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IMPACT OF UNCERTAINTY IN THE NORTH ATLANTIC SWORDFISH OPERATING MODELS ON ESTIMATED STOCK STATUS AND RELATIVE PERFORMANCE OF REFERENCE MANAGEMENT PROCEDURES

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SUMMARY

An MSE framework is being used to evaluate the performance of candidate management procedures (cMPs) for the North Atlantic Swordfish fishery. A base case operating model (OM) has been developed based on the most recent (2017) stock assessment. An uncertainty grid with systematic variations in seven key assumptions in the base case OM has been developed, resulting in an uncertainty grid with 288 OMs. This analysis examines the marginal impact the 7 axes of uncertainty have on the predicted stock dynamics, and the performance of 5 reference management procedures. The results indicate that 6 of the 7 factors have a significant impact on either the estimated stock dynamics or the likely performance of cMPs. One axis, which has two levels in the assumed coefficient of variability in the CPUE indices used in the model conditioning, did not have a significant impact on the estimated stock status and the performance of the 5 reference management procedures. These results suggest that removing this axis from the uncertainty grid would have little impact on the evaluation of candidate management procedures for this fishery.

RÉSUMÉ

Un cadre MSE est utilisé pour évaluer la performance des procédures de gestion potentielles (CMP) pour la pêcherie d'espadon de l'Atlantique Nord. Un cas de base du modèle opérationnel (« OM ») a été élaboré sur la base de l'évaluation la plus récente (2017) du stock. Une grille d'incertitude incluant des variations systématiques de sept hypothèses clés dans le cas de base de l'OM a été mise au point, donnant lieu à une grille d'incertitude comprenant 288 OM. Cette analyse examine l'impact marginal des 7 axes d'incertitude sur la dynamique prévue des stocks, et la performance de 5 procédures de gestion de référence. Les résultats indiquent que 6 des 7 facteurs ont un impact significatif soit sur la dynamique de stock estimée, soit sur la performance probable des CMP. Un axe, qui a deux niveaux dans le coefficient de variabilité postulé des indices de CPUE utilisés dans le conditionnement du modèle, n'a pas eu d'impact significatif sur l'état estimé des stocks et la performance des cinq procédures de gestion de référence. Ces résultats suggèrent que la suppression de cet axe de la grille d'incertitude n'aurait que peu d'impact sur l'évaluation des procédures de gestion potentielles pour cette pêcherie.

RESUMEN

Se está utilizando un marco de MSE para evaluar el desempeño de procedimientos de ordenación candidatos (CMP) para la pesquería de pez espada del Atlántico norte. Se ha desarrollado un caso base del modelo operativo (OM) en base a la evaluación de stock más reciente (2017). Se ha elaborado una matriz de incertidumbre con variaciones sistemáticas en siete supuestos calve en el caso base del OM, que ha dado lugar a una matriz de incertidumbre con 288 OM. Este análisis examina el impacto marginal que tienen los 7 ejes de incertidumbre en la dinámica predicha del stock y en el desempeño de los 5 procedimientos de ordenación de referencia. Los resultados indican que 6 de los 7 factores tienen un impacto significativo bien en la dinámica estimada del stock o bien en el probable desempeño de los CMP. Un eje, que tiene dos niveles en el coeficiente de variabilidad asumido en los índices de CPUE usados en el condicionamiento del modelo, no tuvo un impacto significativo en el estado estimado del stock ni en el desempeño de los 5 procedimientos de ordenación de referencia. Estos resultados sugieren que eliminar este eje de la matriz de incertidumbre tendría poco impacto en la evaluación de los procedimientos de ordenación candidatos para esta pesquería.

KEYWORDS
Management Strategy Evaluation, operating model, closed-loop simulation, performance metrics, candidate management procedures

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1. Introduction

A management strategy evaluation (MSE) approach is being used to evaluate the performance of alternative candidate management procedures (cMPs) for the North Atlantic swordfish fishery. Central to the MSE approach is the construction of operating models (OMs), which are a collection of credible hypotheses of the fishery system, including the population and fishery dynamics and the observation processes involved in collecting the fishery data. Operating models are typically generated via a process known as conditioning, where a fishery dynamics model is fitted to data collected from the fishery. Because there are often uncertainties in the assumptions of the conditioning model (e.g., values of fixed parameters) and other aspects of the fishery data, it is common that a large number of operating models are generated for the fishery, each representing a different but plausible hypothesis for the fishery dynamics. The North Atlantic swordfish MSE has followed this process, and uses a factorial design to develop an OM uncertainty grid that includes alternative assumptions in several different axes.

A base case OM was developed based on the 2017 North Atlantic swordfish stock assessment (Anon. 2017), with the following assumptions: 1) natural mortality (M) for both male and female was fixed at 0.2 for all ages classes; 2) maturity-at-age was set to 50% for age-5 and 100% for all ages greater than 5; and 3) the growth parameters were fixed at the value developed in the 2017 ICCAT swordfish data preparatory meeting. An environmental covariate was included in the model by making the catchability coefficient (q) for the Canadian, Japan, Portugal, Morocco, and Spanish fleets and the Age-1, Age-2, Age-4, and Age-5+ CPUE indices a function of the Atlantic Multidecadal Oscillation (AMO).

An operating model uncertainty grid was constructed with systematic deviations from the assumptions in the base case OM. A full factorial design was used to construct the uncertainty grid, with alternative assumed values for 7 factors.

First, three alternative values were assumed for the natural mortality rate (assumed constant for all years and age classes): 0.1, 0.2, and 0.3 y^{-1}. Second, the standard deviation for the recruitment deviations (σ_R) was assumed two values: 0.2 and 0.6. Third, steepness (h) was fixed at three levels spanning the estimated mean value used in the base case: 0.6, 0.75, and 0.9. Fourth, the CVs for all the CPUE indices were set to two values: 0.3 and 0.6. Fifth, two levels for used for effective sample size (ESS) for the length composition data: 2 and 20.

The sixth factor addressed uncertainty in the catchability coefficient used for the CPUE indices. Two levels were used: the first used the CPUE indices directly, as assumed in the base case and the 2017 assessment and in the second the CPUE indices were adjusted to account for an assumed 1% annual increase in catchability (**Figure 2**).

The final factor in the OM uncertainty grid was the inclusion of the environmental covariate for the catchability parameter for some of the fleets. The uncertainty for this factor included two levels: 1) the environmental covariate was included (same assumption as the base case OM and 2017 stock assessment) and 2) the environmental covariate was not included.

The full factorial design of the 7 factors resulted in 288 operating models in the uncertainty grid. The operating models were conditioned using Stock Synthesis 3 v3.24 (SS3; Methot and Wetzel 2013), using fishery-dependant data from 7 longline fishing fleets (**Table 1; Figure 1 & Figure 2**).

This paper has two objectives: 1) a summary of the impact of these uncertainties on the estimated stock dynamics (e.g., current stock status); and 2) an evaluation of the relative performance of reference candidate management procedures. These results may be used to rank the axes of uncertainty in terms of consequences on the predicted stock dynamics and the performance of the reference management procedures. Axes from the uncertainty grid that do not reveal a significant difference in either the predicted stock dynamics or the performance of the reference management procedures may be candidates to be removed from the uncertainty grid and added to a set of robustness OMs.

2. Methods

2.1 Impact of OM uncertainties on the estimated stock dynamics

Time-series plots of the estimated spawning stock biomass (*SB*) relative to the estimated spawning biomass corresponding to maximum sustainable yield (SB_{MSY}) are shown for each factor and level in the uncertainty grid. These results allow the marginal impact of the alternative levels in the factors on the estimated stock dynamics to be visually evaluated.

An ANOVA test was conducted to evaluate if there is a significant difference in the estimated spawning stock biomass in the most recent year (2017; SB_{2017}) relative to SB_{MSY} across the different levels for each factor. Boxplots are used to show the estimates $SB_{2017}/SB_{\mathrm{MSY}}$ for each level in the 7 factors.

2.2 Impact of OM uncertainties on performance of reference management procedures

The OM uncertainties were also evaluated with respect to their impact on the performance of the following set of reference management procedures:

1. Current Catch (curC) – the TAC is fixed at the level of the most recent catch;
2. Perfect FMSY (FMSYref) – the TAC is calculated each year so that $F = F_{\mathrm{MSY}}$;
3. Index Target 1 (Ind_1) – the TAC is calculated each year based on the ratio of the index to a target level (further details below);
4. Index Target 2 (Ind_2) – Similar to previous, see below for further details;
5. Surplus Production Model (SP_MSY) – A surplus production model is used to set the annual TAC to the level corresponding with fishing at the estimated F_{MSY}.

These reference management procedures were selected as they cover a range of typical candidate management procedures that may be proposed for the swordfish fishery (Ind_1, Ind_2, and SP_MSY) and hypothetical management options that are expected to have widely different performance (curC and FMSYref).

The Index Target methods use the combined index to calculate the annual TAC. The statistical properties of the observation error between the combined index and the historical total stock biomass was calculated within each operating model. These statistical properties were then used to generate the simulated index in the projection period by applying the observation error generated from the statistical properties to the simulated stock biomass in the future projection years.

A target index level $\left(I_{\mathrm{targ}}\right)$ was defined as the average index over the last 6 historical years (2012 – 2017; values for the combined were currently missing for 2016 & 2017). The current index level $\left(I_{\mathrm{curr}}\right)$ was calculated as in each projection year as the average index from the 3 most recent years. The TAC was calculated each year as $\mathrm{TAC}_{y+1} = \mathrm{TAC}_y \Delta_y$, where $\Delta_y = \frac{I_{\mathrm{curr}}}{I_{\mathrm{targ}}}$, with the following constraints:

1. Ind_1: Δ_y had a maximum value of 1.05 (5% increase in TAC) and minimum of 0.95 (5% decrease in TAC);
2. Ind_2: Δ_y had a maximum value of 1.10 (10% increase in TAC) and minimum of 0.90 (10% decrease in TAC).

The five reference management procedures were evaluated for each of the 288 OMs, with 20 simulations per OM and a 50-year projection period. Within each OM, the simulated stock dynamics were identical across the 20 simulations during the historical period, with stochastic recruitment deviations and index observation error in the projection years.

Performance of the reference management procedures was evaluated against 3 criteria:

1. The probability that spawning biomass (SB) is greater than $\mathrm{SB}_{\mathrm{MSY}}$ throughout the projection period;
2. The average short-term catch (first 10-years of the projection period) relative to the highest catch obtainable with a fixed-F policy;
3. The average long-term catch (last 10-years of the projection period) relative to the highest catch obtainable with a fixed-F policy.

These performance metrics were selected to evaluate the type of metrics that are generally used for evaluating performance: biological sustainability and short- and long-term catches. They do not represent the metrics that will be used to select candidate management procedures in the full MSE process for the swordfish fishery.

The marginal impact of each of the 7 factors in the uncertainty grid is presented as boxplots of the performance metrics for each management procedure. An ANOVA test was used to detect for a significant difference ($\alpha=0.05$) in the performance metrics across the levels in each factor, and across the 5 reference management procedures.

3. Results

3.1 Impact of OM uncertainties on the estimated stock dynamics

The ANOVA tests revealed that four factors (*M, h,* increase in *q*, and the environmental covariate) had a significant difference in the predicted SB_{2017}/SB_{MSY} across the levels of uncertainty (**Table 2**). The difference in predicted stock dynamics across the levels was most pronounced for *M* (**Figure 3**) and h (**Figure 5**). The marginal impact of the uncertainty factors was less pronounced for the increase in *q* (**Figure 8**) and the environmental covariate (**Figure 9)**. The time-series plots of the remaining 3 factors, recruitment variability (Figure 4), CPUE CV (Figure 6), and the effective sample size (**Figure 7**), appear almost identical and there was no significant difference in the estimated SB_{2017}/SB_{MSY} for these factors (**Table 2**).

The boxplots of the estimated SB_{2017}/SB_{MSY} show the same pattern, with the largest marginal impact on the estimated stock status from the uncertainty levels in *M* (**Figure 10**), *h* (**Figure 12**), increase in catchability (**Figure 15**), and the environmental covariate (**Figure 16**), and very similar distributions across the levels of recruitment variability (**Figure 11**), CPUE CV (**Figure 13**), and the effective sample size (**Figure 14**).

3.2 Impact of OM uncertainties on performance of reference management procedures

There was considerable difference in the performance of the 5 reference management procedures across the 3 levels of natural mortality (**Figure 17; Table 3**). The two levels of recruitment variability had the least impact on short-term yield, but there was a significant difference in the three performance across the levels for management procedures, with the exception of long-term yield for Ind_2 (**Figure 18; Table 3**). The three levels of steepness had a significant difference in all performance metrics except the short-term yield for the FMSYref and long-term yield for curC, FMSYref, and Ind_1 (**Figure 19; Table 3**).

There was no significant difference in the probability SB > SB_{MSY} and mean long-term yield for all 5 reference management procedures for OMs with CPUE CV = 0.3 and those with CPUE CV = 0.6 (**Figure 20; Table 3**). There was a significant difference in the mean short-term yield, although the distributions were quite similar between the two levels (**Figure 20**).

The two levels of effective sample size resulted in significant difference in performance of the 5 reference management procedures, except for long-term yield for FMSYref and Ind_2 (**Figure 21; Table 3**).

Similarly, the two levels of increase in catchability resulted in a significant difference in performance for all 5 management procedures, except for short-term yield for curC and long-term yield for Ind_2 (**Figure 22; Table 3**). Finally, the two levels of environmental covariate had little impact on the long-term yield, but a significant difference in the probability of SB>SB_{MSY} for all 5 management procedures (**Figure 23; Table 3**).

4. Discussion

This paper evaluated the marginal impact of the axes of uncertainty on the predicted stock dynamics and the performance of a set of reference management procedures. The results demonstrate that the uncertainty in natural mortality (*M*) and steepness (*h*) are most consequential in terms of the predicted stock dynamics and the performance of the management procedures. The axes with the increase in catchability and the environmental covariate resulted in a significant difference in estimated stock status between the levels, and different performance of the reference management procedures, particularly for the performance metric related to SB>SB_{MSY}.

The two levels of recruitment variability resulted in similar estimates of current stock status. However, the performance of the reference management procedures varied across the levels in this axis, with OMs with the lower recruitment variability (0.2) resulting in higher probability of SB>SB_{MSY} and higher average long-term yield. Likewise, the two levels of effective sample size (ESS) resulted in similar estimates of current stock status, but a significant difference in performance of most of the management procedures, with the OMs with ESS = 2 generally resulting in higher probability of SB>SB_{MSY} and higher short-term and long-term yield.

The axis with two levels of CPUE CV was the only one of the 7 factors that did not result in significant difference in the estimated stock status and had no significant difference in the probability SB > SB_{MSY} and mean long-term yield for the 5 reference management procedures. This result suggests that this axis of uncertainty is inconsequential in terms of the predicted stock dynamics and the likely performance of candidate management procedures.

One potential shortcoming of this analysis is that it did not examine the interactions between the axes of uncertainty. Given the multiple levels for 7 factors, it was not possible to evaluate all of the interactions between the factors within the scope of this analysis. Interactions between some of the factors, such as natural mortality and steepness, are visible in the time-series plots. However, the significant difference in the marginal evaluation of these factors is sufficient to warrant their inclusion in the uncertainty grid. Further work could be conducted to evaluate interaction between the CPUE CV factor, which was marginally inconsequential, and the other factors in the uncertainty grid. Alternatively, the CPUE CV factor could be moved from the uncertainty grid to a set of robustness OMs.

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Table 1. Summary of the fishing fleets, data types, and time periods for the fishery data used to condition the operating models for the North Atlantic swordfish MSE.

Code	Description	Time Period	Data
SPN_1	Spanish Longline	1950 - 2017	Catch, CPUE, Length Comp.
US_2	US Longline Observer Fleet	1950 - 2017	Catch, CPUE, Length Comp., Mean Weight
CAN_ERLY_5	Canada Longline - Early	1950 - 1978	Catch, CPUE
CAN_LATE_4	Canada Longline - Late	1979 - 2017	Catch, CPUE, Length Comp., Mean Weight
JPN_ERLY_5	Japan - Early	1957 - 2005	Catch, CPUE, Length Comp.
JPN_MID_6	Japan - Mid	2006 - 2010	Catch, CPUE, Length Comp.
JPN_LATE_7	Japan - Late	2011 - 2017	Catch, CPUE, Length Comp.
PORT_8	Portugal	1964 - 2017	Catch, CPUE, Length Comp.
CHIN-TAI_9	Chinese-Taipai	1963 - 2017	Catch, Length Comp.
MOR_10	Morocco	1961 - 2017	Catch, CPUE, Length Comp.
OTH_11	Other	1957 - 2017	Catch
Age-1	Age-1 CPUE from Spanish Fleet	1982 - 2015	CPUE
Age-2	Age-2 CPUE from Spanish Fleet	1982 - 2015	CPUE
Age-3	Age-3 CPUE from Spanish Fleet	1982 - 2015	CPUE
Age-4	Age-4 CPUE from Spanish Fleet	1982 - 2015	CPUE
Age-5+	Age-5+ CPUE from Spanish Fleet	1982 - 2015	CPUE

Table 2. The mean and standard deviation of the estimated stock status (SB/SB_{MSY} in 2017) for each factor and level in the 288 operating models in the uncertainty grid for the North Atlantic swordfish. Factors that have a significant difference (P<.05) in estimated stock status across the levels are indicated with a * (ANOVA).

Factor	Level	Mean	Standard Deviation
Natural Mortality (M)*	0.1	0.706	0.191
	0.2	1.06	0.331
	0.3	1.57	0.655
Recruitment Variability (sigmaR)	0.2	1.14	0.567
	0.6	1.08	0.559
Steepness (h)*	0.6	0.886	0.282
	0.75	1.01	0.395
	0.90	1.44	0.745
CPUE CV	0.3	1.09	0.503
	0.6	1.13	0.619
Effective Sample Size (ESS)	2	1.13	0.459
	20	1.10	0.652
Increase in Catchability*	FALSE	1.32	0.613
	TRUE	0.906	0.418
Environmental Covariate*	FALSE	1.23	0.617
	TRUE	0.998	0.479

Table 3. The mean (standard deviation) of the three performance metrics of the 5 reference management procedures, calculated across the 288 Operating Models (OMs) for each level of the 7 factors in the uncertainty grid. Factors where there was a significant difference in the performance metrics are indicated with a superscript *. Grey shaded cells indicate results where there was no significant difference in the relevant performance metric between OMs with different levels of a factor. There was no significant difference in the first and third performance metrics for all 5 reference management procedures for OMs with CPUE CV = 0.3 and those with CPUE CV = 0.6.

Factor	Level	Performance Metric	Management Procedure – mean (standard deviation)				
			curC	FMSYref	Ind_1	Ind_2	SP_MSY
Natural Mortality	0.1	Prob. SB>SBMSY	0.16 (0.25)*	0.12 (0.1)*	0.45 (0.21)*	0.51 (0.12)*	0.33 (0.26)*
	0.2		0.59 (0.32)*	0.34 (0.14)*	0.68 (0.16)*	0.63 (0.12)*	0.7 (0.26)*
	0.3		0.81 (0.22)*	0.43 (0.1)*	0.8 (0.14)*	0.75 (0.12)*	0.88 (0.16)*
	0.1	Mean Short-Term Yield (t)	1.06 (0.16)*	0.8 (0.2)*	0.89 (0.09)	0.74 (0.08)*	0.88 (0.13)*
	0.2		0.98 (0.1)*	1.1 (0.19)*	0.86 (0.08)	0.78 (0.09)*	0.95 (0.08)*
	0.3		0.9 (0.12)*	1.3 (0.21)*	0.87 (0.12)	0.86 (0.14)*	0.95 (0.1)*
	0.1	Mean Long-Term Yield (t)	0.42 (0.39)*	0.99 (0.01)*	0.89 (0.36)*	1.09 (0.31)*	0.99 (0.08)*
	0.2		0.76 (0.2)*	0.99 (0.01)*	0.9 (0.14)*	0.69 (0.17)*	0.97 (0.06)*
	0.3		0.81 (0.08)*	0.98 (0.01)*	0.7 (0.14)*	0.54 (0.12)*	0.82 (0.1)*
Recruitment Variability	0.2	Prob. SB>SBMSY	0.59 (0.4)*	0.33 (0.19)*	0.74 (0.19)*	0.68 (0.16)*	0.71 (0.32)*
	0.6		0.45 (0.34)*	0.26 (0.14)*	0.56 (0.22)*	0.58 (0.13)*	0.57 (0.32)*
	0.2	Mean Short-Term Yield (t)	0.93 (0.09)*	1.01 (0.19)*	0.82 (0.05)*	0.74 (0.05)*	0.9 (0.06)*
	0.6		1.02 (0.17)*	1.13 (0.34)*	0.92 (0.1)*	0.85 (0.14)*	0.96 (0.14)*
	0.2	Mean Long-Term Yield (t)	0.74 (0.29)*	0.99 (0)*	0.95 (0.2)*	0.8 (0.33)	0.91 (0.07)*
	0.6		0.59 (0.31)*	0.98 (0.01)*	0.72 (0.25)*	0.75 (0.31)	0.94 (0.13)*
Steepness	0.6	Prob. SB>SBMSY	0.35 (0.34)*	0.25 (0.17)*	0.58 (0.23)*	0.6 (0.16)*	0.5 (0.32)*
	0.75		0.52 (0.37)*	0.29 (0.17)*	0.64 (0.21)*	0.62 (0.14)*	0.64 (0.31)*
	0.9		0.69 (0.36)*	0.34 (0.16)*	0.72 (0.21)*	0.68 (0.16)*	0.78 (0.29)*
	0.6	Mean Short-Term Yield (t)	1.09 (0.14)*	1.04 (0.3)	0.93 (0.1)*	0.83 (0.12)*	1 (0.1)*
	0.75		0.96 (0.09)*	1.05 (0.28)	0.87 (0.07)*	0.79 (0.12)*	0.92 (0.09)*
	0.9		0.87 (0.1)*	1.11 (0.28)	0.82 (0.07)*	0.77 (0.12)*	0.86 (0.09)*
	0.6	Mean Long-Term Yield (t)	0.61 (0.34)	0.99 (0.01)	0.84 (0.23)	0.9 (0.32)*	0.95 (0.07)*
	0.75		0.68 (0.3)	0.99 (0.01)	0.85 (0.26)	0.76 (0.31)*	0.93 (0.09)*
	0.9		0.7 (0.27)	0.98 (0.01)	0.81 (0.27)	0.66 (0.28)*	0.9 (0.14)*
CPUE CV	0.3	Prob. SB>SBMSY	0.51 (0.37)	0.3 (0.17)	0.65 (0.21)	0.64 (0.15)	0.64 (0.31)
	0.6		0.53 (0.39)	0.3 (0.18)	0.64 (0.24)	0.63 (0.16)	0.63 (0.34)

Factor	Level	Performance Metric	Management Procedure – mean (standard deviation)				
			curC	**FMSYref**	**Ind_1**	**Ind_2**	**SP_MSY**
	0.3	Mean	1 (0.14) *	1.09 (0.28)	0.89 (0.1) *	0.81 (0.13) *	0.95 (0.11) *
	0.6	Short-Term Yield (t)	0.96 (0.15) *	1.05 (0.29)	0.86 (0.09) *	0.78 (0.1) *	0.91 (0.11) *
	0.3	Mean	0.68 (0.29)	0.99 (0.01)	0.84 (0.25)	0.77 (0.32)	0.93 (0.1)
	0.6	Long-Term Yield (t)	0.64 (0.32)	0.99 (0.01)	0.83 (0.26)	0.78 (0.32)	0.92 (0.11)
Effective Sample Size	2	Prob.	0.58 (0.33) *	0.32 (0.16) *	0.69 (0.18) *	0.66 (0.14) *	0.71 (0.26) *
	20	SB>SBMSY	0.46 (0.42) *	0.27 (0.18) *	0.6 (0.26) *	0.6 (0.16) *	0.56 (0.37) *
	2	Mean	0.99 (0.12)	1.16 (0.24) *	0.9 (0.09) *	0.83 (0.11) *	0.97 (0.1) *
	20	Short-Term Yield (t)	0.96 (0.16)	0.98 (0.3) *	0.84 (0.09) *	0.76 (0.12) *	0.89 (0.11) *
	2	Mean	0.79 (0.16) *	0.99 (0.01) *	0.88 (0.19) *	0.77 (0.3)	0.94 (0.1) *
	20	Long-Term Yield (t)	0.54 (0.37) *	0.99 (0.01) *	0.79 (0.3) *	0.78 (0.34)	0.91 (0.11) *
Increase in catchability	FALSE	Prob.	0.63 (0.37) *	0.35 (0.18) *	0.72 (0.2) *	0.69 (0.14) *	0.73 (0.31) *
	TRUE	SB>SBMSY	0.41 (0.36) *	0.24 (0.15) *	0.57 (0.22) *	0.57 (0.14) *	0.54 (0.32) *
	FALSE	Mean	0.99 (0.12)	1.16 (0.24) *	0.9 (0.09) *	0.83 (0.11) *	0.97 (0.1) *
	TRUE	Short-Term Yield (t)	0.96 (0.16)	0.98 (0.3) *	0.84 (0.09) *	0.76 (0.12) *	0.89 (0.11) *
	FALSE	Mean	0.79 (0.16) *	0.99 (0.01) *	0.88 (0.19) *	0.77 (0.3)	0.94 (0.1) *
	TRUE	Long-Term Yield (t)	0.54 (0.37) *	0.99 (0.01) *	0.79 (0.3) *	0.78 (0.34)	0.91 (0.11) *
Environmental Covariate	FALSE	Prob.	0.58 (0.38) *	0.33 (0.18) *	0.68 (0.22) *	0.66 (0.16) *	0.68 (0.32) *
	TRUE	SB>SBMSY	0.46 (0.38) *	0.27 (0.16) *	0.61 (0.23) *	0.6 (0.15) *	0.59 (0.33) *
	FALSE	Mean	0.97 (0.15)	1.14 (0.31) *	0.88 (0.1)	0.82 (0.13) *	0.94 (0.12) *
	TRUE	Short-Term Yield (t)	0.98 (0.14)	1 (0.25) *	0.86 (0.09)	0.78 (0.1) *	0.91 (0.1) *
	FALSE	Mean	0.7 (0.29) *	0.99 (0.01) *	0.84 (0.24)	0.78 (0.32)	0.92 (0.12)
	TRUE	Long-Term Yield (t)	0.63 (0.32) *	0.99 (0.01) *	0.83 (0.27)	0.78 (0.32)	0.93 (0.1)

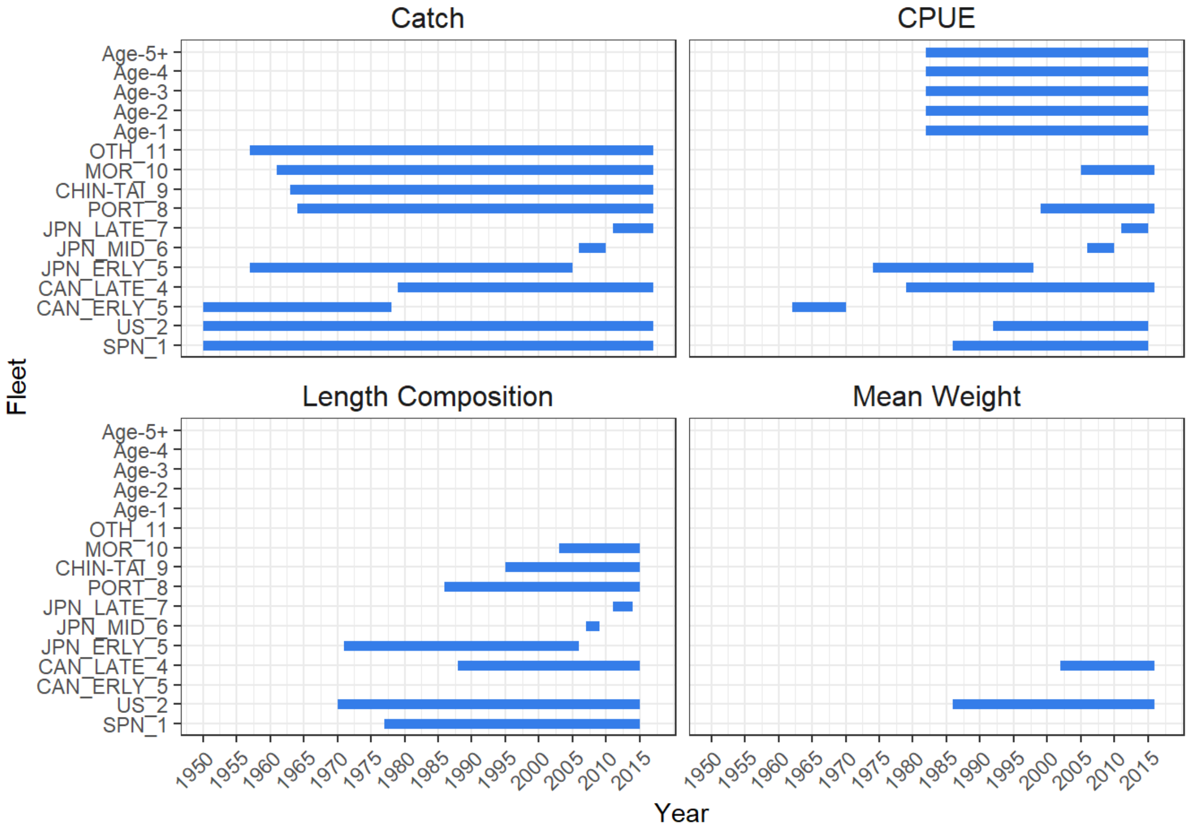

Figure 1. The time periods for the data used to condition the operating models for the North Atlantic swordfish MSE. See **Table 1** for description of the fleets.

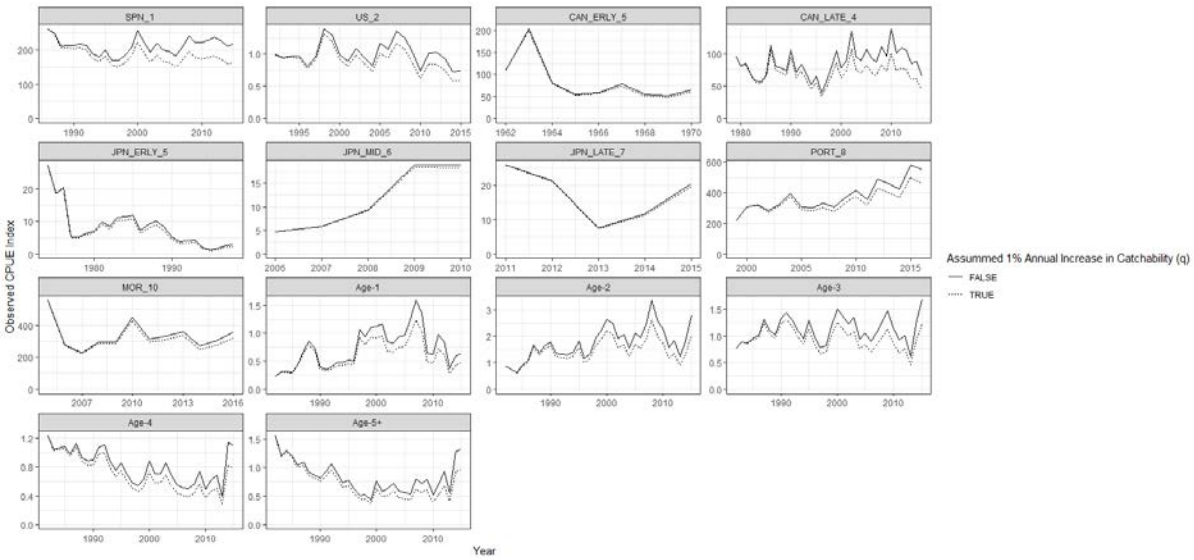

Figure 2. The CPUE indices used in conditioning the North Atlantic swordfish operating models. The dashed black lines show the CPUE indices that were adjusted to account for an assumed 1% annual increase in catchability, which was included as an axis of uncertainty in the OM uncertainty grid. See **Table 1** for description of the fleets.

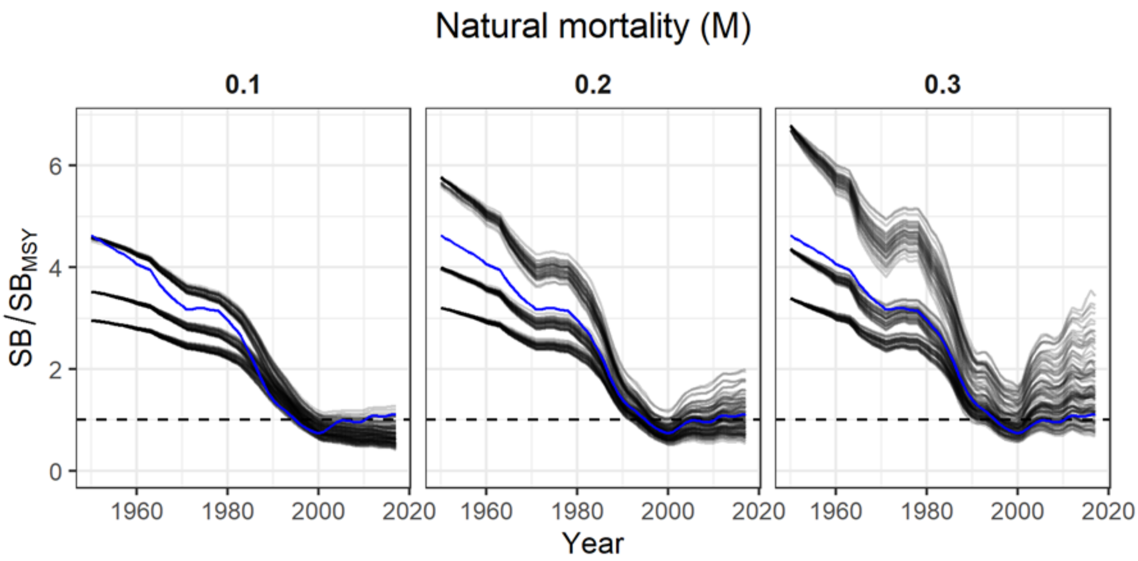

Figure 3. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the three levels of natural mortality in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

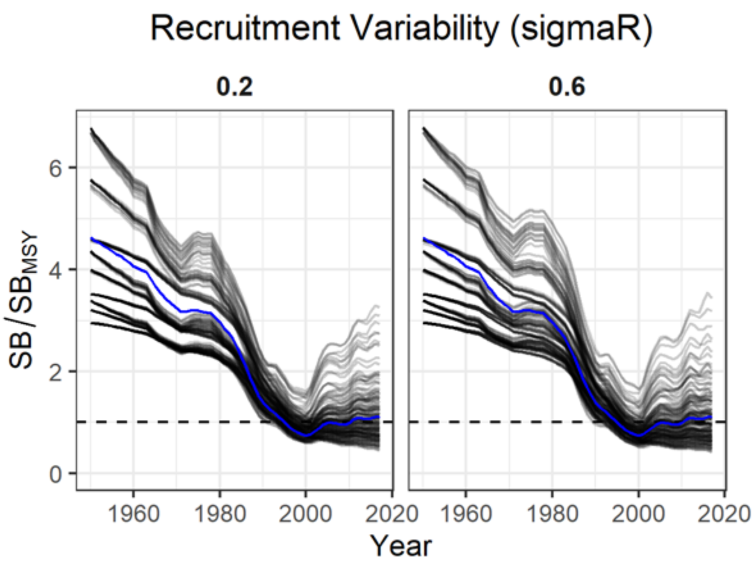

Figure 4. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the two levels of recruitment variability in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

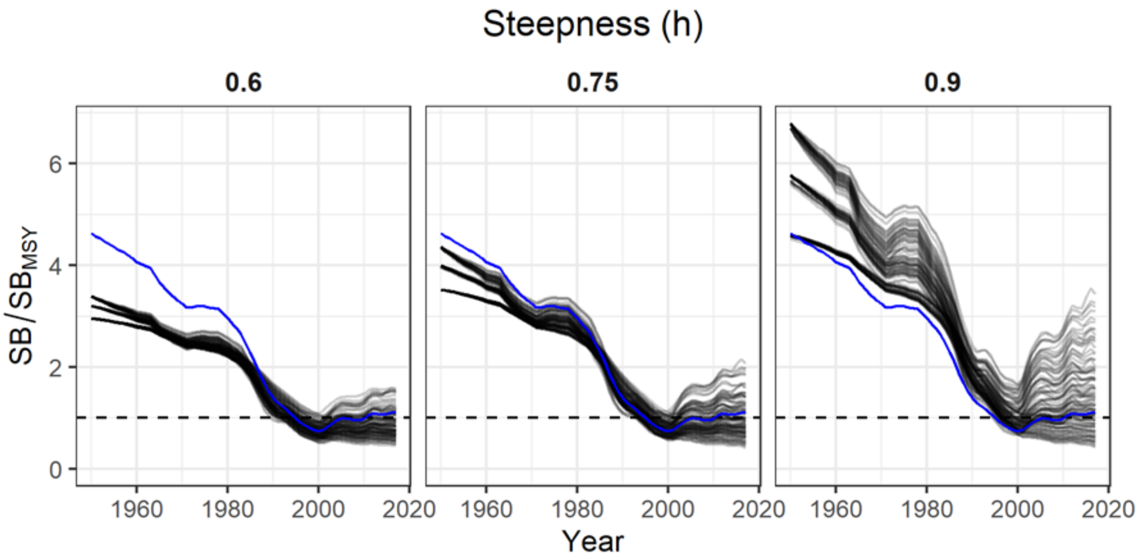

Figure 5. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the three levels of steepness in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

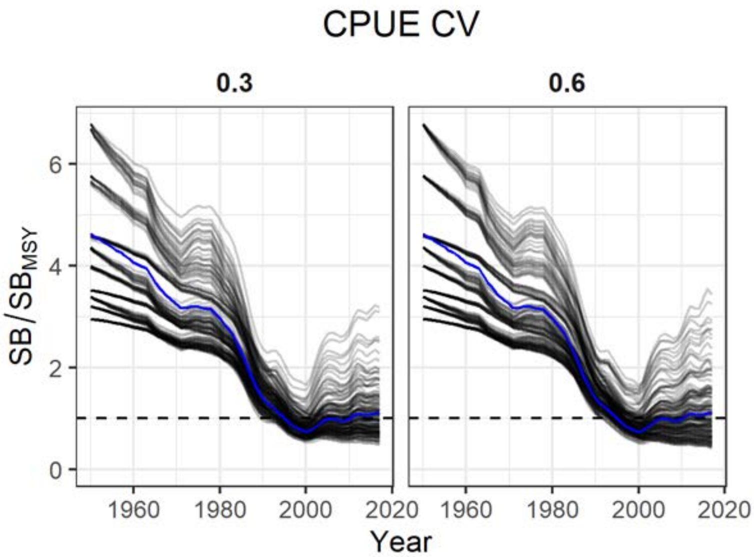

Figure 6. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the two levels of CV for the CPUE indices in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

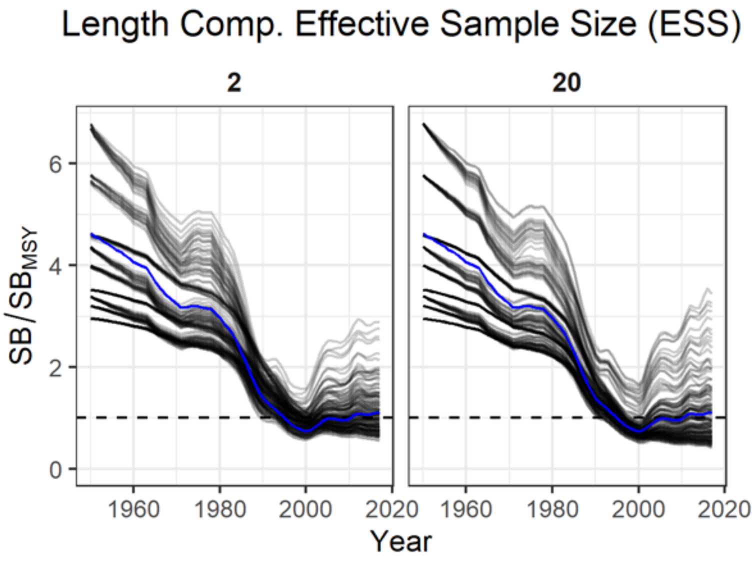

Figure 7. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the two levels of effective sample size for the length composition data in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

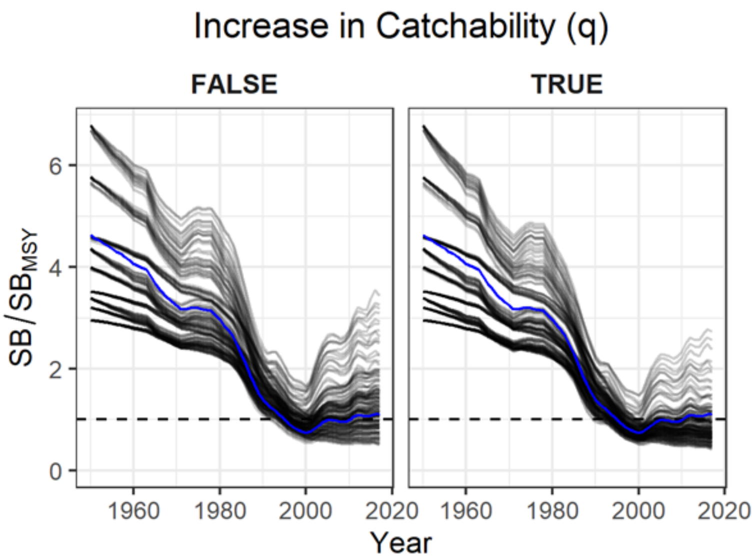

Figure 8. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the two levels of adjustment for a hypothesized increase in catchability in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

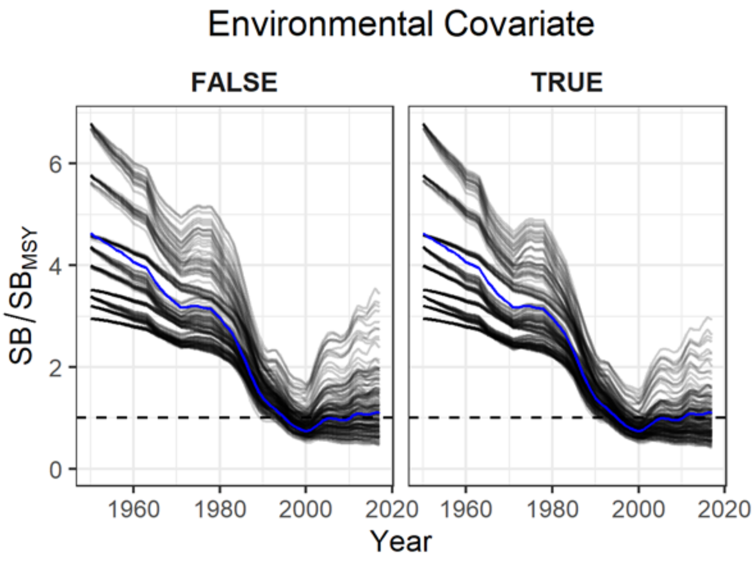

Figure 9. Time-series of the estimated spawning biomass (*SB*) relative to SB_{MSY} faceted by the two levels of the environmental covariate in the 288 operating models in the uncertainty grid. The estimate from the base case OM is shown as the blue line. The horizontal dashed black line indicates SB_{MSY}.

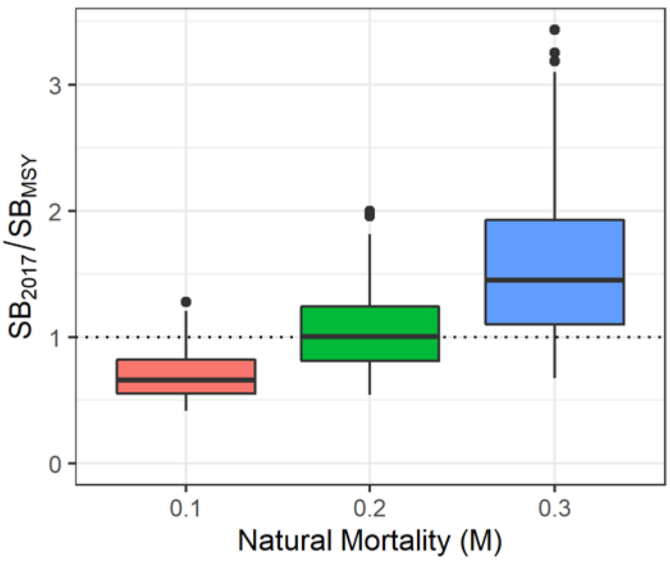

Figure 10. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the three levels of natural mortality in the 288 operating models in the uncertainty grid.

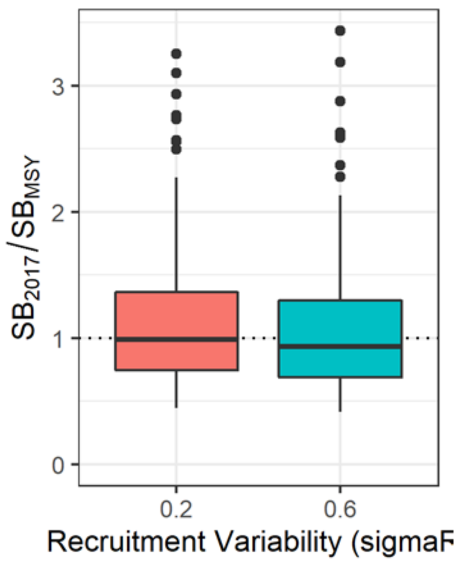

Figure 11. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the two levels of recruitment variability in the 288 operating models in the uncertainty grid.

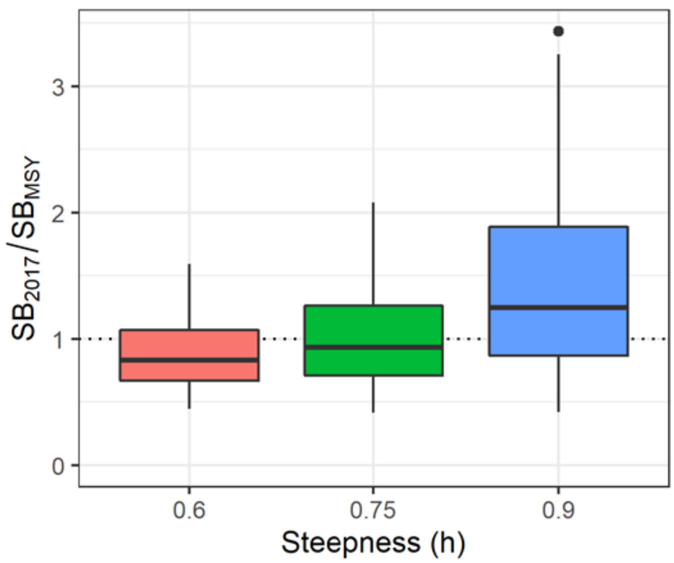

Figure 12. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the three levels of steepness in the 288 operating models in the uncertainty grid.

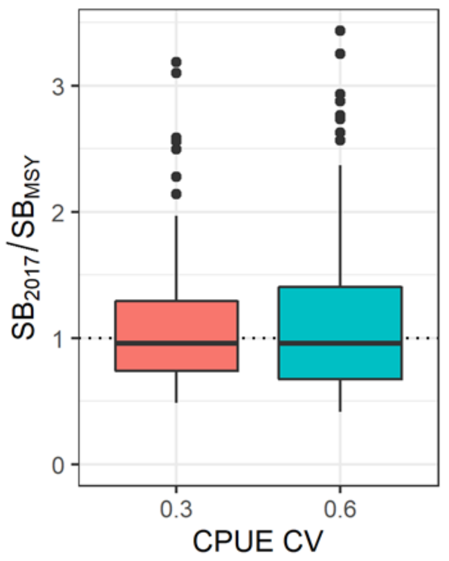

Figure 13. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the two levels of CPUE CV in the 288 operating models in the uncertainty grid.

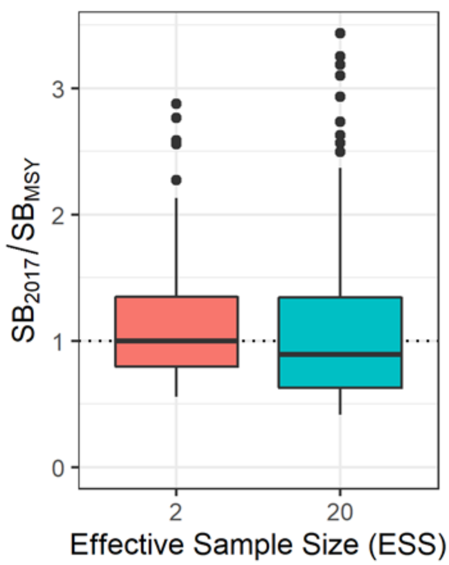

Figure 14. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the two levels of effective sample size (ESS) in the 288 operating models in the uncertainty grid.

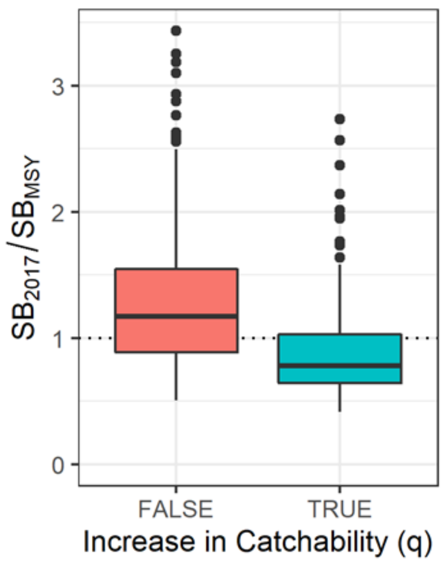

Figure 15. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the two levels of 1% annual increase in catchability in the 288 operating models in the uncertainty grid.

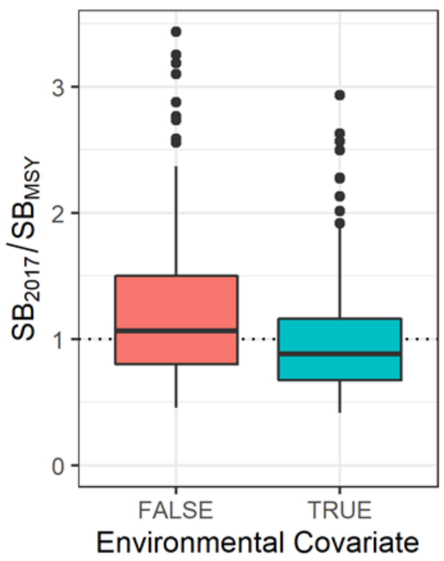

Figure 16. Boxplots of estimated stock status spawning biomass (*SB*) in 2017 relative to SB_{MSY} for the two levels of environmental covariate in the 288 operating models in the uncertainty grid.

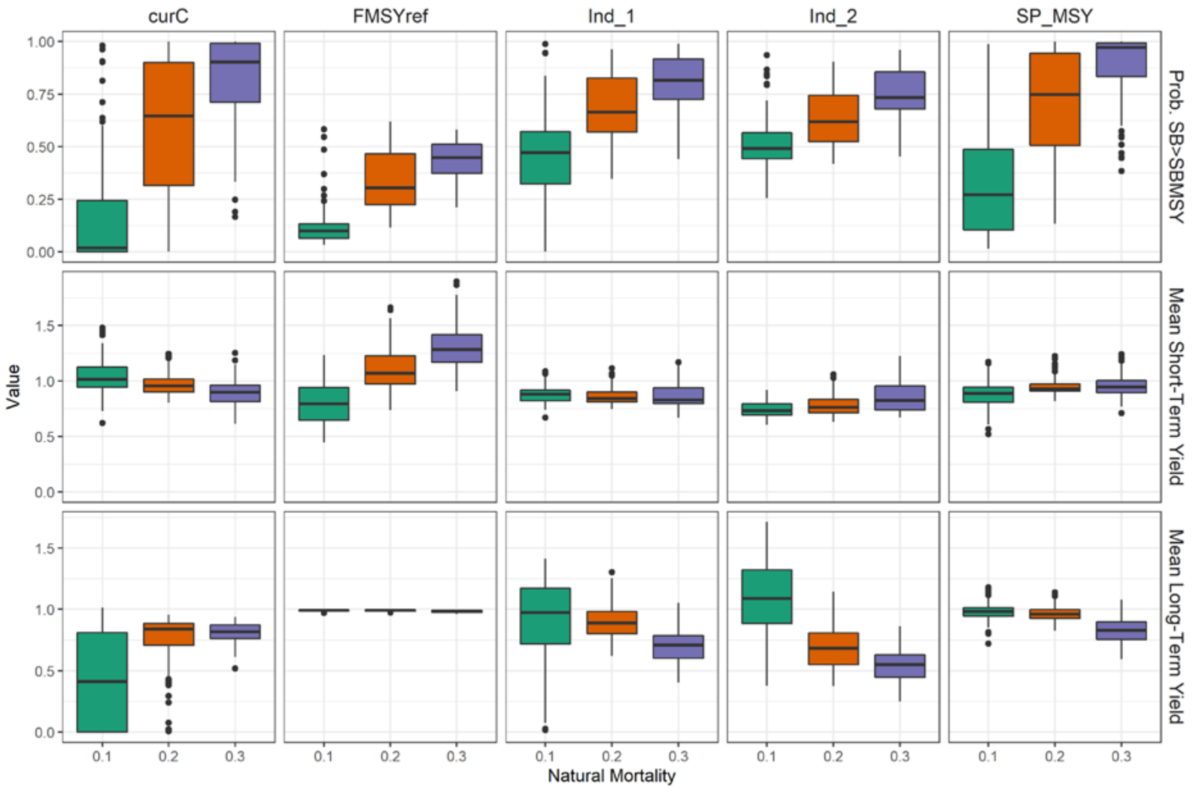

Figure 17. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the three levels of natural mortality included in the 288 operating models in the uncertainty grid.

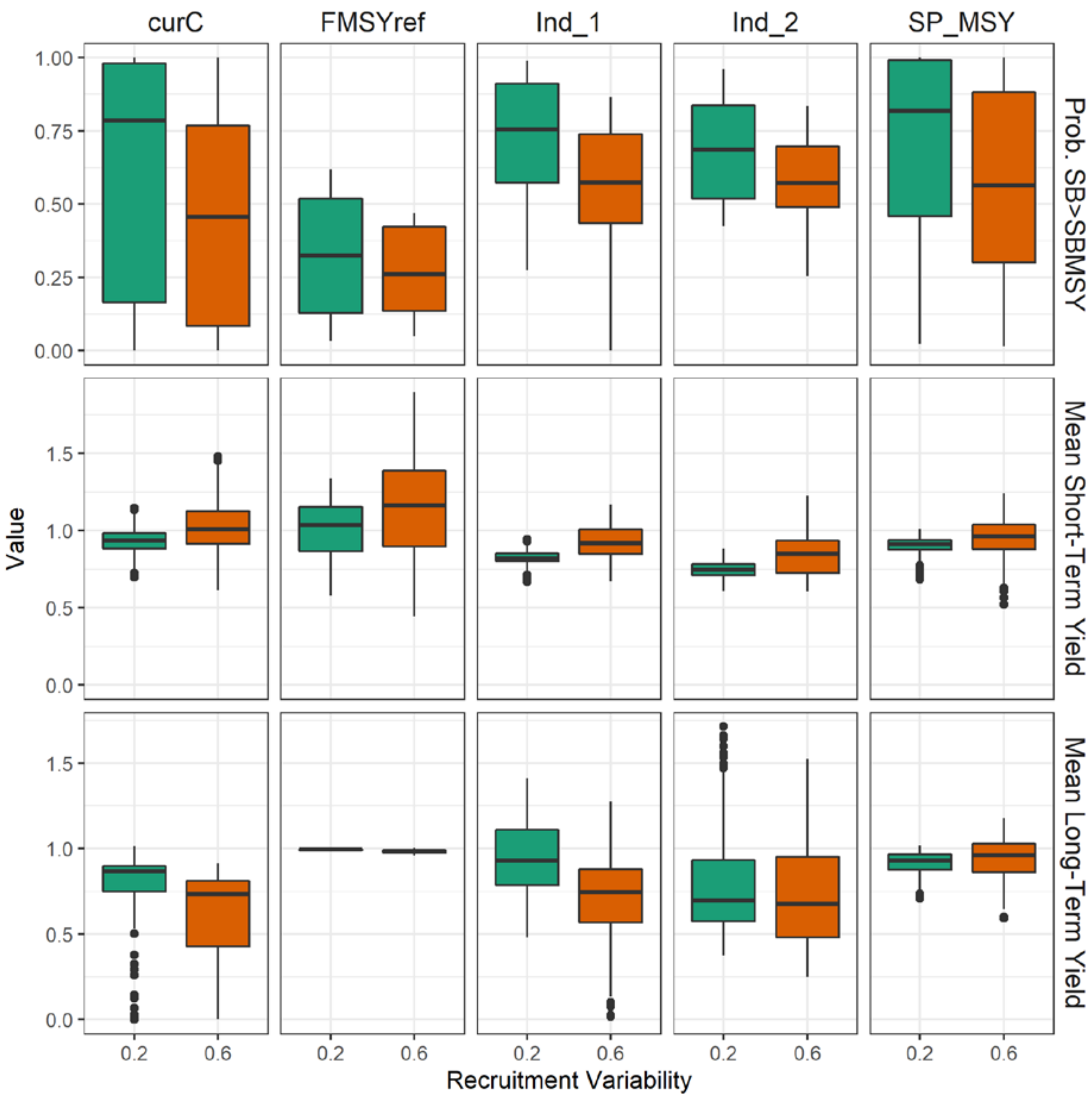

Figure 18. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the two levels of recruitment variability included in the 288 operating models in the uncertainty grid.

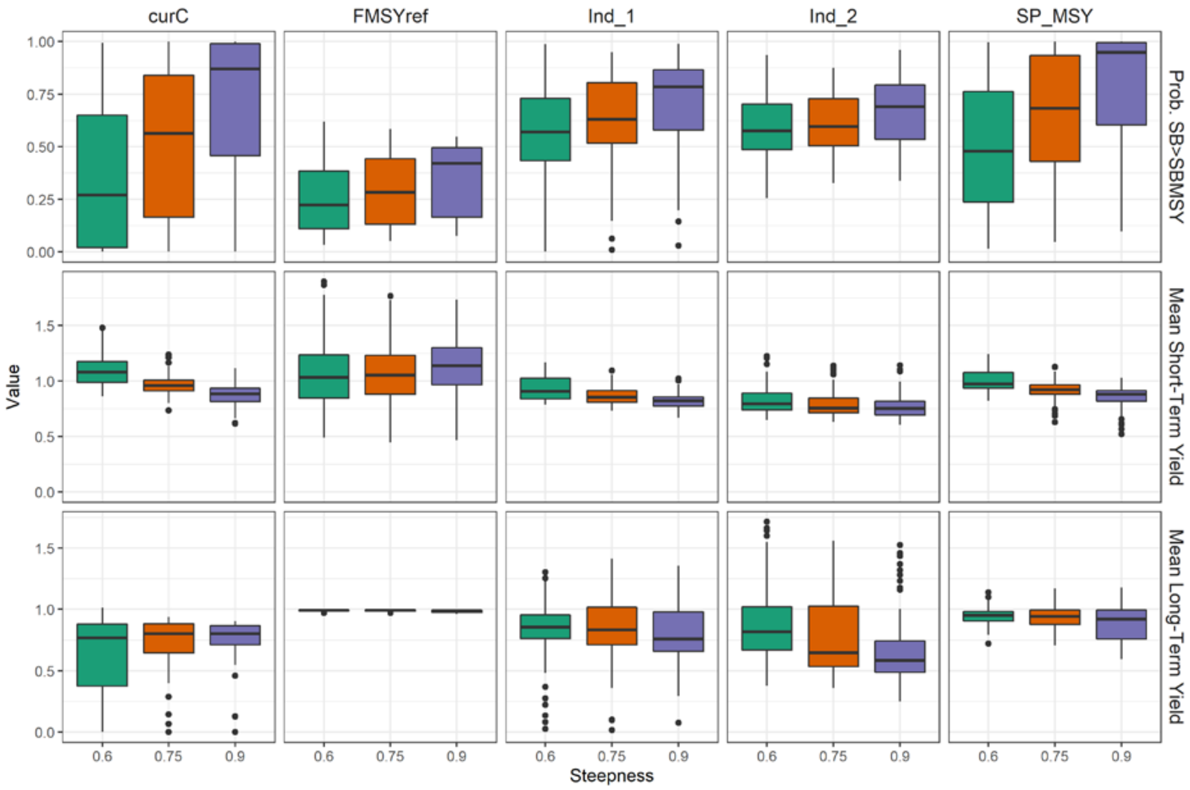

Figure 19. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the three levels of steepness included in the 288 operating models in the uncertainty grid.

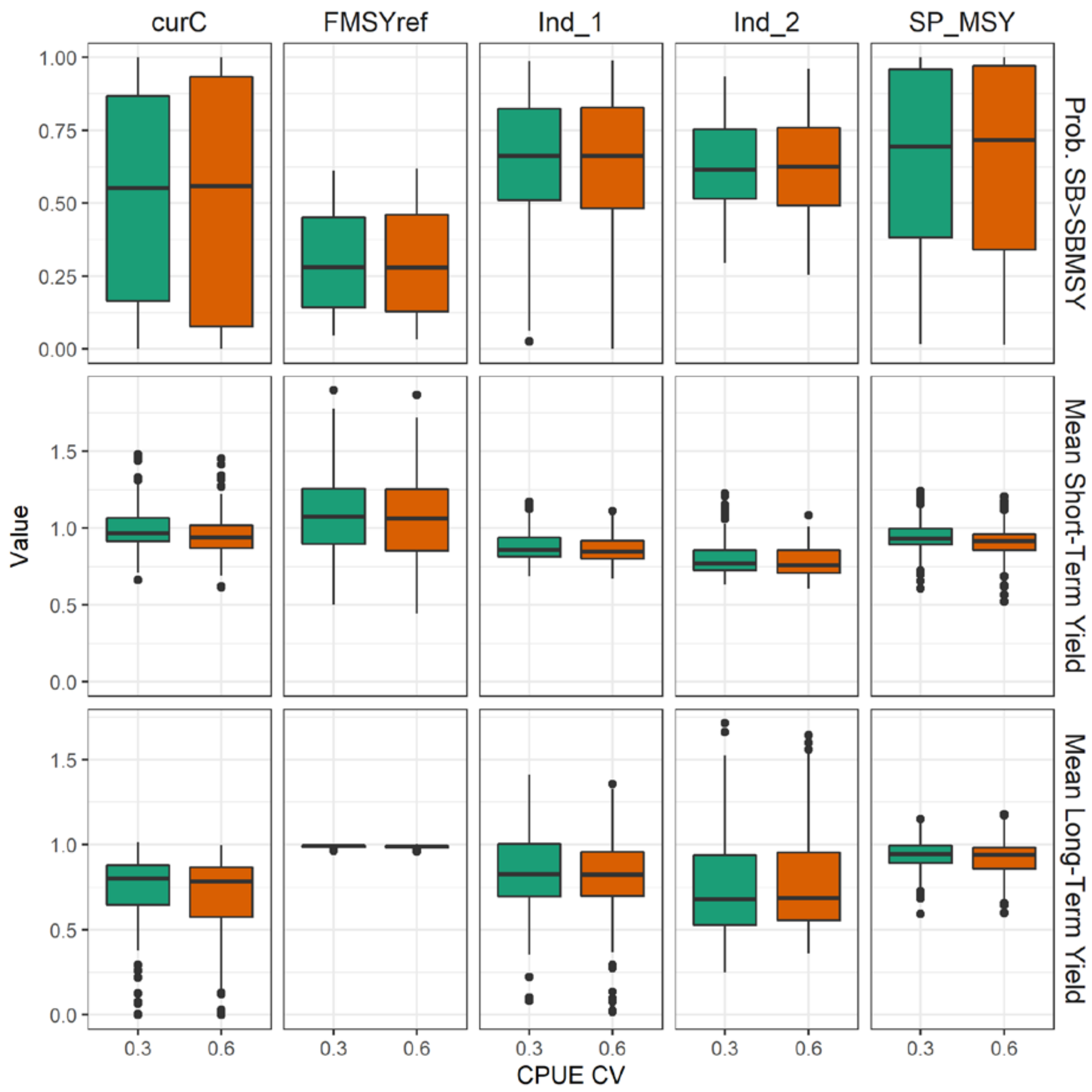

Figure 20. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the two levels of CPUE CV included in the 288 operating models in the uncertainty grid.

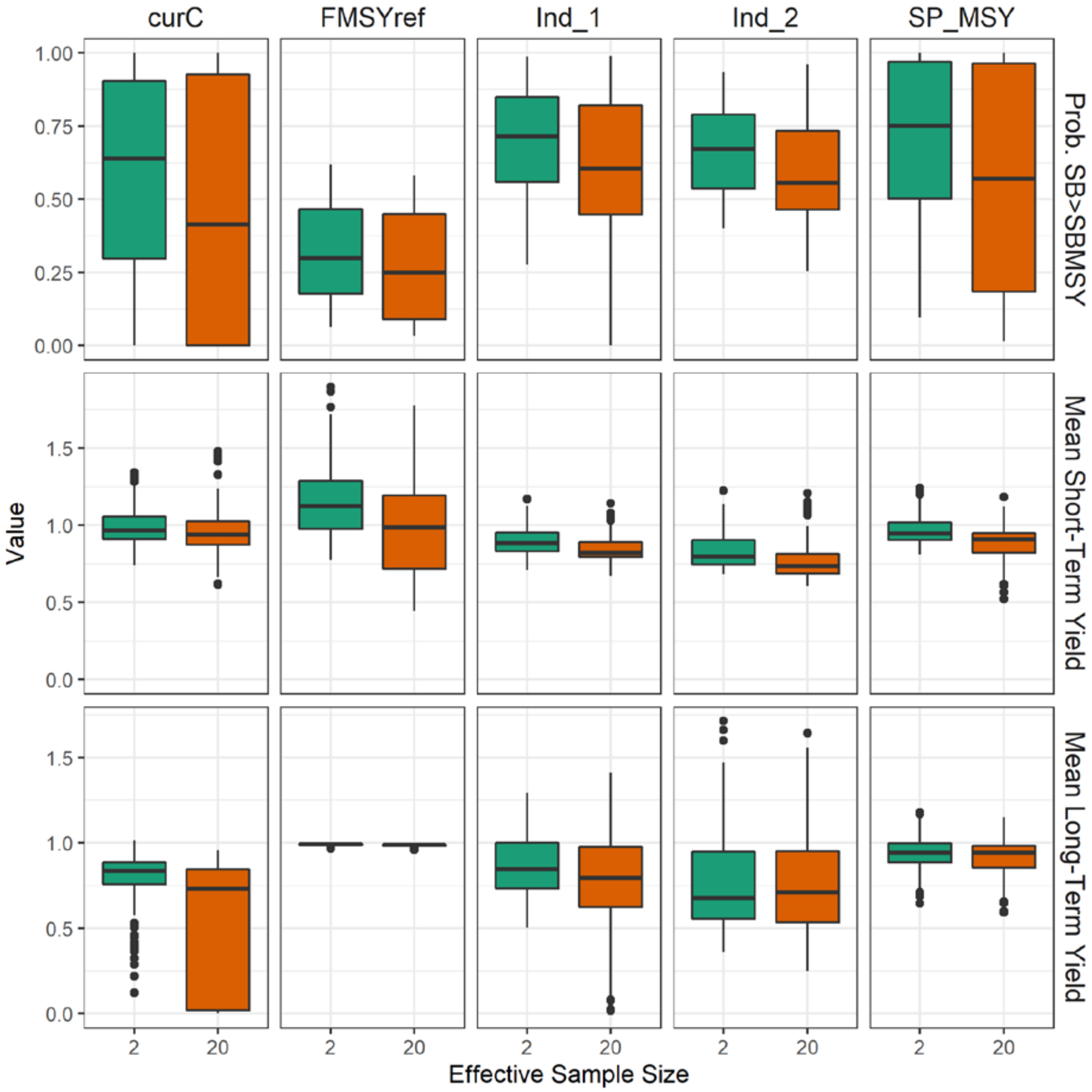

Figure 21. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the two levels of effective sample size included in the 288 operating models in the uncertainty grid.

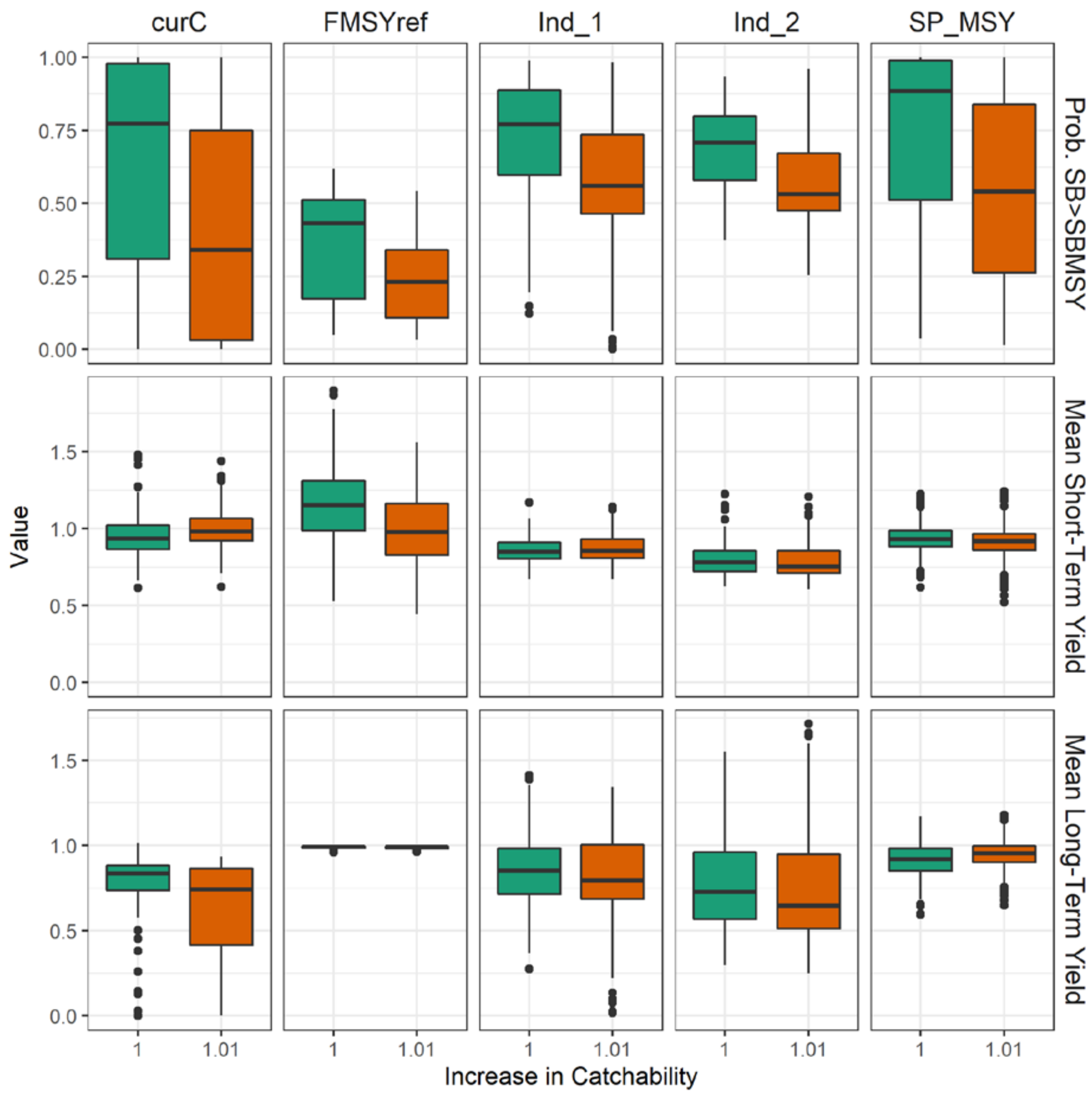

Figure 22. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the two levels of increase in catchability included in the 288 operating models in the uncertainty grid.

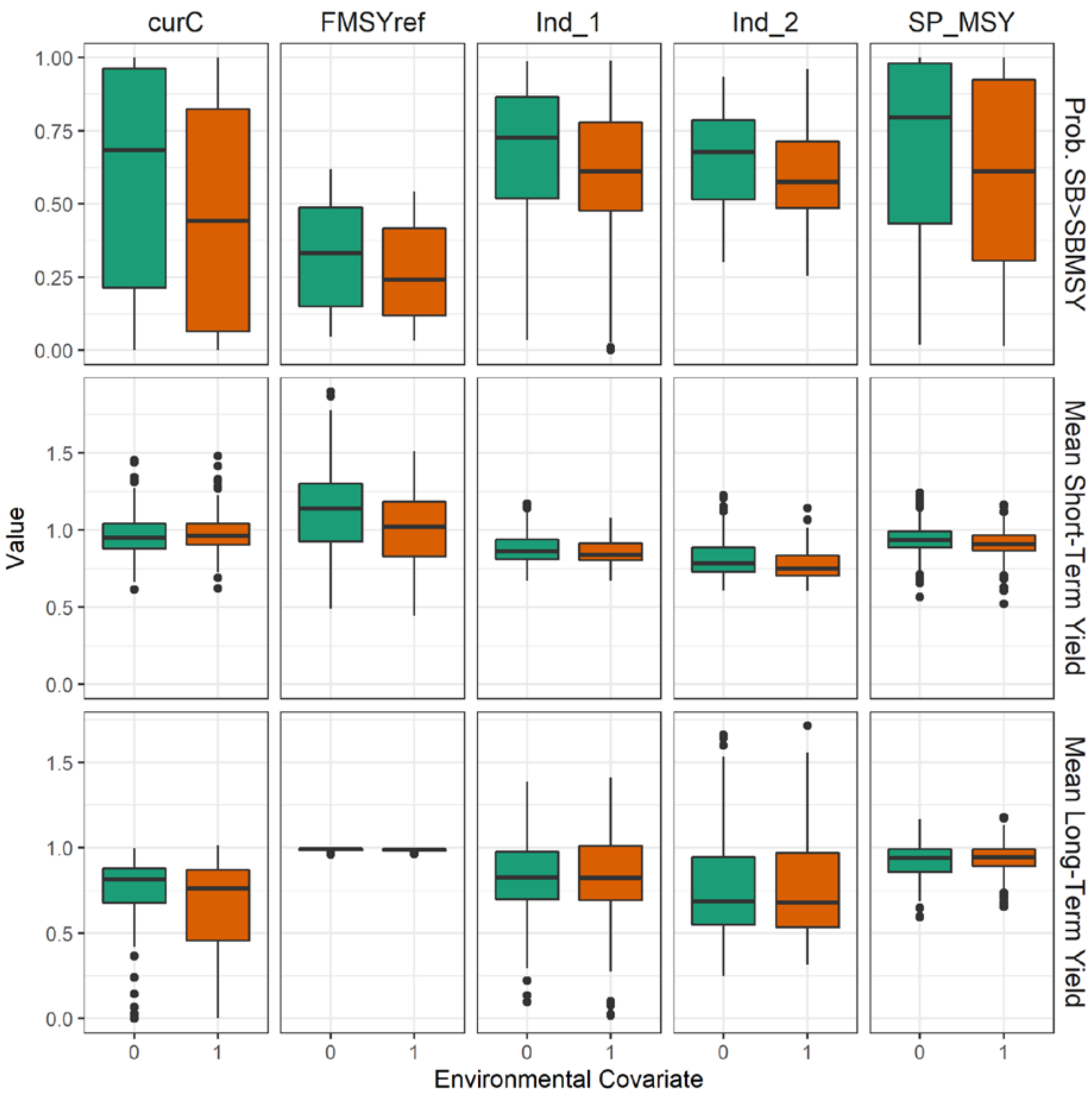

Figure 23. Boxplots of the three performance metrics (rows) and five reference management procedures (columns) for the two levels of environmental covariate included in the 288 operating models in the uncertainty grid.