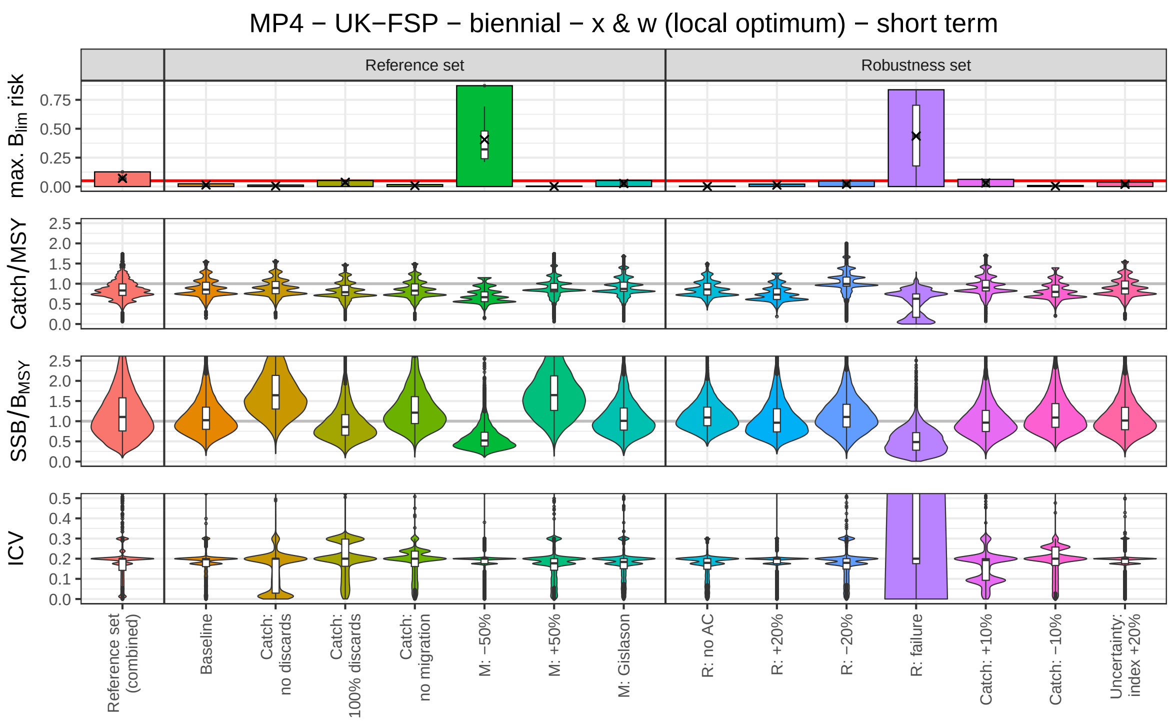


Figure S14: Short-term performance statistics for MP4 of Table 4 for all operating models.

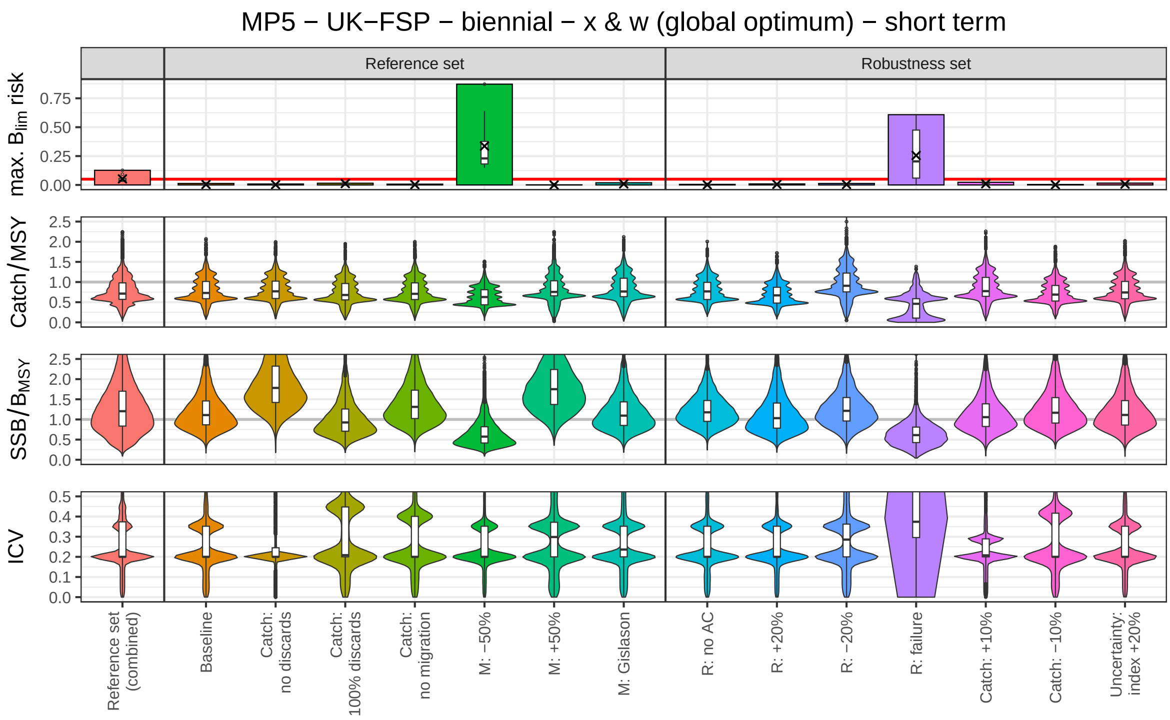


Figure S15: Short-term performance statistics for MP5 of Table 4 for all operating models.

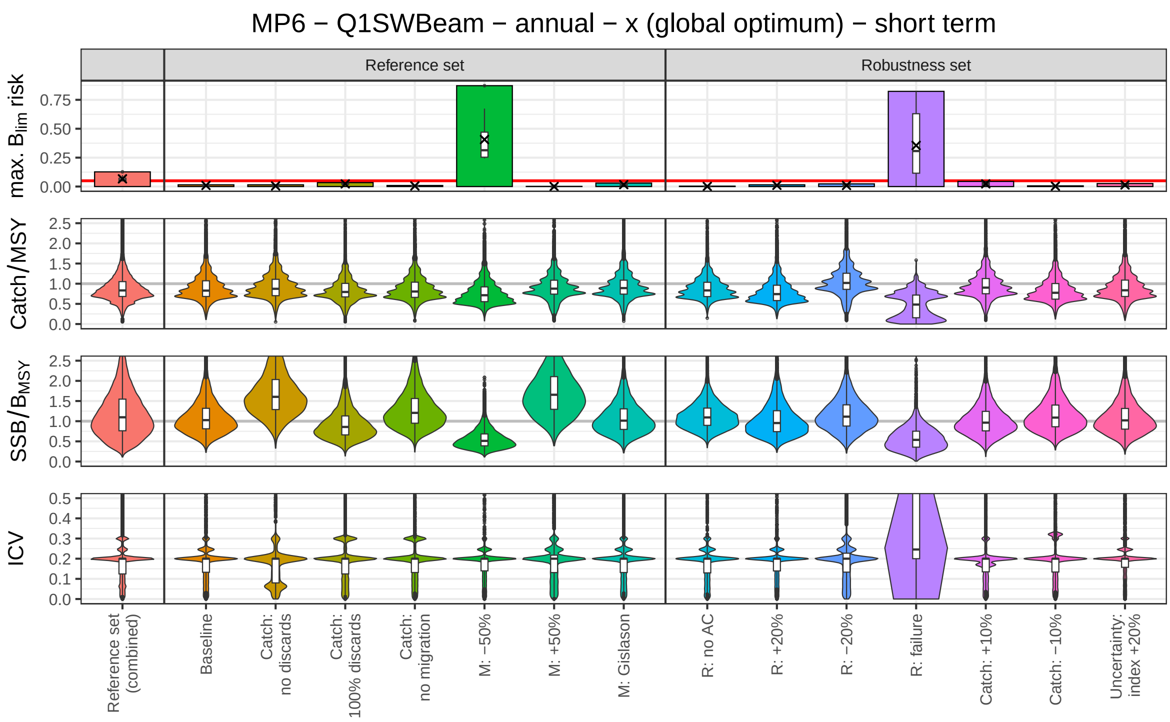


Figure S16: Short-term performance statistics for MP6 of Table 4 for all operating models.

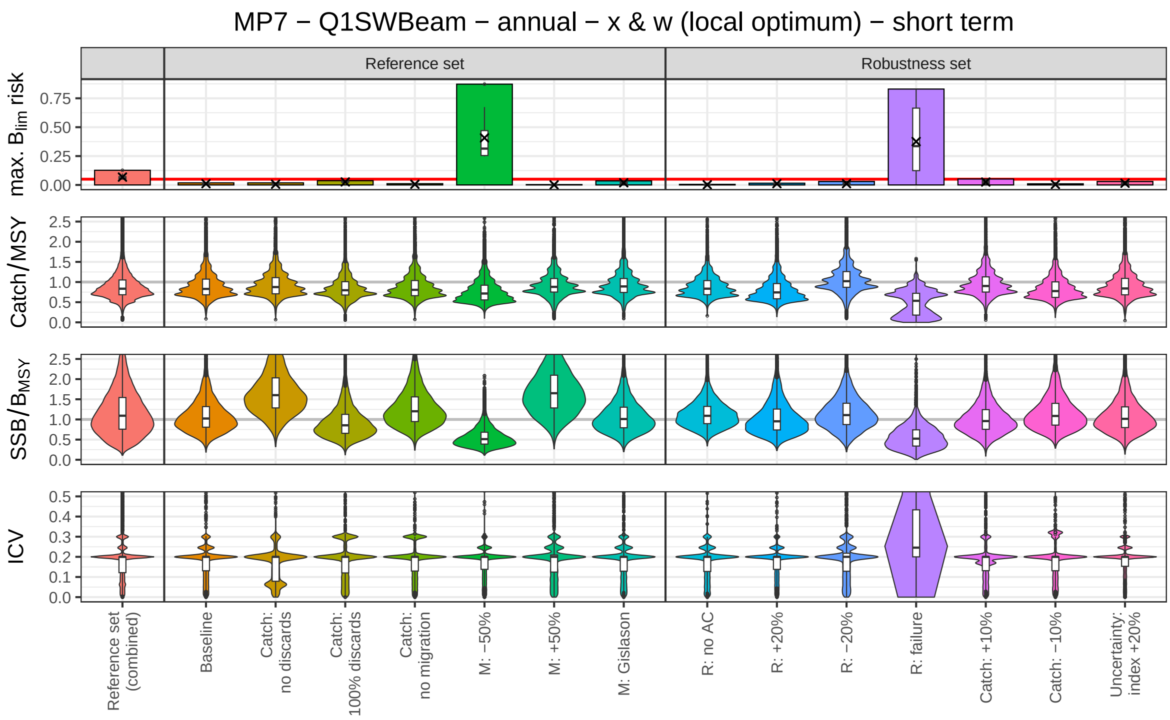


Figure S17: Short-term performance statistics for MP7 of Table 4 for all operating models.

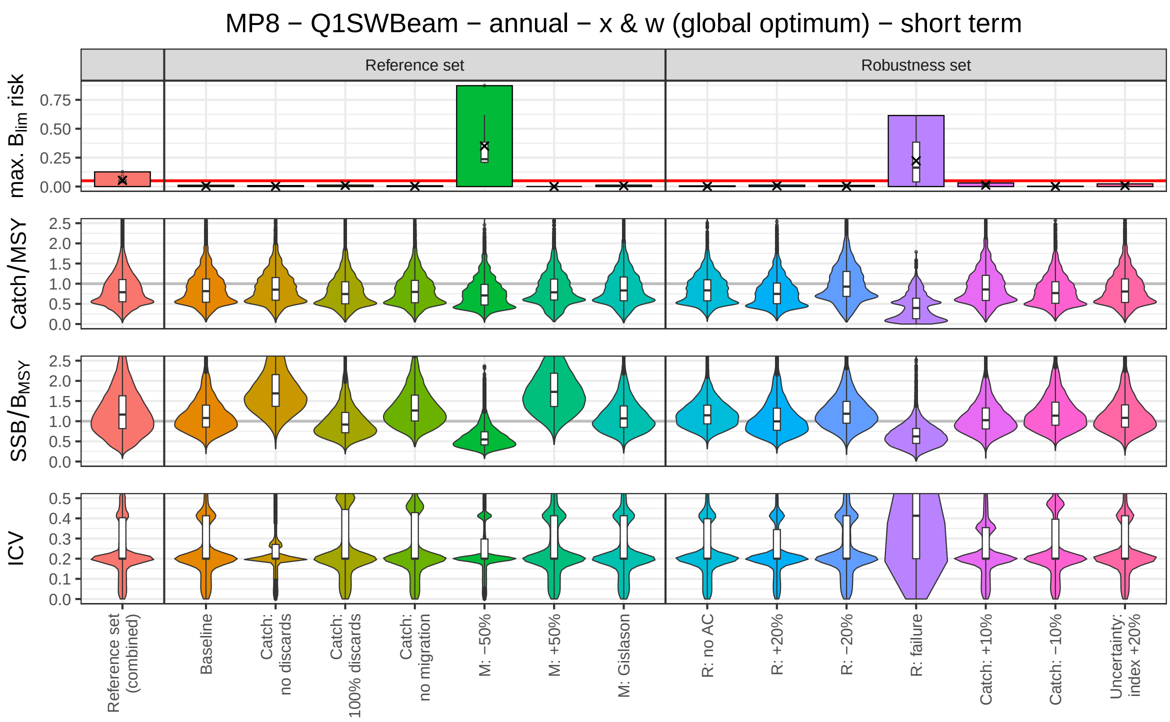


Figure S18: Short-term performance statistics for MP8 of Table 4 for all operating models.

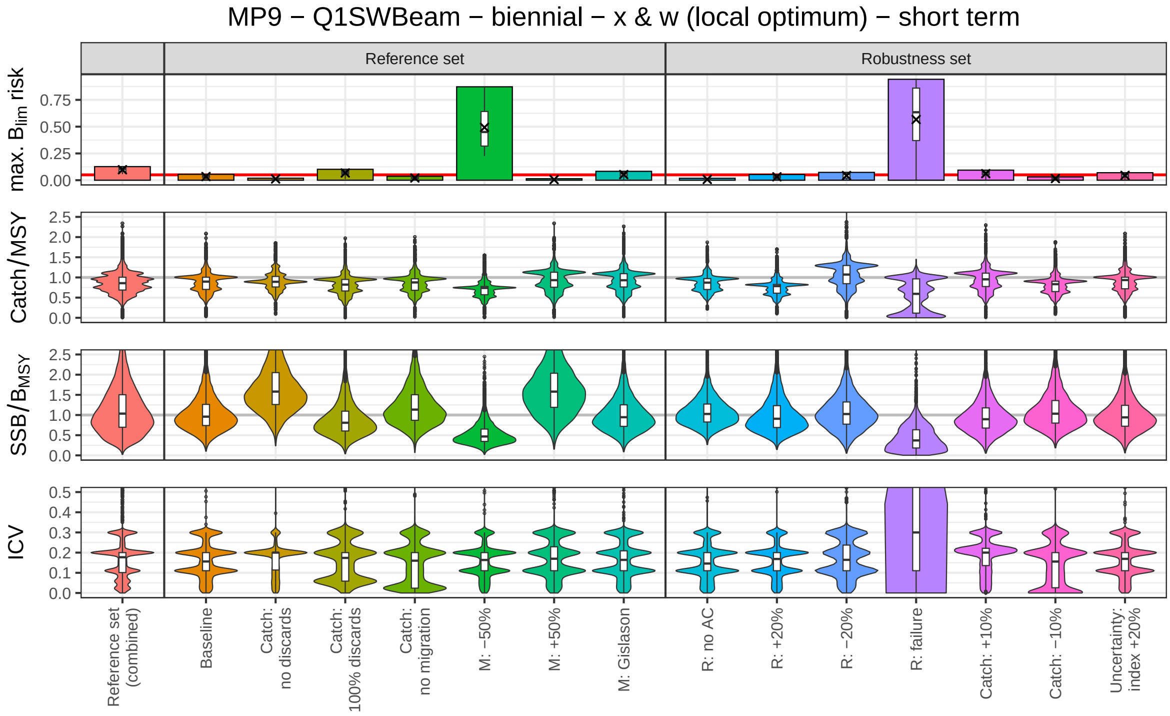


Figure S19: Short-term performance statistics for MP9 of Table 4 for all operating models.

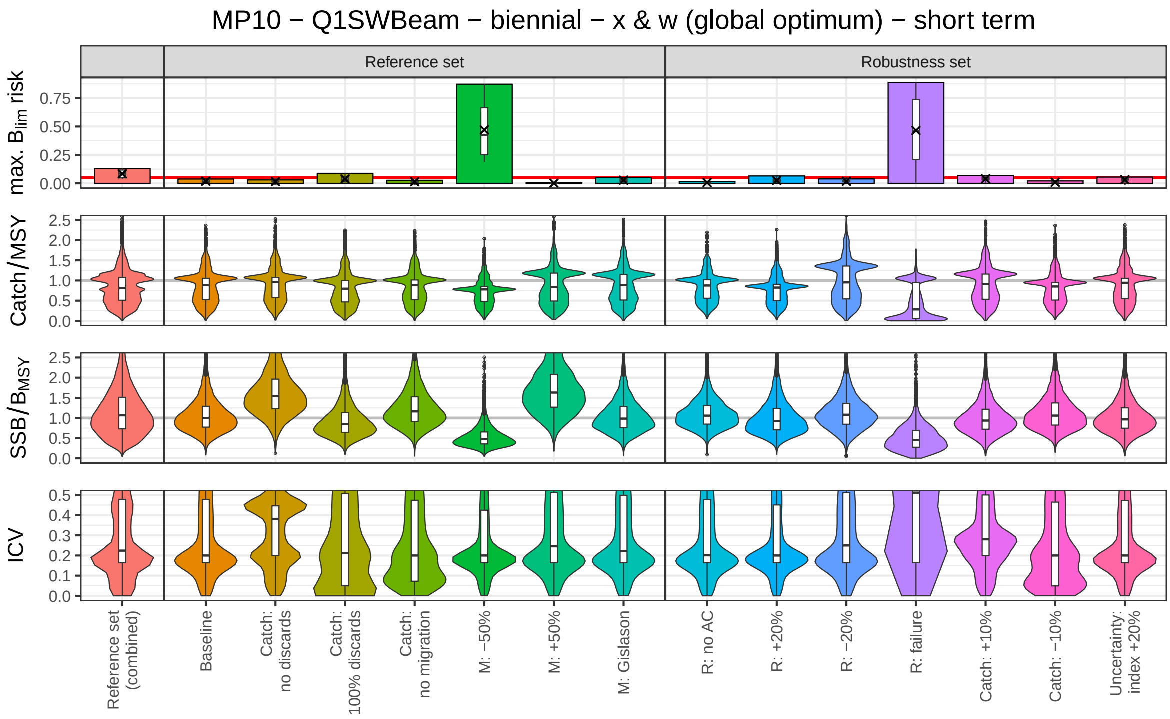


Figure S20: Short-term performance statistics for MP10 of Table 4 for all operating models.

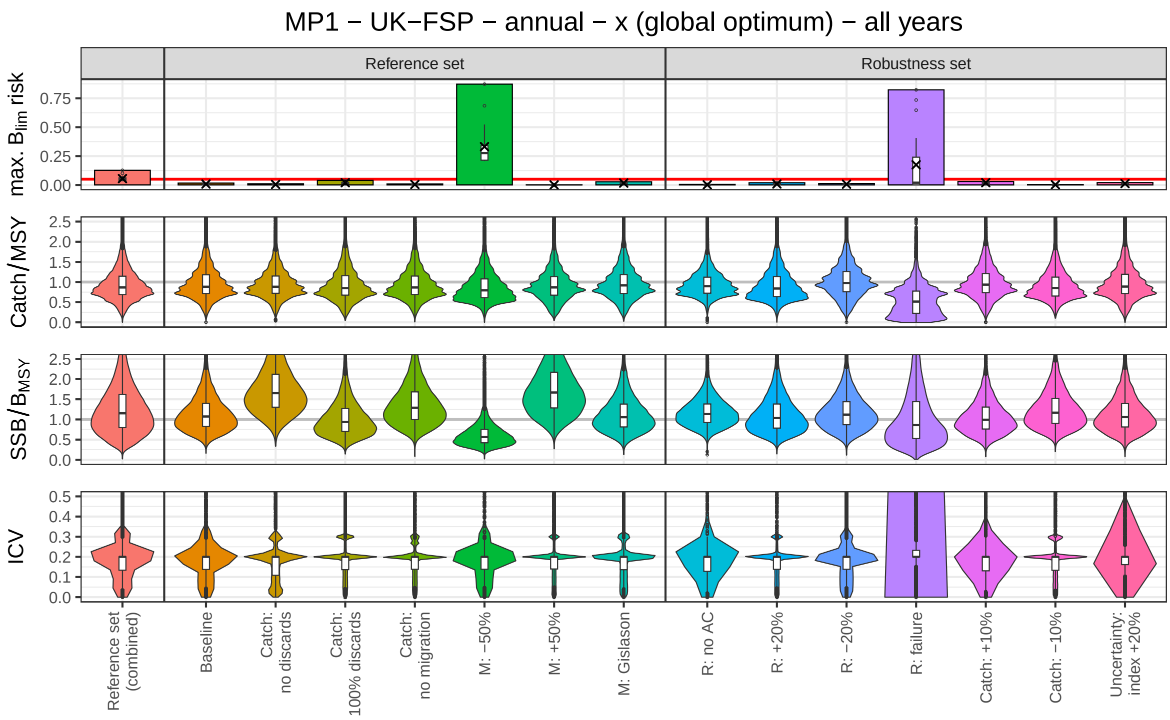


Figure S21: All years performance statistics for MP1 of Table 4 for all operating models.

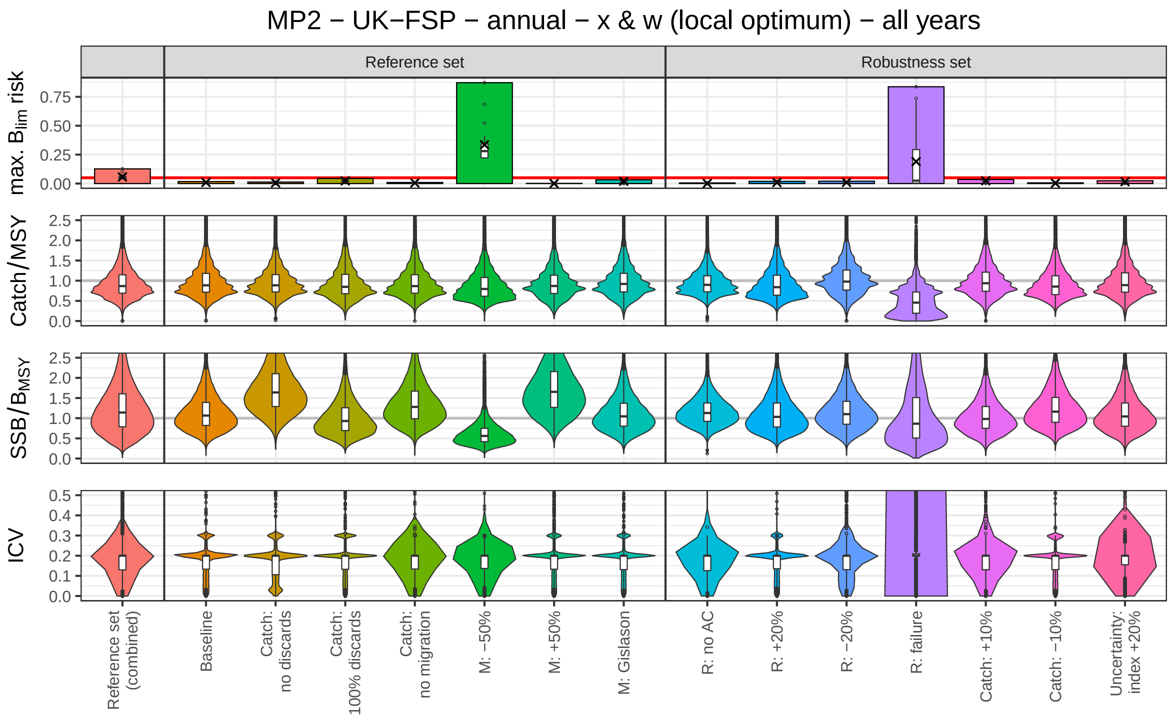


Figure S22: All years performance statistics for MP2 of Table 4 for all operating models.

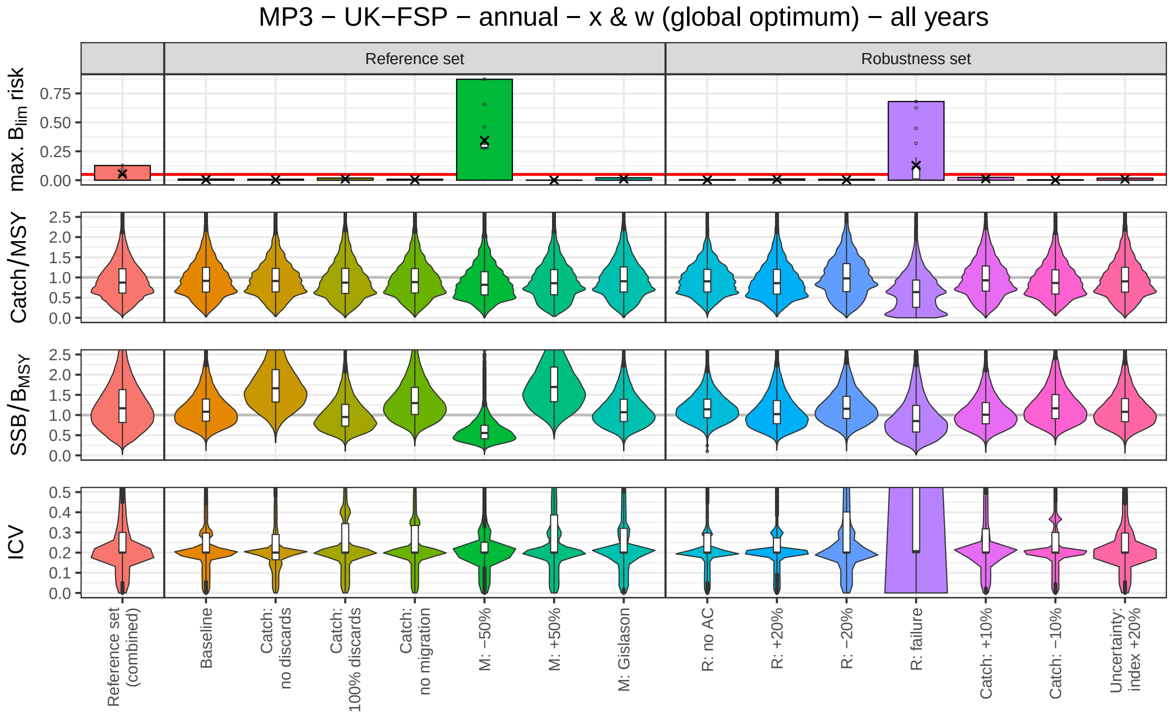


Figure S23: All years performance statistics for MP3 of Table 4 for all operating models.

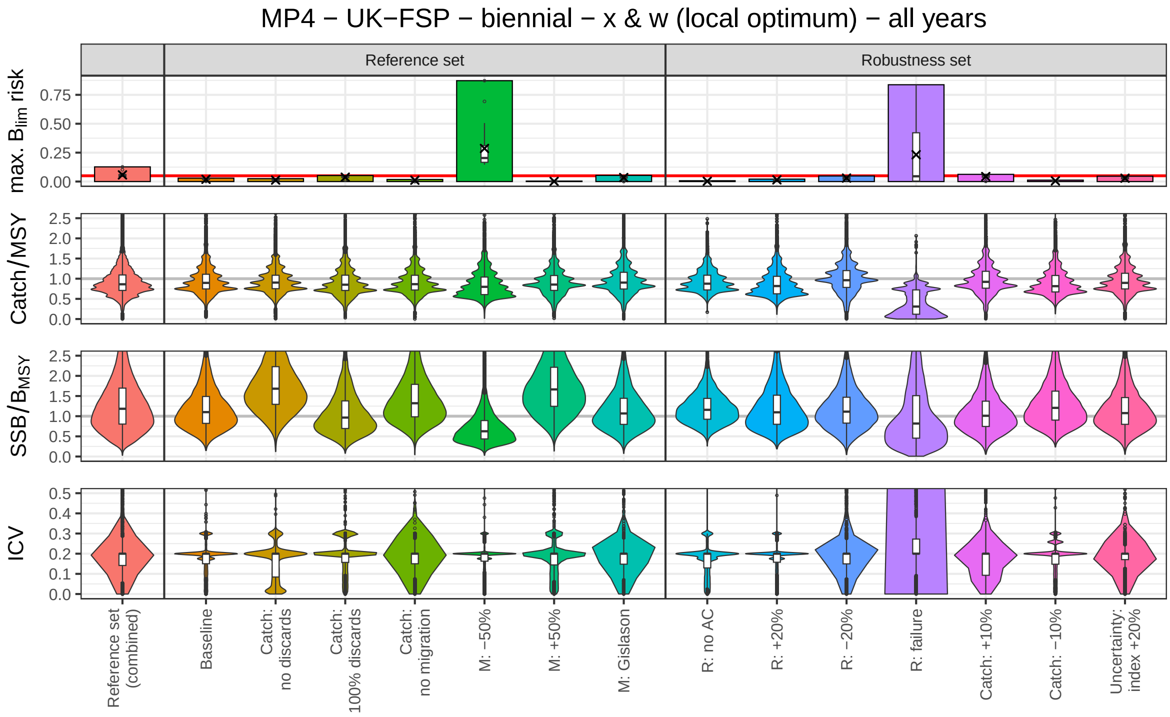


Figure S24: All years performance statistics for MP4 of Table 4 for all operating models.

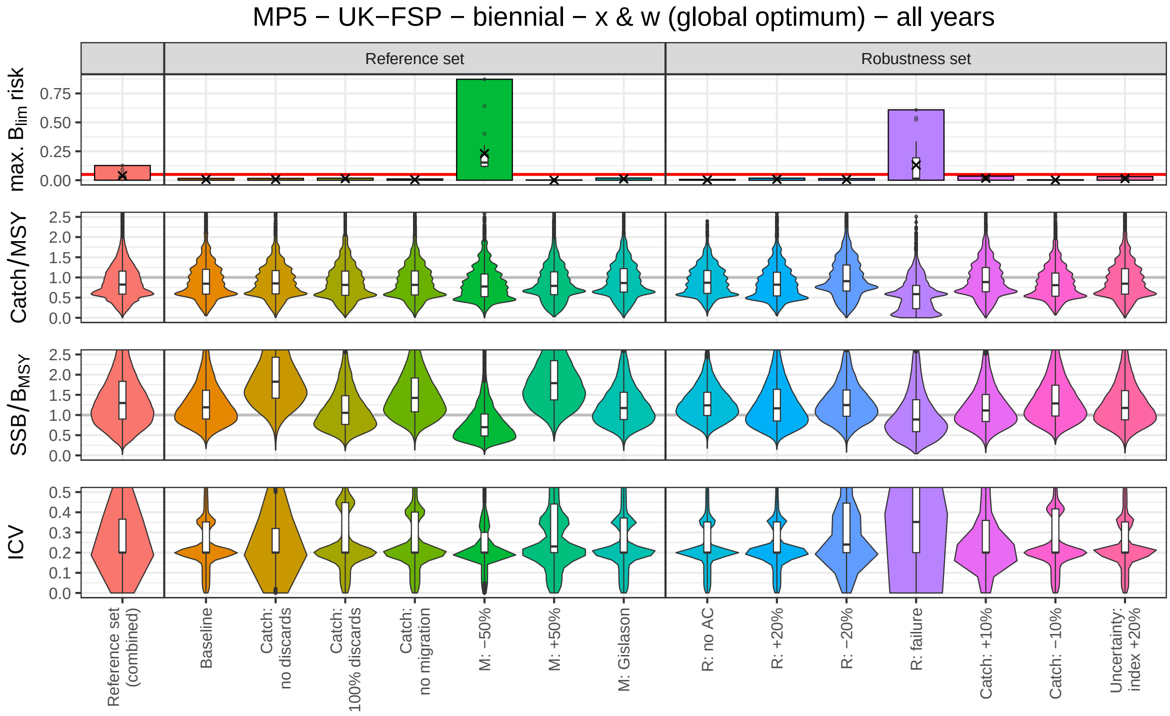


Figure S25: All years performance statistics for MP5 of Table 4 for all operating models.

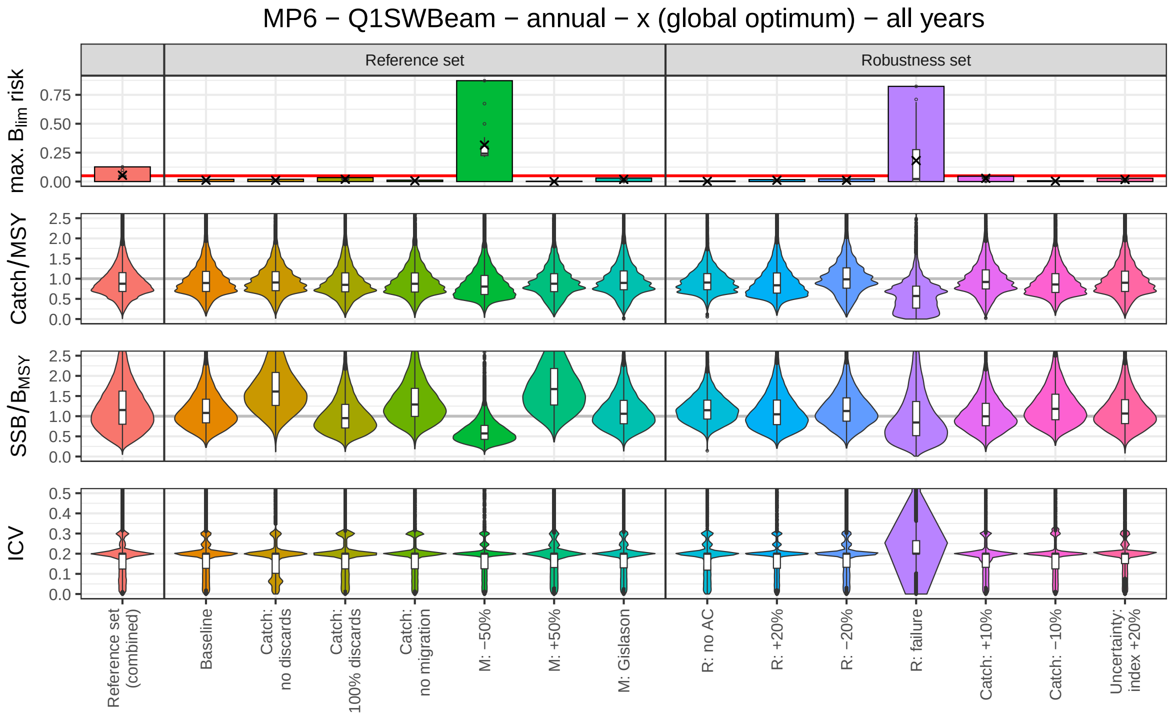


Figure S26: All years performance statistics for MP6 of Table 4 for all operating models.

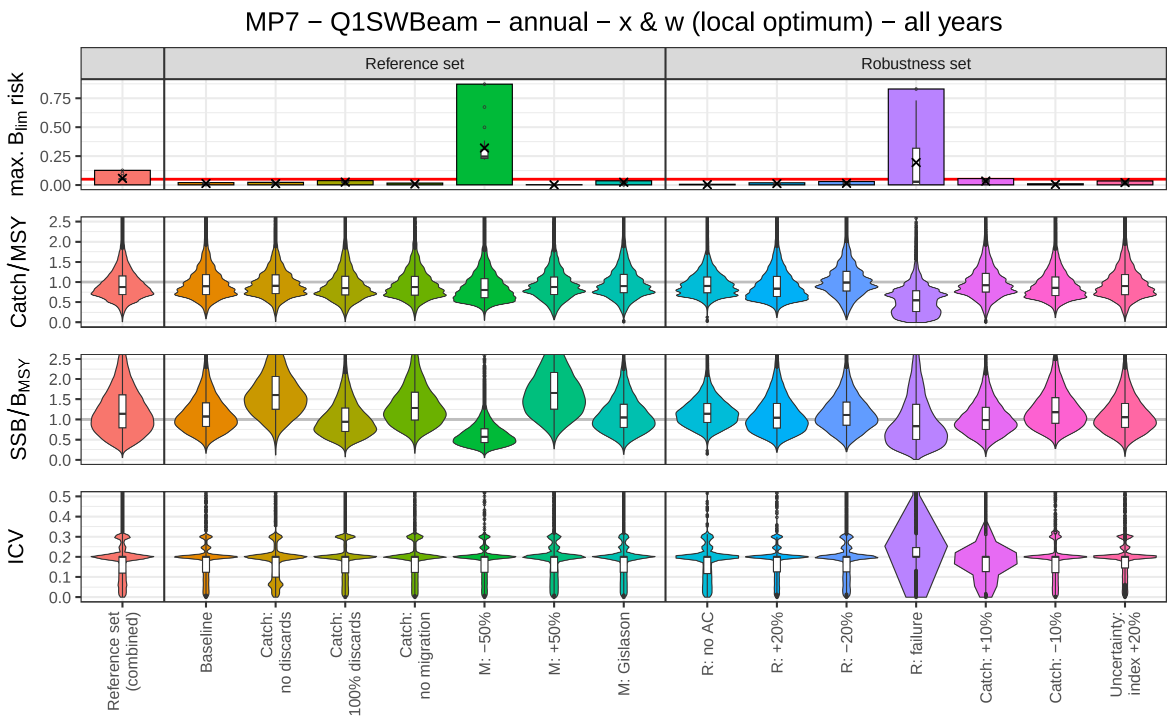


Figure S27: All years performance statistics for MP7 of Table 4 for all operating models.

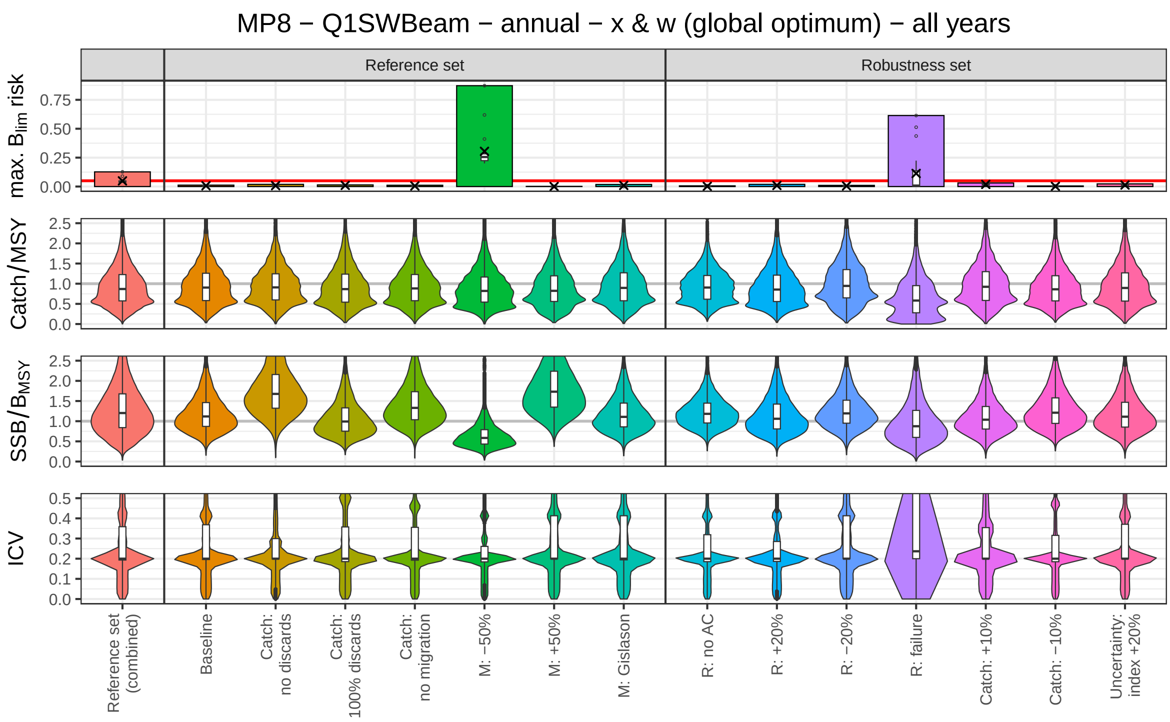


Figure S28: All years performance statistics for MP8 of Table 4 for all operating models.

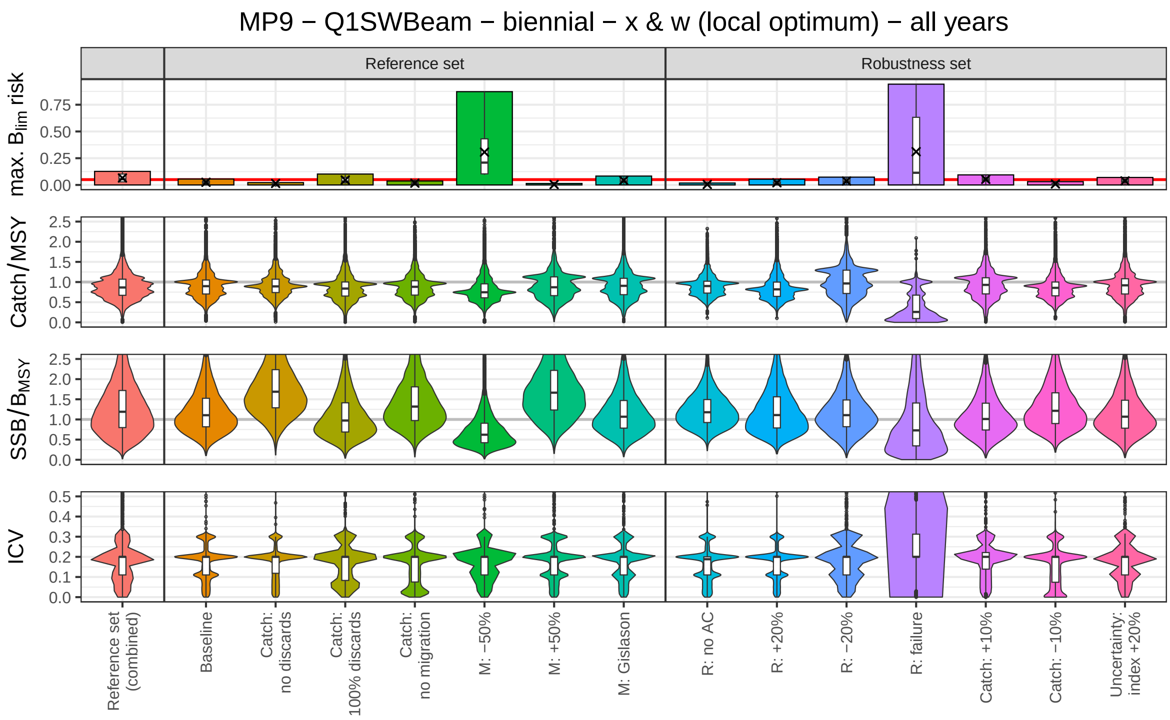


Figure S29: All years performance statistics for MP9 of Table 4 for all operating models.

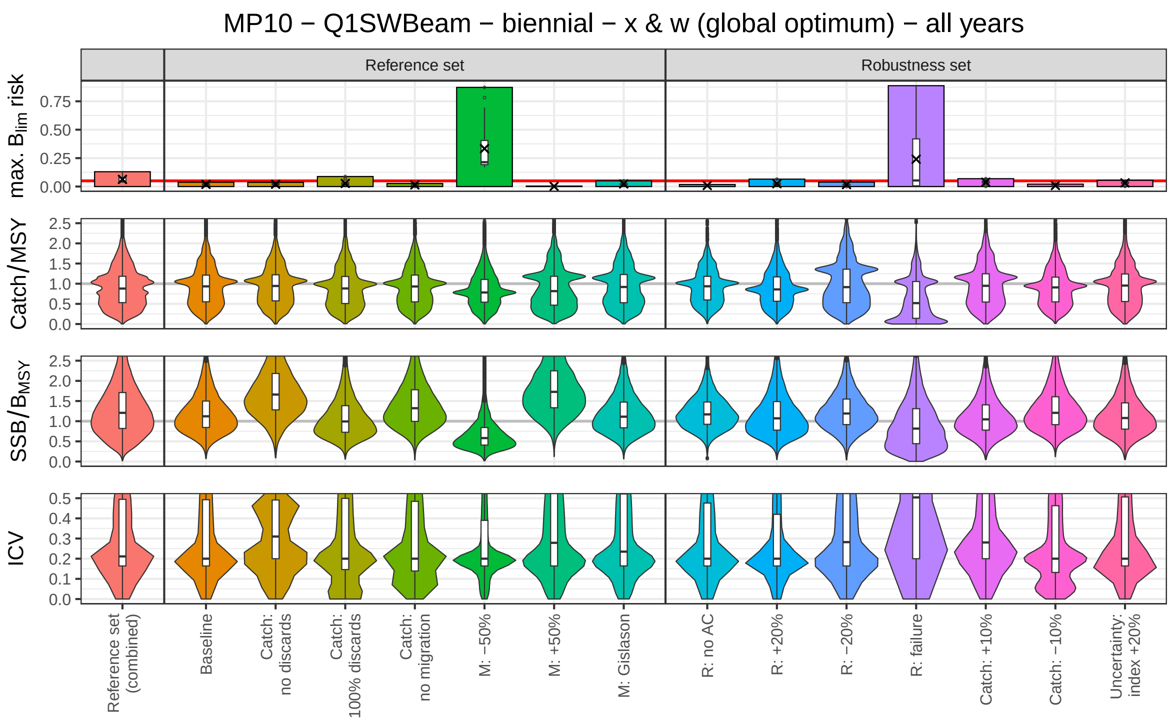


Figure S30: All years performance statistics for MP10 of Table 4 for all operating models.

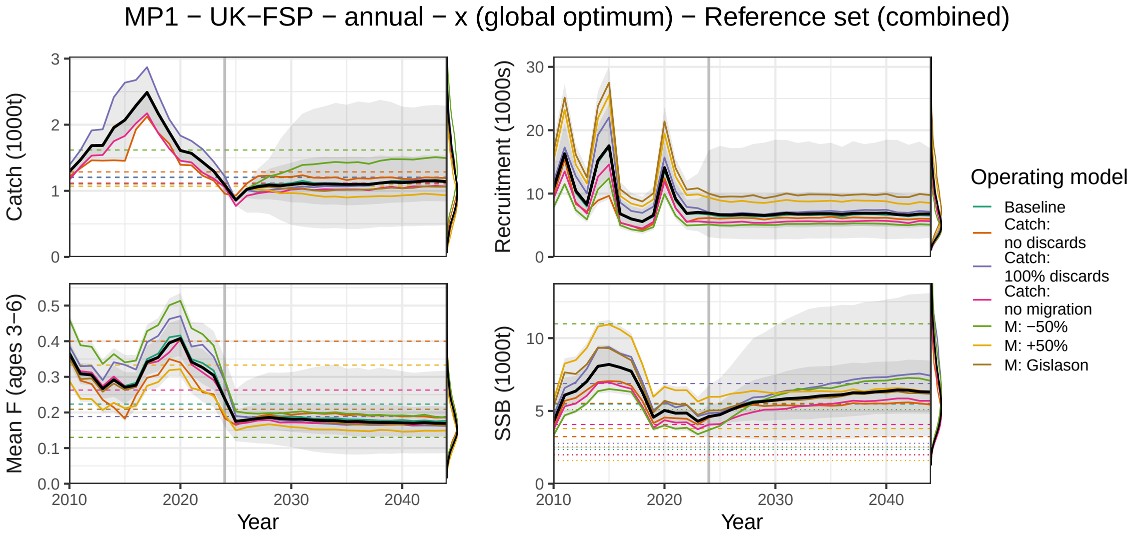
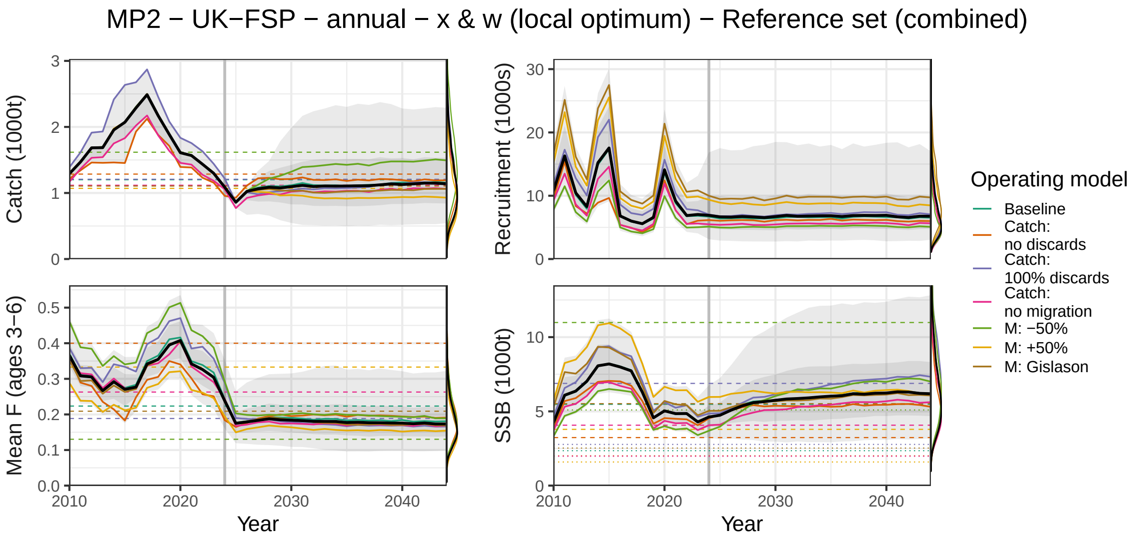


Figure S31: Reference set. MSE trajectories corresponding to MP1 in Table 4). See Figure 11 for details.



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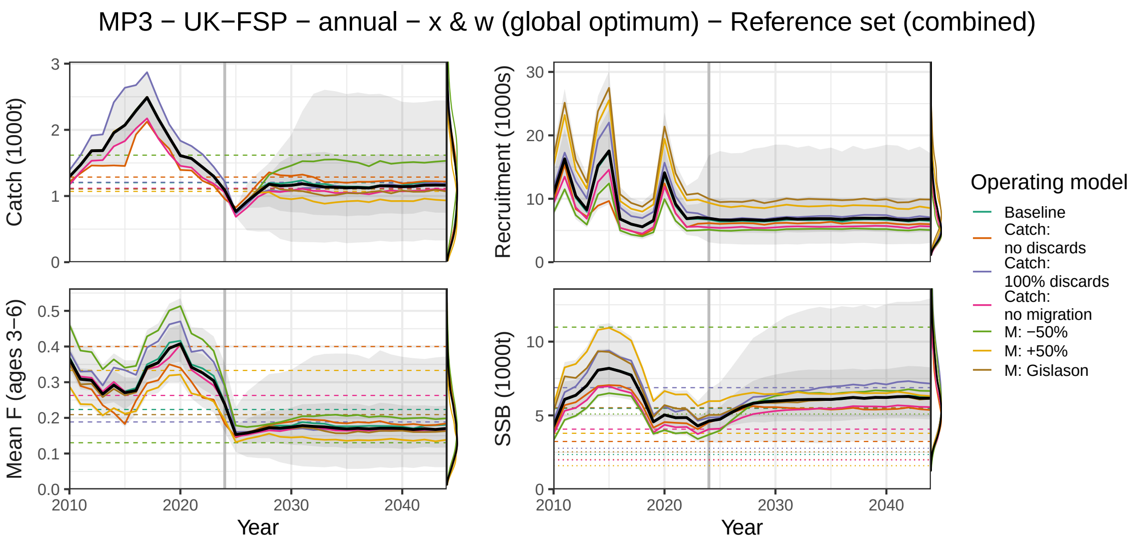

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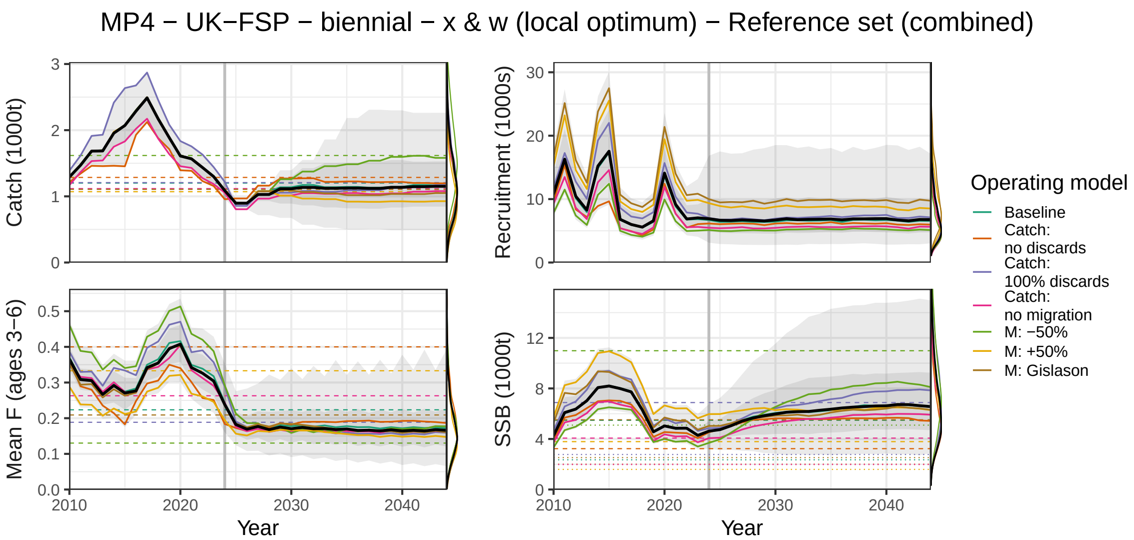

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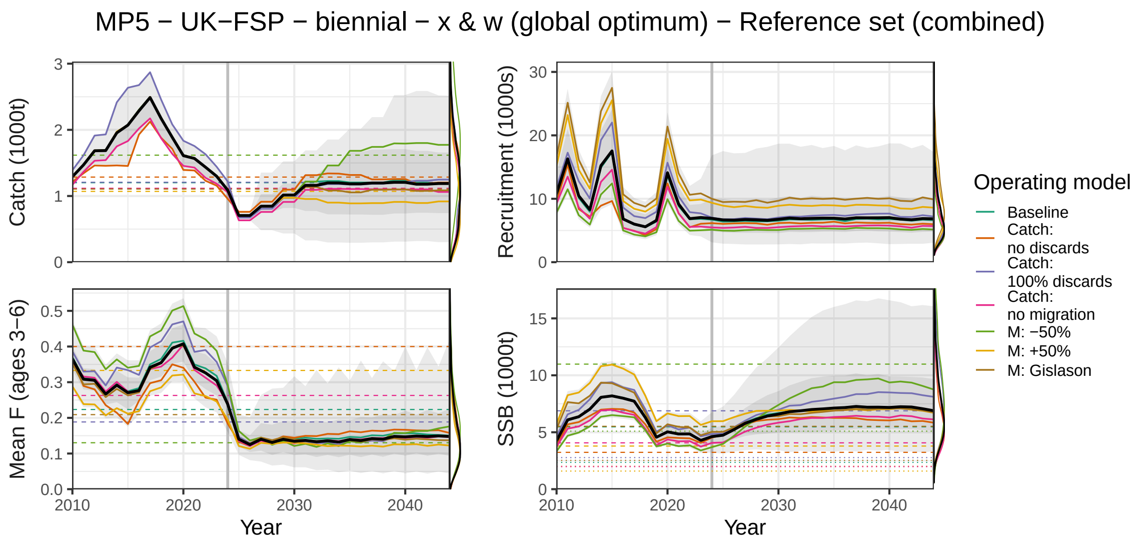

Figure S35: Reference set. MSE trajectories corresponding to MP5 in Table 4). See Figure 11 for details.

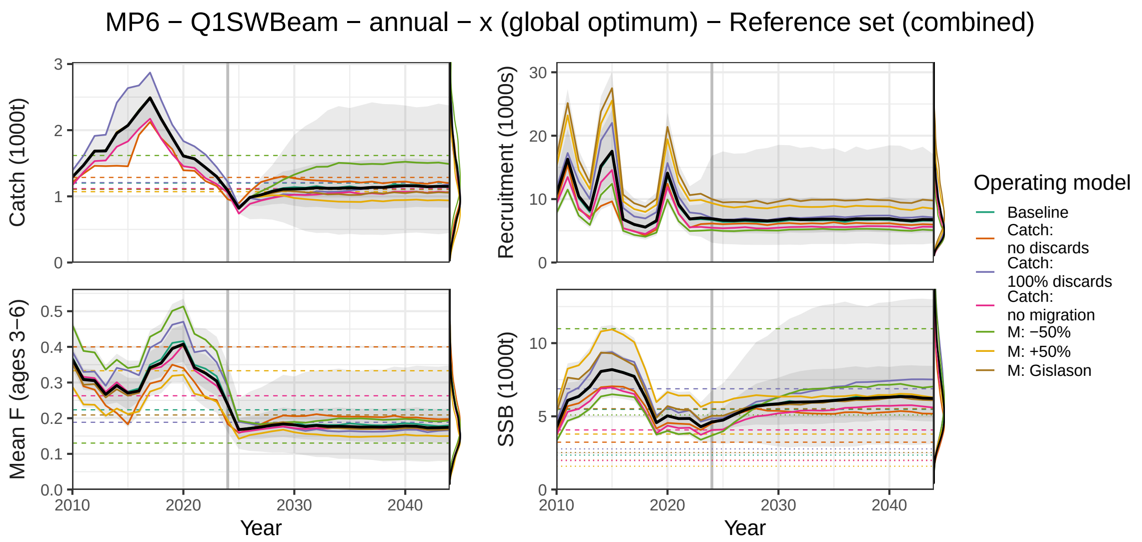

Figure S36: Reference set. MSE trajectories corresponding to MP6 in Table 4). See Figure 11 for details.

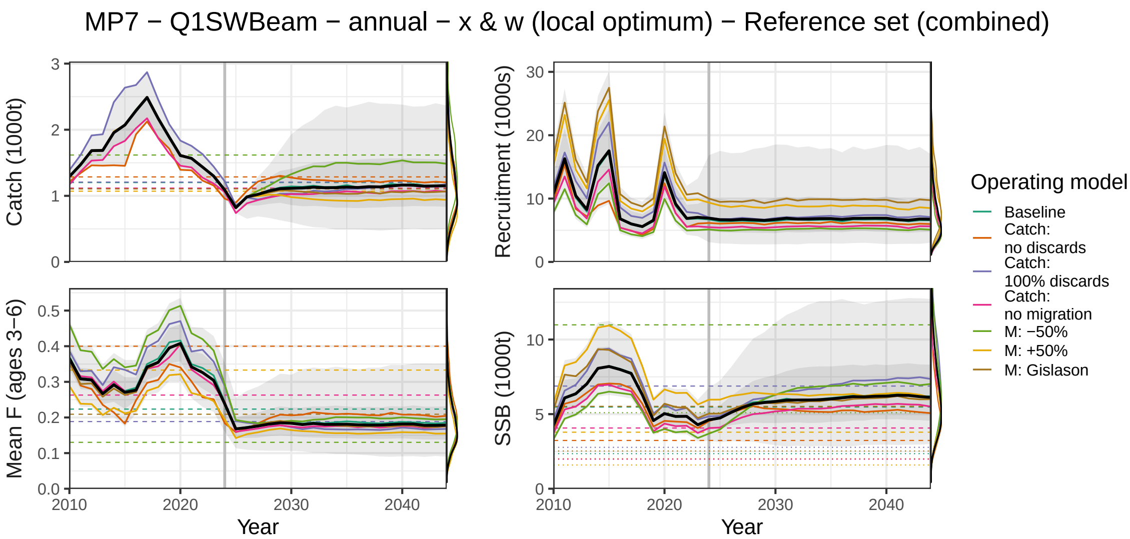

Figure S37: Reference set. MSE trajectories corresponding to MP7 in Table 4). See Figure 11 for details.

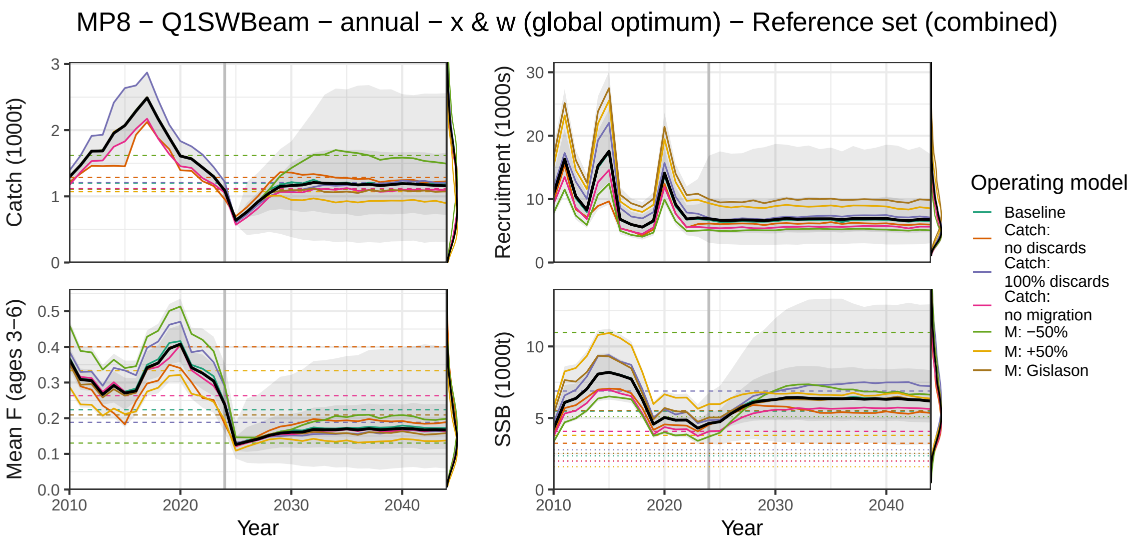

Figure S38: Reference set. MSE trajectories corresponding to MP8 in Table 4). See Figure 11 for details.

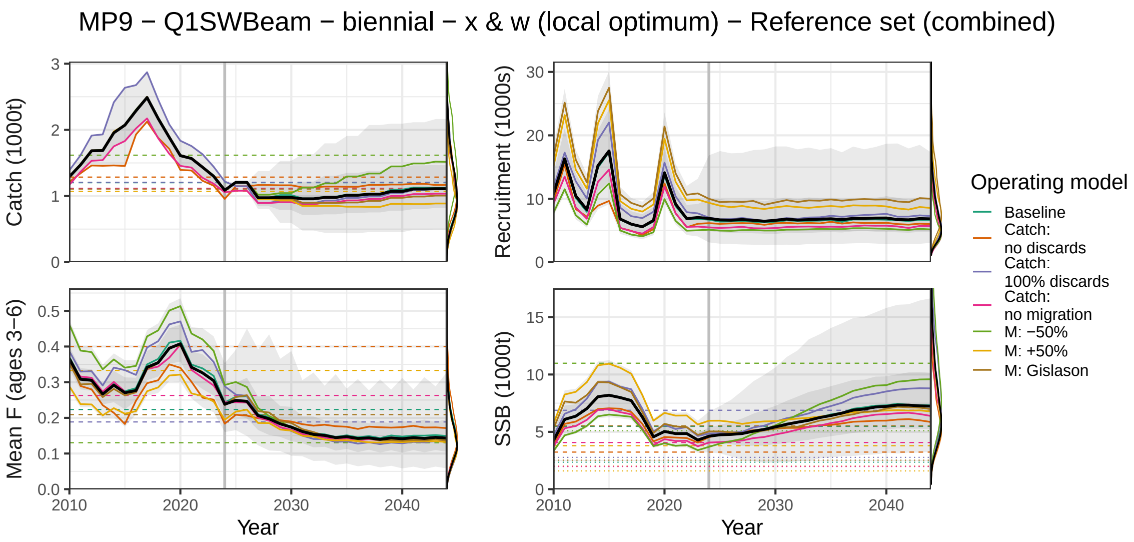

Figure S39: Reference set. MSE trajectories corresponding to MP9 in Table 4). See Figure 11 for details.

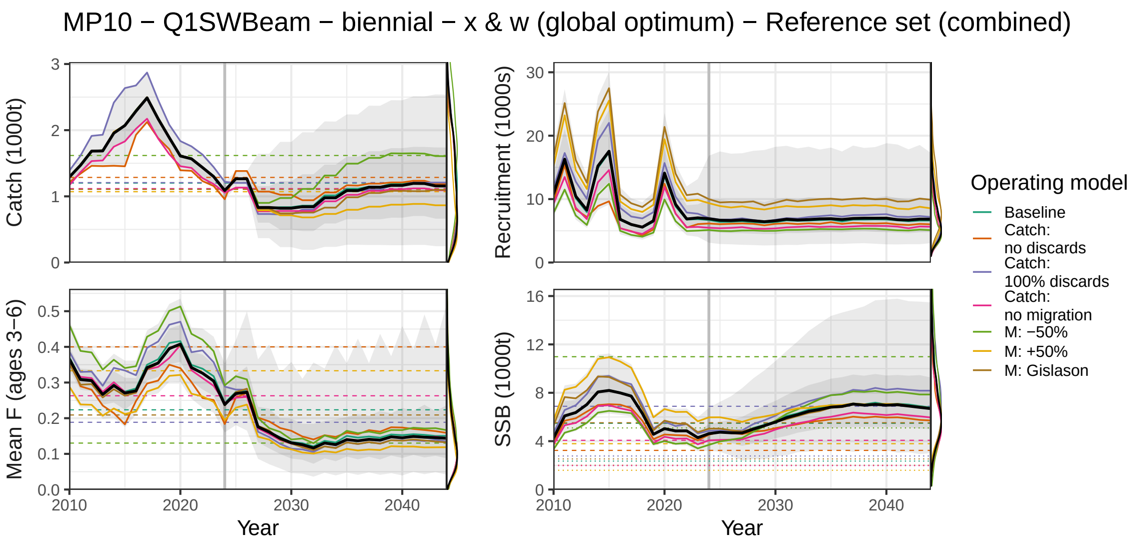

Figure S40: Reference set. MSE trajectories corresponding to MP10 in Table 4). See Figure 11 for details.

Table S1: Links to trajectory plots for the optimised chr rule versions and all operating models. The management procedure identifiers (MP1–10) correspond to those defined in Table 4.

Operating model										
Baseline	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Catch: no discards	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Catch: 100% discards	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Catch: no migration	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
M: -50%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
M: -50%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
M: Gislason	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
R: no AC	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
R: +20%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
R: -20%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
R: failure	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Catch: +10%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Catch: -10%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Uncertainty: index +20%	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10

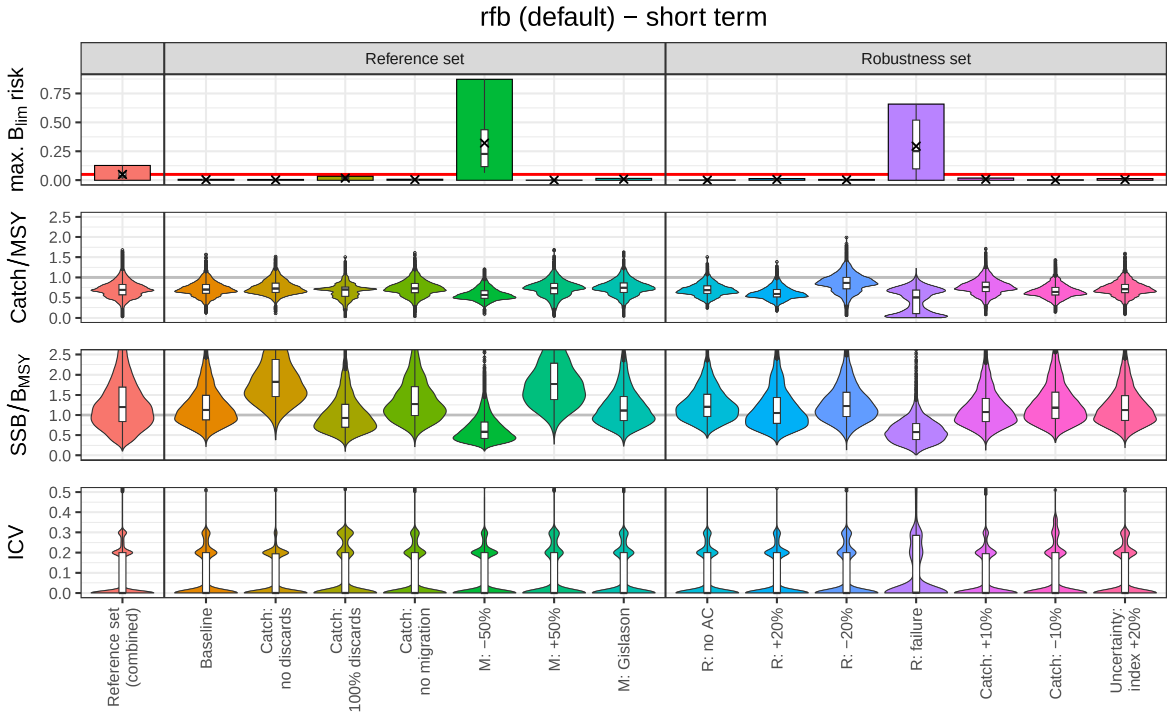

Figure S41: rfb rule. Short-term performance statistics for all operating models. See Figure 10 for details.

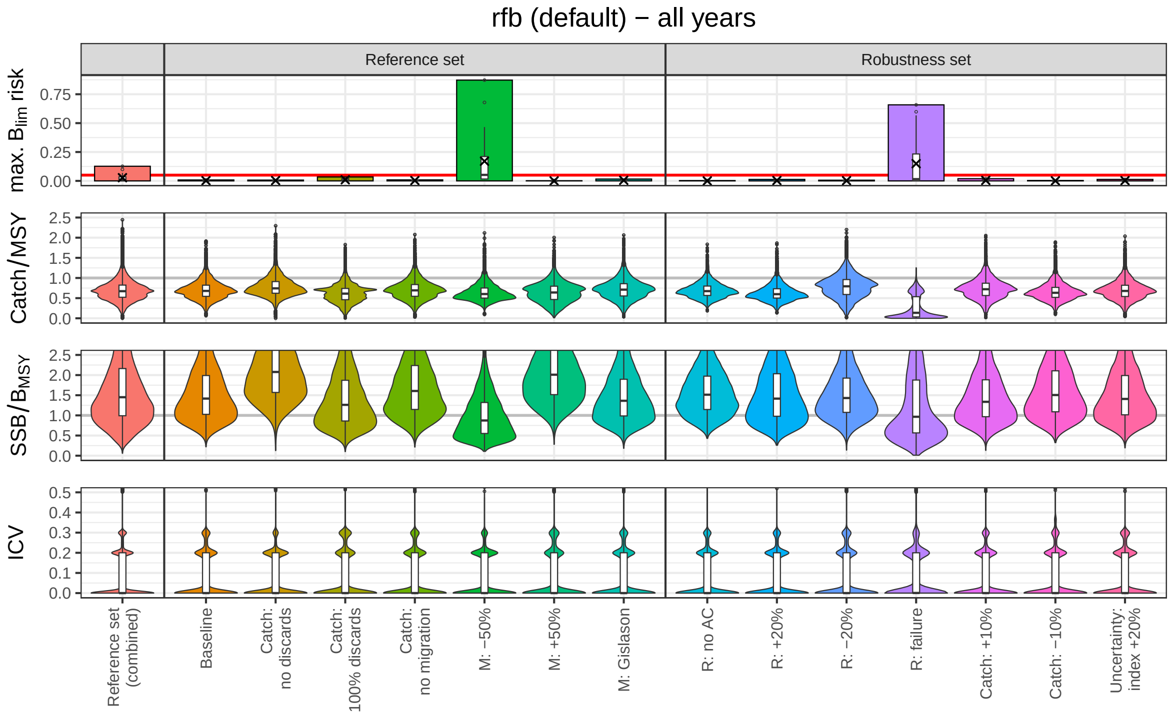

Figure S42: rfb rule. Short-term performance statistics for all operating models. See Figure 10 for details.

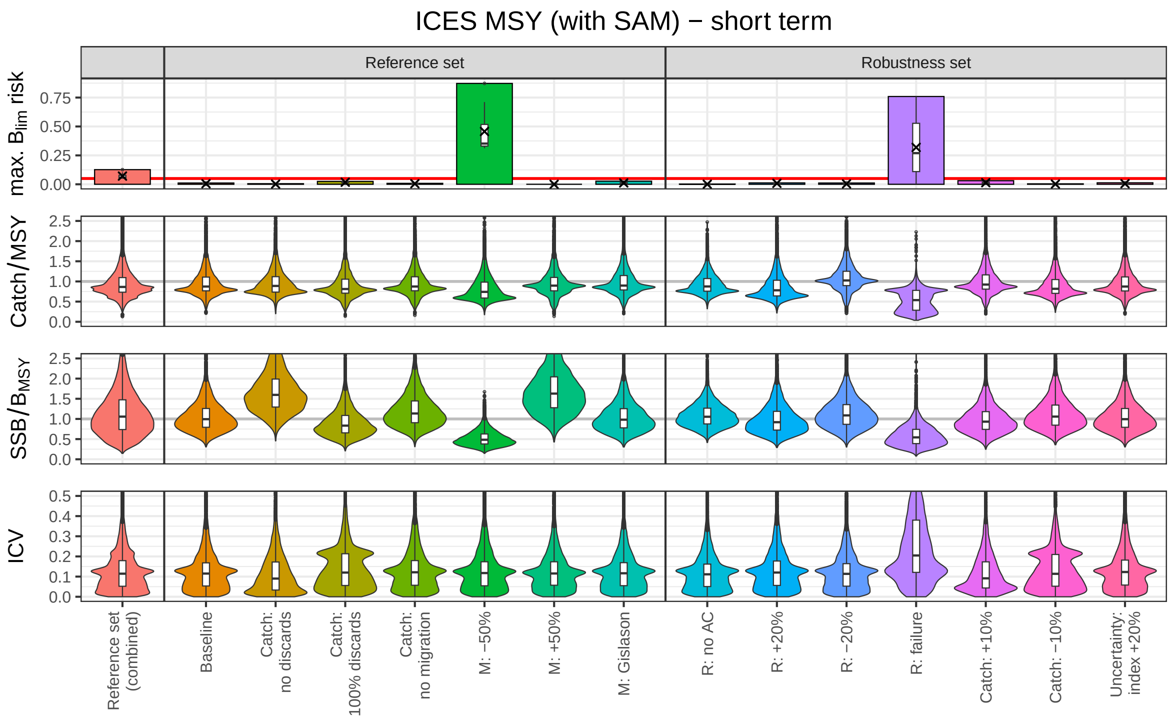

Figure S43: ICES MSY rule. All years performance statistics for all operating models. See Figure 10 for details.

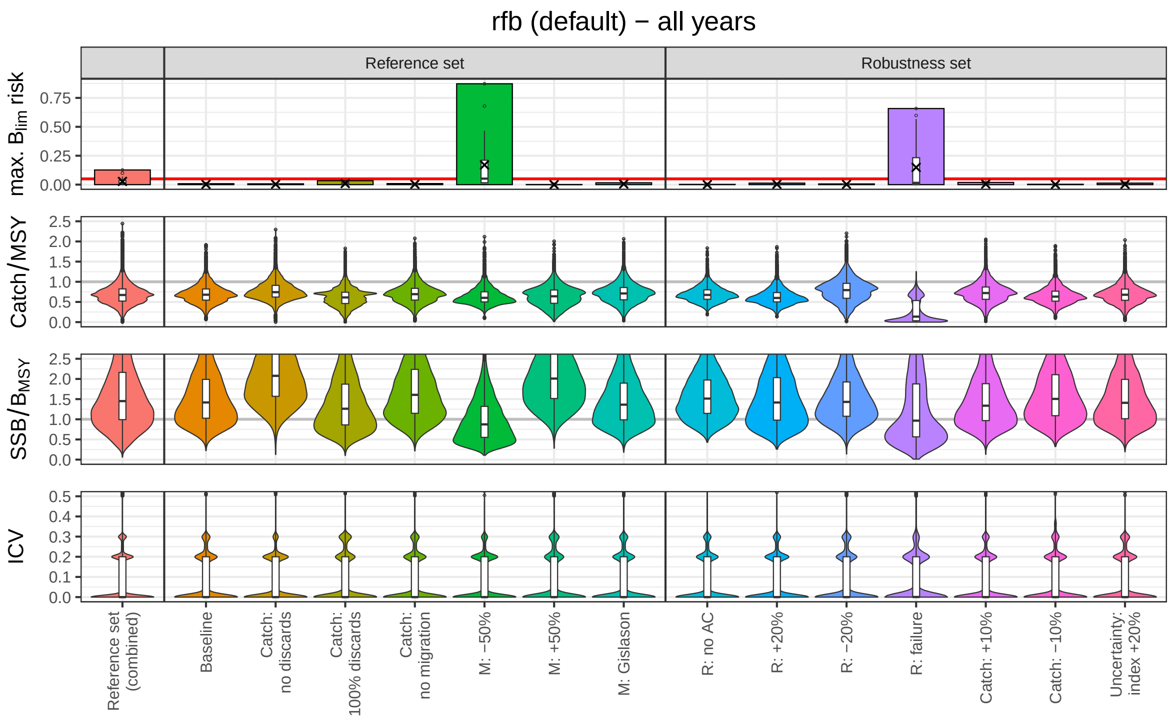

Figure S44: ICES MSY rule. All years performance statistics for all operating models. See Figure 10 for details.