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DEVELOPING CANDIDATE MANAGEMENT PROCEDURES FOR THE WESTERN ATLANTIC SKIPJACK TUNA

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SUMMARY

During the 2022 ICCAT Atlantic Skipjack Stock Assessment, the model adopted for management advice was based on the Stock Synthesis and included a set of scenarios, including an uncertainty grid for the growth pattern and steepness, totalizing nine different models. The present analysis aimed to update the initial trials of the management strategy evaluation for Western Atlantic skipjack tuna by reconditioning the operating models using the SS outputs of the last assessment. The analysis also included evaluating the relative performance of pre-selected management procedures across a set of performance metrics. In general, simulations presented excellent performance metrics across management procedures regarding the safety, status, yield, and stability of Western Atlantic Skipjack Tuna.

RÉSUMÉ

Lors de l'évaluation 2022 du stock de listao de l'Atlantique de l'ICCAT, le modèle adopté pour l'avis de gestion était basé sur Stock Synthesis et comprenait un ensemble de scénarios, dont une grille d'incertitude pour le schéma de croissance et la pente, totalisant neuf modèles différents. La présente analyse visait à actualiser les essais initiaux de l'évaluation de la stratégie de gestion pour le listao de l'Atlantique Ouest en reconditionnant les modèles opérationnels à l'aide des résultats de Stock Synthesis de la dernière évaluation. L'analyse comprenait également l'évaluation de la performance relative des procédures de gestion présélectionnées sur une série de paramètres de performance. En général, les simulations présentaient d'excellents paramètres de performance pour l'ensemble des procédures de gestion concernant la sécurité, l'état, la production et la stabilité du listao de l'Atlantique Ouest.

RESUMEN

Durante la evaluación del stock de listado del Atlántico de ICCAT de 2022, el modelo adoptado para el asesoramiento de ordenación se basó en Stock Synthesis e incluyó un conjunto de escenarios, entre ellos una matriz de incertidumbre para el patrón de crecimiento y la pendiente, totalizando nueve modelos diferentes. El presente análisis tenía como objetivo actualizar los ensayos iniciales de la evaluación de estrategias de ordenación para el listado del Atlántico occidental mediante el recondicionamiento de los modelos operativos utilizando los resultados de Stock Synthesis de la última evaluación. El análisis también incluyó la evaluación del desempeño relativo de los procedimientos de ordenación preseleccionados a través de un conjunto de mediciones del desempeño. En general, las simulaciones presentaron excelentes desempeños en todos los procedimientos de ordenación con respecto a la seguridad, estado, rendimiento y estabilidad del listado del Atlántico occidental.

KEYWORD

Management procedures, stock assessment, performance metrics, closed-loop simulation, harvest strategy

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1. Introduction

The development of the Western Atlantic Skipjack MSE commenced in 2020, as documented by Huynh et al. (2020), through a collaboration between Brazilian scientists and experts who created the openMSE (Open-Source Software for Management Strategy Evaluation). In the years 2021 and 2022, the first set of operational models was created by conditioning catch, CPUE, and size data from different fishing fleets, and incorporating the majority of the uncertainties in life-history parameters (Mourato et al., 2022a; Mourato et al., 2022b). The results of these studies indicated that the candidate management procedures (CMPs) for safety, status, yield, and stability showed excellent performance metrics (PMs) (Mourato et al., 2022b). In the year 2022, the Commission discussed the Western Atlantic Skipjack MSE and adopted the conceptual management objectives based on safety, status, yield, and stability criteria (Res. 22-02). In early 2023, the Tropical Tunas Species Group reviewed the progress of the Western Atlantic Skipjack MSE and proposed additional adjustments to the CMPs and the PMs.

The purpose of this document is to provide information regarding the development of the Western Atlantic Skipjack MSE for fisheries management. The document outlines the current status of the MSE development, in line with the decisions made by the Tropical Tunas Species Group and the inputs received from the ICCAT Commission, with regard to the conceptual management objectives.

2. Methods

2.1 Operating models

During the 2022 ICCAT Atlantic skipjack stock assessment, the model adopted for management advice was based on the Stock Synthesis (see Cardoso et al., 2022). This document presented a set of scenarios, including an uncertainty grid for the growth pattern and steepness, totaling nine different models. In the present analysis, we used the 27 OMs from the previous work (Mourato et al., 2022, see **Table 1** for details), but adding nine OMs (1-9) with perfect TAC implementations, nine OMs (10-18) with 10% error overage on TAC implementations and nine OMs (19-27) with 20% error overage on TAC implementations. Besides, other components were included in the OMs conditioning after using the *SS2OM* R function (see openMSE vignettes at https://openmse.com/features-importing-ss3/2-om/), which included the manual implementation of the observed data used in the assessment (the catch, abundance indices, and size data, Cardoso et al., 2022) on the data slots.

2.2 Development of the performance metrics

Following the guidance of the MSE Tropical Tunas Technical Sub-group and the adopted conceptual management objectives based on safety, status, yield, and stability criteria (Res. 22-02), the present analysis included 20 performance metrics (PMs) (see **Table 2** for details).

2.3 Development of the candidate management procedures

We used part of management procedures (MPs) presented in the previous work (see Mourato et al., 2022b for details), which was based on constant catches (*CC* of 20, 30, and 40 kt), index-based (*Iratio*, *Islope1*, and *GBslope*; see Huynh et al., 2020 and Mourato et al., 2022), and assessment model-based harvest control rules (HCRs). However, for the last, following the guidance of the MSE Tropical Tunas Technical Sub-group, the target reference point (TRP) was set as SB_{MSY}, and the limit reference point (LRP) at 40% SB_{MSY}. **Figure 1** illustrates the HCRs applied in the MSE simulations for the assessment model-based MPs. The green area represents the values equal or higher than TRP, which is associated with 100% of relative fishing mortality at the MSY level. In contrast, the yellow area shows the region between the LRP and TRP where fishing mortality decreases based on depletion or relative SB at MSY levels. The red area indicates the stock status with a lower level than LRP (stock collapse) but keeping fishing mortality at 10% of relative fishing mortality at the MSY level. Based on the rules of this HCR, the following assessment model-based MPs were applied in the MSE simulations:

- ***SCA_100_40_SB$_{MSY}$*** - A statistical catch-at-age model with an 100-40 control rule based on spawning biomass at MSY level and minimum F at 10% of $F_{MSY;}$
- ***SP_100_40_SB$_{MSY}$*** - A surplus production model with an 100-40 control rule based on spawning biomass at MSY level and minimum F at 10% of F_{MSY};
- ***SPSS_100_40_ SB$_{MSY}$*** - A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level and minimum F at 10% of $F_{MSY;}$

- ***SP_01*** **-** A surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} with fixed TAC for the 1st management cycle (i.e. the first three years);
- ***SP_02*** **-** A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} with fixed TAC for the 1st management cycle (i.e. the first three years);
- ***SP_03*** **-** A surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} without fixed TAC for the 1st management cycle (i.e. the first three years);
- ***SP_04*** **-** A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} without fixed TAC for the 1st management cycle (i.e. the first three years);
- ***SP_05*** **-** A surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} without fixed TAC for the 1st management cycle (i.e. the first three years). For this CMP, F was set three times larger;
- ***SP_06*** **-** A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} without fixed TAC for the 1st management cycle (i.e. the first three years). For this CMP, F was set three times larger.

For the CMPs based on surplus production models, the parametrization followed the assumptions of the Schaefer model ($B_{MSY}/K = 0.5$) and the initial value for the intrinsic growth rate parameter (*r*) was set based on a lognormal distribution with a mean of 0.5 and CV of 0.3, which was consistent with the last assessment (Sant'Ana et al., 2022). Also, for the state-space models the process error and observation error were freely estimated by the model (see SAMtool package for details).

2.4 MSE setup

The projection period for this exercise of the closed-loop MSE simulation was 30 years with 100 replicates. The management period and implementation of the MPs was set for 3-year intervals. The selectivity is based on the F-at-age in the terminal year of the historical period (e.g. 2020). A coefficient of variation of 0.4 and the autocorrelation based on the operating model conditioning was used as the model's error structure. The Beverton-Holt model was used to describe the stock-recruitment relationship and the parameter *SigmaR* was set at 0.4 for all operating models. The parameterization regarding the probability of individuals staying in each stock ("*prob_staying*", "*Size_area_1*" and "*Frac_area_1*"), were set at 0.5. This value-level approximates a single area model but allows some exchanges (migrations) between western and eastern stocks. The observation model parameters were set up following the "*Precise_unbiased*" model available in OpenMSE package.

3. Results and Discussion

All MSE simulations converged satisfactorily, and the number of interactions was sufficient for stabilizing each selected CMP inside the model. **Tables 3**, **4**, **5**, and **6** show the averaged statistics of PMs across the adopted conceptual management objectives based on safety, status, yield, and stability criteria including set of OMs with perfect (OMs 1-9), 10% error overage (OMs 10-18), and 20% error overage (OMs 19-27) for TAC implementation, respectively. The analysis of the trade-offs of the performance of MPs (**Figures 2**, **3**, and **4**) was also based on the averaged statistics of PMs across the reference set of OMs with different TAC implementation approaches, and included PMs concerned to the safety, status, yield, and stability.

In general, all PMs across the different scenarios of TAC implementation showed similar results for each CMP. Regarding the PMs for the safety criteria, all CMPs (except *CC_40kt*) had satisfactory results to keep the stock in a healthy condition with high probabilities (> 80%). At the same time, for the stability criteria, the scenarios with error overage on TAC implementation presented less stability in terms of yield (**Figures 2**, **3**, and **4**). It was noticed that the assessment model CMPs (SPs 05 and 06, and SCA) presented lower stability than the other CMPs (**Tables 3**, **4**, **5**, and **6**).

Concerning the trade-off between status ("*PGK*") and yield ("*AvC*"), the results are very similar between scenarios, with the great majority of CMPs presenting high probabilities (> 80%) to keep the stock on the Kobe green quadrant. However, these probabilities are lower for the "*CC_30kt*", "*SP_05*", "*SP_06*", and "*CC_40kt*" CMPs, with the last being less than 50%. Regarding yield, a significant difference was observed among index-slope and assessment model CMPs, with the last ones resulting in catches 40% higher with values around 22,000 t. In all scenarios, it was observed a low proportion (< 10%) of simulations where the biomass is among LRP and TRP for all CMPs, except for the empirical constant catch CMPs with TACs higher than 20,000 (**Tables 3**, **4**, **5**, and **6**; **Figures 2**, **3**, and **4**). Trade-off plots also show that a set of candidate assessment model CMPs resulted in less stability in terms of TAC. Concerning the status of the stock for the median period (4-10th project years), the performance of the numerical results for the CPMs shows a very satisfactory values, with the great majority of the simulations being placed above of 1 for the relative biomass and below 1 for the relative fishing mortality (except for the constant catches with TAC at 30 and 40 kt) (**Figures 2**, **3**, and **4**).

The proportion of years in each Kobe quadrant is depicted in **Figures 5**, **6**, and **7**. All CMPs generally resulted in a more significant proportion of the green area throughout the years. However, as other CPMs indicate, the empirical constant catches CMPs with TACs higher than 30 kt and "*SP_05*", "*SP_06*" produce higher proportions for the red quadrant. The Kobe plots for the terminal year (30th) are shown in **Figures 8**, **9**, and **10.** In general, all CMPs presented similar results with the majority of simulation being placed in the green quadrant, however, for the "*CC_30kt*", "*SP_05*", "*SP_06*", and "*CC_40kt*" CMPs the results are more pessimistic with large part of simulations being placed in the red quadrant.

The projected catches, and biomass and fishing mortality relative to the MSY time series is presented for all scenarios (**Figure 10-22**). In general, "*CC_35kt*" and "*CC_40kt*" CMPs resulted in a decline in biomass in the future. In contrast, the rest of the CMPs show a relatively stable trend, with few exceptions, such as "*Islope1*" CMP, that resulted in a significant increase of biomass in the projection period.

The present analysis updates the initial operating models presented by Huynh et al. (2020), Mourato et al. (2022a) and Mourato et al. (2022b) by including the suggestions of TT Species Group concerning the requested PMs to evaluate the performance of CMPs regarding the conceptual management objectives. The results demonstrate that the uncertainty in natural mortality, growth parameters, and alternative steepness values are most consequential in predicting stock dynamics. Additional management procedures and/or performance metrics can also be explored in future MSE simulation (mainly those based on climatic change scenarios), nevertheless, the model-based MPs tested here can be considered viable candidates for the management of the Western Atlantic skipjack tuna stock. Despite the number of operating models seeming to be sufficiently wide-ranging and probably covering much of the main sources of uncertainty, it is important to include as few OMs as possible so that MSE results are more easily interpreted.

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Table 1. Operating model scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

Operating model	***Growth vector***	***Steepness***	***SigmaR***	***Scenario***
OM 1	25th	0.6	0.4	Perfect TAC implementation
OM 2	50th			
OM 3	75th			
OM 4	25th	0.7		
OM 5	50th			
OM 6	75th			
OM 7	25th	0.8		
OM 8	50th			
OM 9	75th			
OM 10	25th	0.6		10% overage TAC error implementation
OM 11	50th			
OM 12	75th			
OM 13	25th	0.7		
OM 14	50th			
OM 15	75th			
OM 16	25th	0.8		
OM 17	50th			
OM 18	75th			
OM 19	25th	0.6		20% overage TAC error implementation
OM 20	50th			
OM 21	75th			
OM 22	25th	0.7		
OM 23	50th			
OM 24	75th			
OM 25	25th	0.8		
OM 26	50th			
OM 27	75th			

Table 2. List of performance metrics considered in the close-loop MSE simulation for the management strategy evaluation of the western Atlantic Skipjack stock.

Management Objectives (Res. 22-02)	***Proposed Corresponding Performance Metric Statistics***
Status The stock should have a 70% or greater probability of occurring in the green quadrant of the Kobe matrix using a 30-year projection period as determined by the SCRS.	**PGK_{short}**: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) in year 1-3 **PGK_{medium}**: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) in year 4-10 **PGK_{long}**: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) over years 11-30 **PGK:** Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) over years 1-30 **POF**: Probability of $F>F_{MSY}$ over years 1-30 **PNOF:** Probability of $F<F_{MSY}$ over years 1-30
Safety There should be no greater than 10% probability of the stock falling below B_{LIM} ($0.4*B_{MSY}$) at any point during the 30-year projection period.	**LRP_{short}**: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-3 **LRP_{medium}**: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 4-10 **LRP_{long}**: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 11-30 **LRP**: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-30 **$nLRP_{short}$**: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-3 **$nLRP_{medium}$**: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 4-10 **$nLRP_{long}$**: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 11-30 **nLRP**: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-30
Yield Maximize overall catch levels in the short (1-3 years), medium (4-10 years) and long (11-30 years) terms.	**AvC_{short}** – Median catches (t) over years 1-3 **AvC_{medium}** – Median catches (t) over years 4-10 **AvC_{long}** – Median catches (t) over years 11-30
Stability Any changes in TAC between management periods should be 20 20% or less.	**$VarC_{medium}$** – Variation in TAC (%) between management cycles over years 4-10 **$VarC_{long}$** – Variation in TAC (%) between management cycles over years 11-30 **Var_{all}** – Variation in TAC (%) between management cycles over years 1-30

Table 3. Safety PMs for each MPs showing the averaged statistics across the OMs implemented with (a) perfect TAC implementation [OMs 1-9]; (b) 10% TAC implementation error [10-18], and; (c) 20% TAC implementation error [19-27].

Safety

Management Procedures	LRP	LRP_long	LRP_med	LRP_short	nLRP	nLRP_long	nLRP_med	nLRP_short
SPSS_100_40_SBMSY	0.005	0.007	0.003	0.001	0.995	0.993	0.997	0.999
SP_100_40_SBMSY	0.003	0.003	0.002	0	0.997	0.997	0.998	1
SP_06	0.146	0.175	0.11	0.042	0.854	0.825	0.89	0.958
SP_05	0.128	0.139	0.115	0.085	0.872	0.861	0.885	0.915
SP_04	0.003	0.005	0.001	0.001	0.997	0.995	0.999	0.999
SP_03	0.004	0.006	0.002	0.001	0.996	0.994	0.998	0.999
SP_02	0.004	0.005	0.003	0	0.996	0.995	0.997	1
SP_01	0.006	0.008	0.005	0	0.994	0.992	0.995	1
SCA_100_40_SBMSY	0.013	0.013	0.019	0	0.987	0.987	0.981	1
Islope1	0.004	0.005	0.003	0	0.996	0.995	0.997	1
Iratio	0.006	0.007	0.006	0	0.994	0.993	0.994	1
GB_slope	0.012	0.015	0.007	0	0.988	0.985	0.993	1
CC_40kt	0.384	0.501	0.212	0.01	0.616	0.499	0.788	0.99
CC_30kt	0.103	0.14	0.044	0	0.897	0.86	0.956	1
CC_20kt	0.005	0.006	0.003	0	0.995	0.994	0.997	1

Performance Metrics

(a) Perfect TAC implementation

Safety

Management Procedures	LRP	LRP_long	LRP_med	LRP_short	nLRP	nLRP_long	nLRP_med	nLRP_short
SPSS_100_40_SBMSY	0.005	0.007	0.003	0.001	0.995	0.993	0.997	0.999
SP_100_40_SBMSY	0.002	0.003	0.001	0	0.998	0.997	0.999	1
SP_06	0.148	0.178	0.106	0.042	0.852	0.822	0.894	0.958
SP_05	0.131	0.142	0.119	0.085	0.869	0.858	0.881	0.915
SP_04	0.003	0.005	0	0	0.997	0.995	1	1
SP_03	0.005	0.006	0.003	0.001	0.995	0.994	0.997	0.999
SP_02	0.004	0.005	0.003	0	0.996	0.995	0.997	1
SP_01	0.007	0.008	0.006	0	0.993	0.992	0.994	1
SCA_100_40_SBMSY	0.013	0.014	0.018	0	0.987	0.986	0.982	1
Islope1	0.004	0.005	0.003	0	0.996	0.995	0.997	1
Iratio	0.007	0.007	0.009	0	0.993	0.993	0.991	1
GB_slope	0.014	0.018	0.012	0	0.986	0.982	0.988	1
CC_40kt	0.384	0.5	0.212	0.01	0.616	0.5	0.788	0.99
CC_30kt	0.102	0.137	0.045	0.001	0.898	0.863	0.955	0.999
CC_20kt	0.005	0.006	0.004	0	0.995	0.994	0.996	1

Performance Metrics

(b) 10% TAC Implementation Error

Safety

Management Procedures	LRP	LRP_long	LRP_med	LRP_short	nLRP	nLRP_long	nLRP_med	nLRP_short
SPSS_100_40_SBMSY	0.006	0.007	0.002	0.001	0.994	0.993	0.998	0.999
SP_100_40_SBMSY	0.002	0.003	0.001	0	0.998	0.997	0.999	1
SP_06	0.149	0.18	0.106	0.042	0.851	0.82	0.894	0.958
SP_05	0.129	0.139	0.116	0.087	0.871	0.861	0.884	0.913
SP_04	0.003	0.004	0.002	0	0.997	0.996	0.998	1
SP_03	0.006	0.007	0.005	0	0.994	0.993	0.995	1
SP_02	0.003	0.004	0.002	0	0.997	0.996	0.998	1
SP_01	0.007	0.008	0.006	0	0.993	0.992	0.994	1
SCA_100_40_SBMSY	0.015	0.015	0.02	0	0.985	0.985	0.98	1
Islope1	0.005	0.006	0.003	0	0.995	0.994	0.997	1
Iratio	0.01	0.011	0.014	0	0.99	0.99	0.986	1
GB_slope	0.019	0.024	0.013	0	0.981	0.976	0.987	1
CC_40kt	0.386	0.502	0.214	0.014	0.614	0.498	0.786	0.986
CC_30kt	0.102	0.136	0.048	0.001	0.898	0.864	0.952	0.999
CC_20kt	0.005	0.006	0.005	0	0.995	0.994	0.995	1

Performance Metrics

(c) 20% TAC Implementation Error

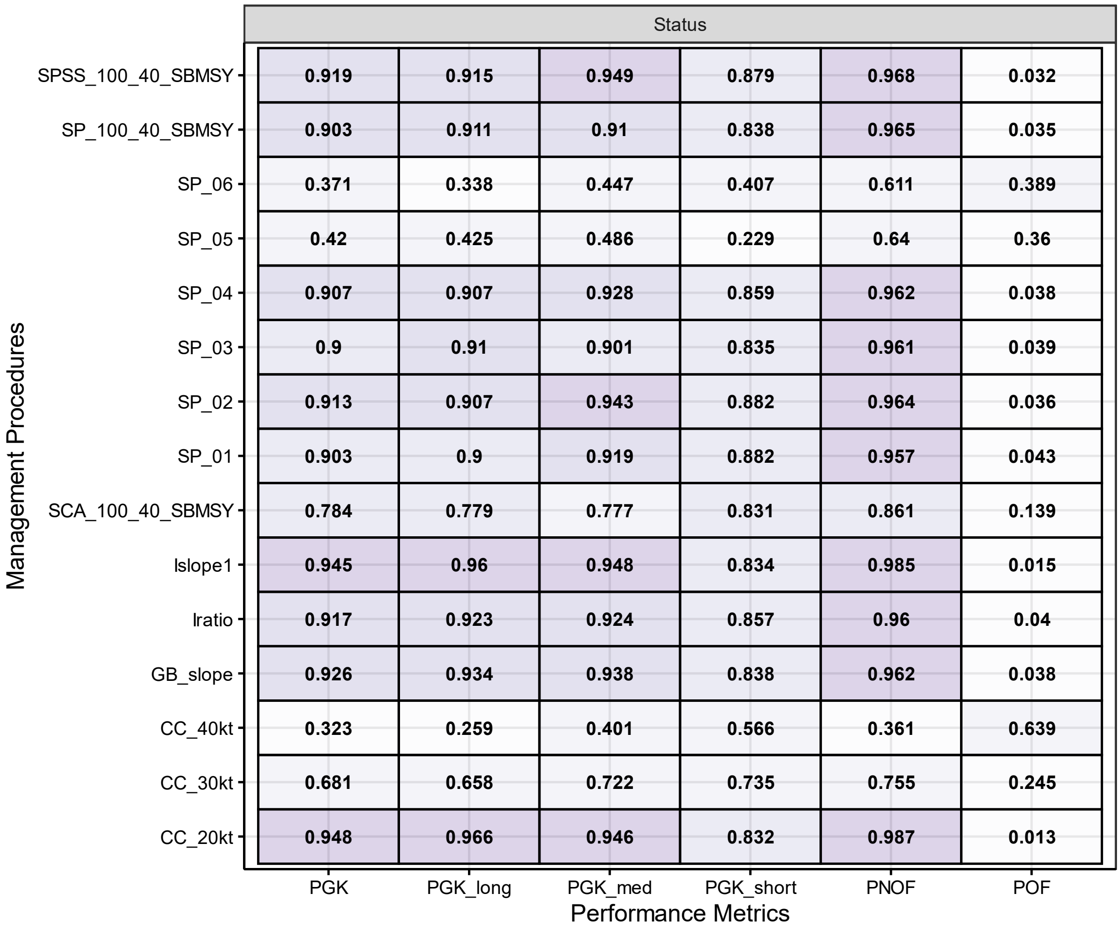
Table 4. Status PMs for each MP showing the averaged statistics across the reference set of OMs with (a) perfect TAC implementation [OMs 1-9]; (b) 10% TAC implementation error [10-18], and; (c) 20% TAC implementation error [19-27].

Status

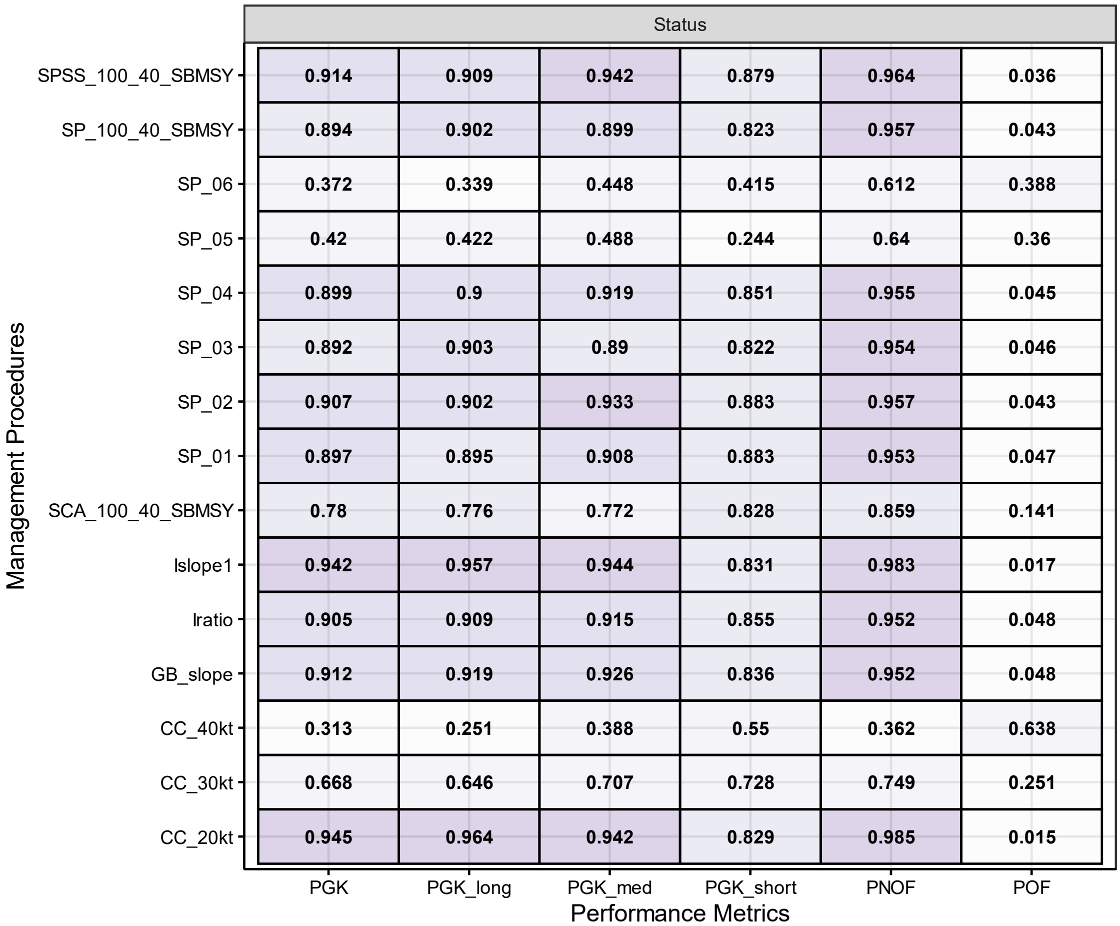
Management Procedures	PGK	PGK_long	PGK_med	PGK_short	PNOF	POF
SPSS_100_40_SBMSY	0.922	0.916	0.957	0.879	0.97	0.03
SP_100_40_SBMSY	0.906	0.911	0.916	0.845	0.967	0.033
SP_06	0.37	0.338	0.448	0.401	0.611	0.389
SP_05	0.419	0.425	0.487	0.221	0.64	0.36
SP_04	0.912	0.91	0.937	0.861	0.966	0.034
SP_03	0.905	0.912	0.911	0.842	0.964	0.036
SP_02	0.916	0.909	0.949	0.883	0.967	0.033
SP_01	0.905	0.901	0.926	0.883	0.959	0.041
SCA_100_40_SBMSY	0.789	0.786	0.777	0.832	0.864	0.136
Islope1	0.945	0.961	0.95	0.831	0.986	0.014
Iratio	0.92	0.925	0.931	0.857	0.962	0.038
GB_slope	0.928	0.937	0.941	0.841	0.964	0.036
CC_40kt	0.33	0.266	0.402	0.588	0.362	0.638
CC_30kt	0.688	0.666	0.729	0.741	0.756	0.244
CC_20kt	0.947	0.965	0.947	0.83	0.988	0.012

Performance Metrics

(a) Perfect TAC implementation



(b) 10% TAC Implementation Error



(c) 20% TAC Implementation Error

Table 5. TAC stability PMs for each MP showing the averaged statistics across the reference set of OMs with (a) perfect TAC implementation [OMs 1-9]; (b) 10% TAC implementation error [10-18], and; (c) 20% TAC implementation error [19-27].

Management Procedures	Stability		
	VarC	VarClong	VarCmedium
SPSS_100_40_SBMSY	0.12	0.13	0.192
SP_100_40_SBMSY	0.063	0.061	0.164
SP_06	0.629	0.687	0.951
SP_05	0.658	0.659	1
SP_04	0.108	0.123	0.181
SP_03	0.05	0.051	0.13
SP_02	0.106	0.125	0.153
SP_01	0.061	0.062	0.106
SCA_100_40_SBMSY	0.904	0.905	0.916
Islope1	0.013	0.016	0.019
Iratio	0.103	0.12	0.146
GB_slope	0.06	0.067	0.082
CC_40kt	0	0	0
CC_30kt	0	0	0
CC_20kt	0	0	0

Performance Metrics

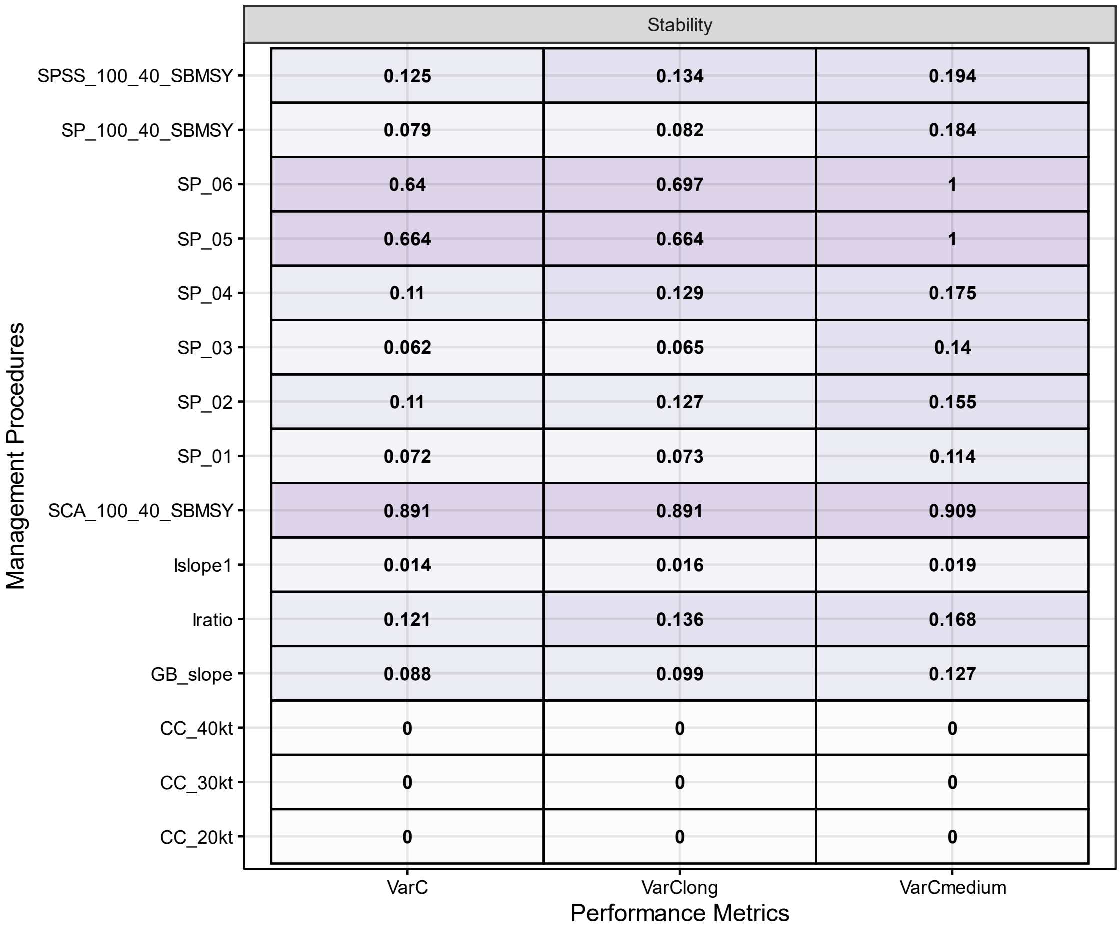
(a) Perfect TAC implementation

Stability

Management Procedures	VarC	VarClong	VarCmedium
SPSS_100_40_SBMSY	0.12	0.13	0.192
SP_100_40_SBMSY	0.069	0.07	0.363
SP_06	0.639	0.698	1
SP_05	0.664	0.662	1
SP_04	0.108	0.123	0.183
SP_03	0.053	0.053	0.131
SP_02	0.107	0.126	0.156
SP_01	0.062	0.063	0.11
SCA_100_40_SBMSY	0.896	0.894	0.913
Islope1	0.014	0.016	0.019
Iratio	0.11	0.127	0.152
GB_slope	0.071	0.08	0.101
CC_40kt	0	0	0
CC_30kt	0	0	0
CC_20kt	0	0	0

Performance Metrics

(b) 10% TAC Implementation Error



(c) 20% TAC Implementation Error

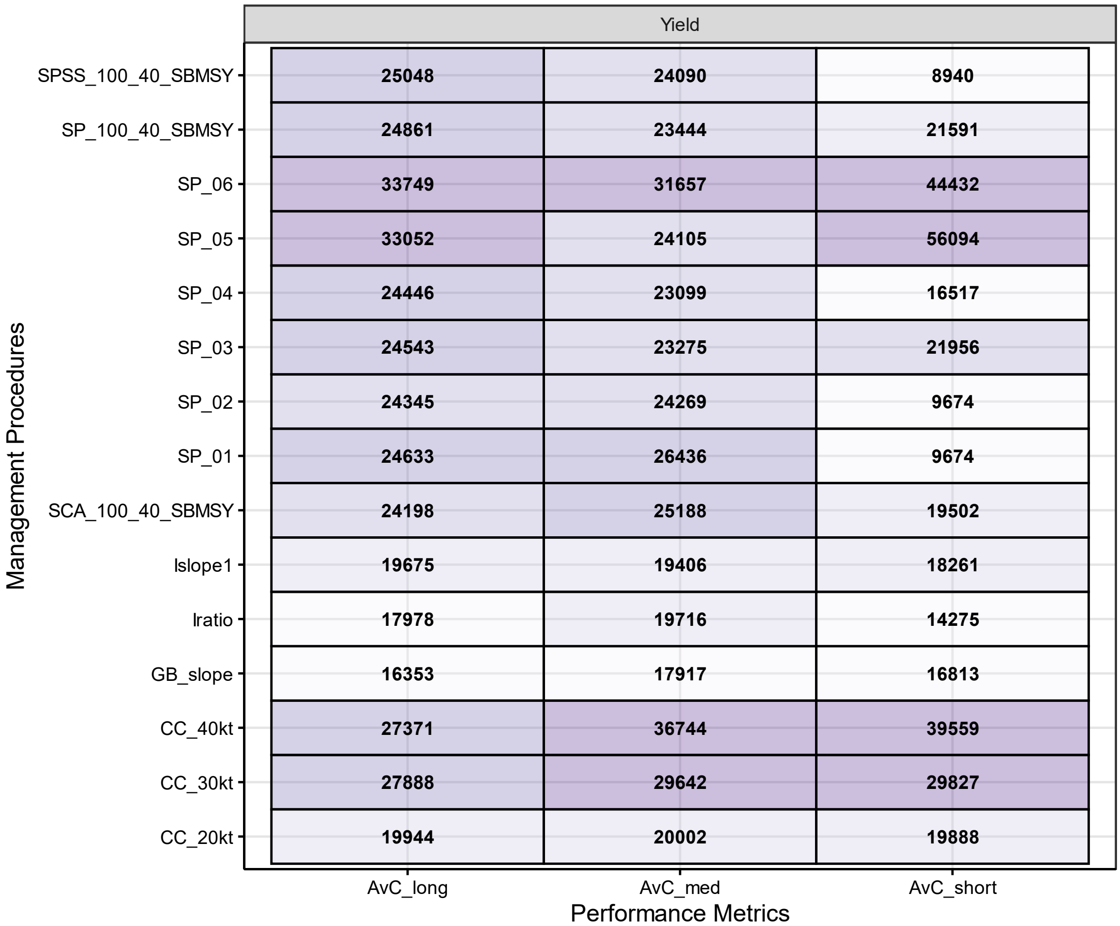
Table 6. Yield PMs for each MP showing the averaged statistics across the reference set of OMs with (a) perfect TAC implementation [OMs 1-9]; (b) 10% TAC implementation error [10-18], and; (c) 20% TAC implementation error [19-27]. The color gradient (by row) spans green to orange to red, corresponding to values of 0, 0.5, and 1, respectively, for each performance metric.

Yield

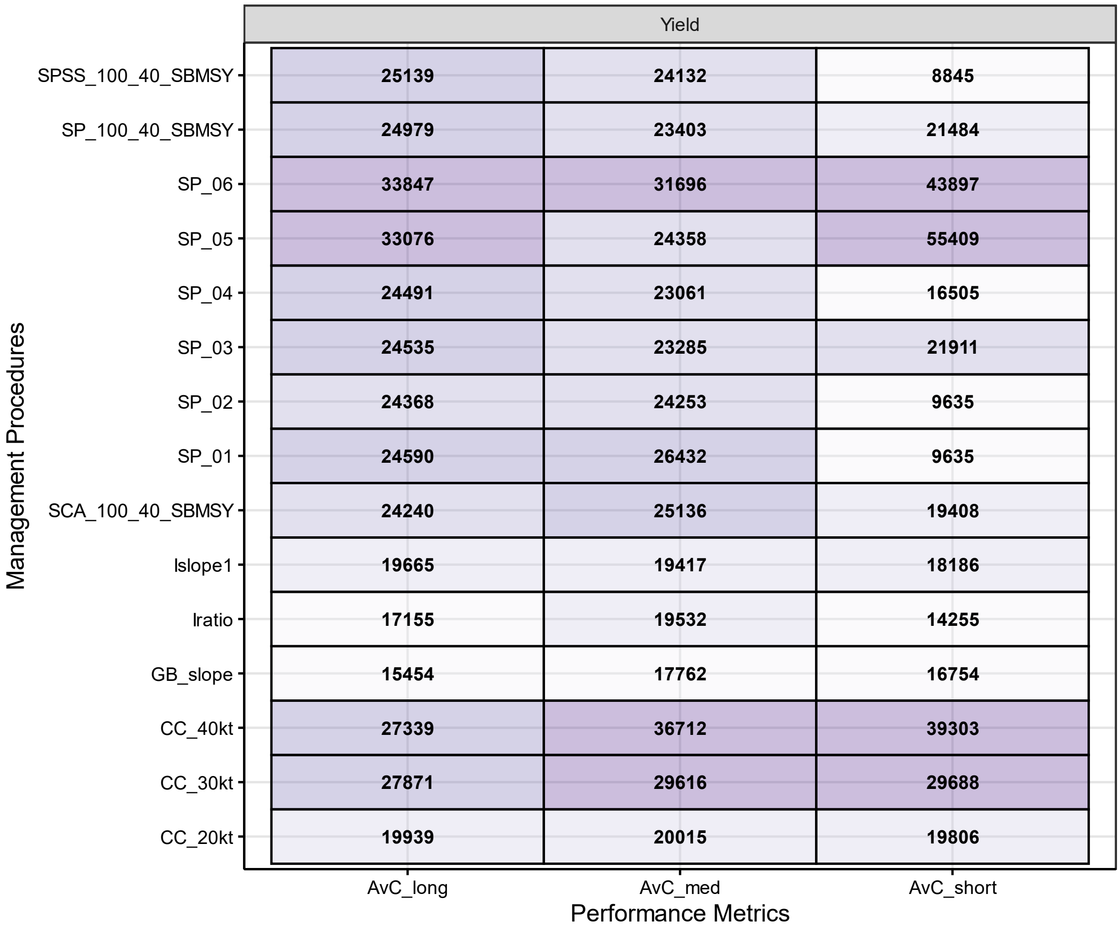
Management Procedures	AvC_long	AvC_med	AvC_short
SPSS_100_40_SBMSY	24992	24140	9042
SP_100_40_SBMSY	24811	23464	21721
SP_06	33706	31568	44848
SP_05	32986	23795	56563
SP_04	24424	23015	16545
SP_03	24524	23254	22018
SP_02	24312	24204	9729
SP_01	24616	26418	9729
SCA_100_40_SBMSY	24183	25121	19668
Islope1	19678	19389	18363
Iratio	18414	19929	14367
GB_slope	16823	18014	16875
CC_40kt	27360	36713	39840
CC_30kt	27866	29647	29999
CC_20kt	19948	19986	20000

Performance Metrics

(a) Perfect TAC implementation



(b) 10% TAC Implementation Error



(c) 20% TAC Implementation Error

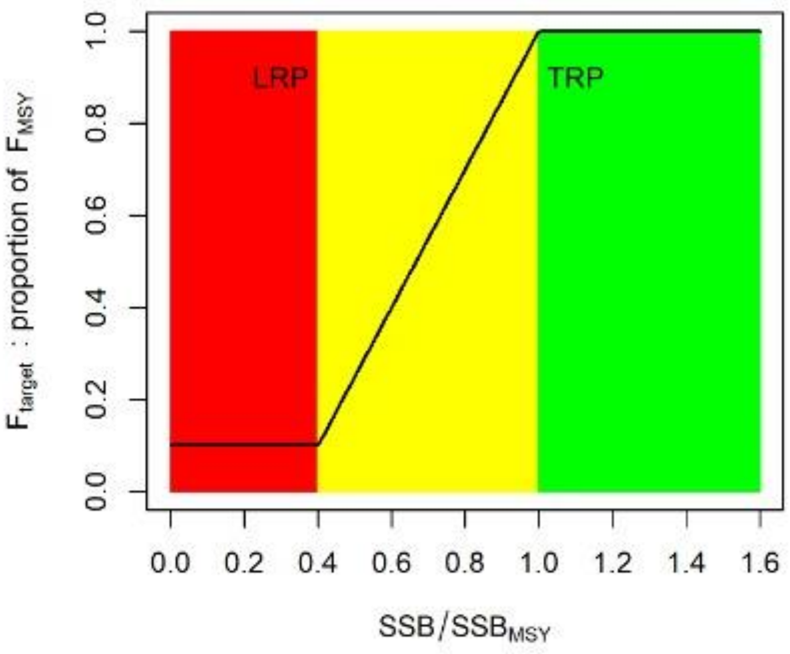
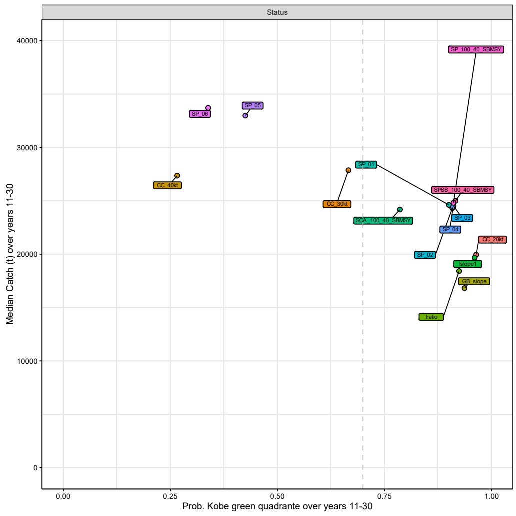
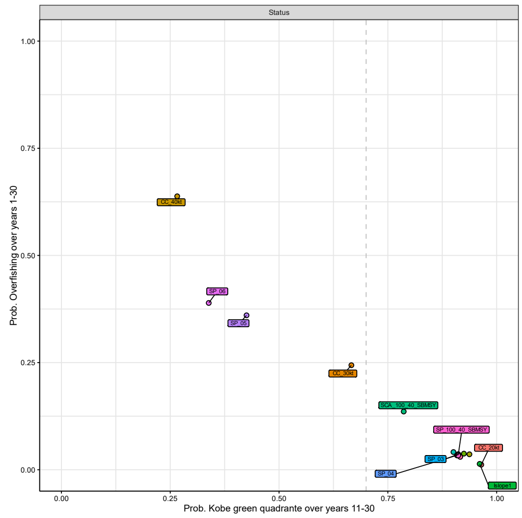
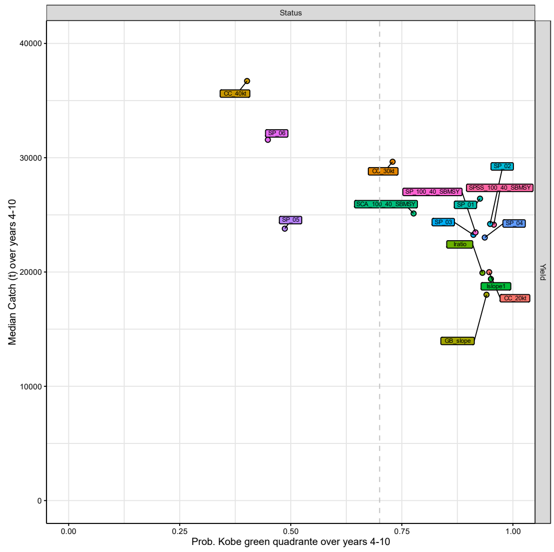
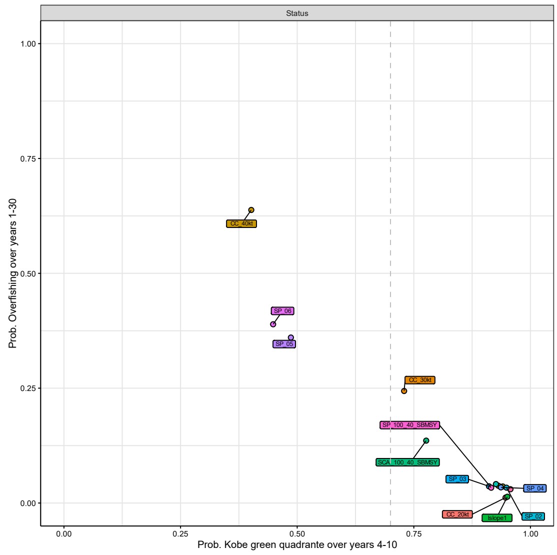


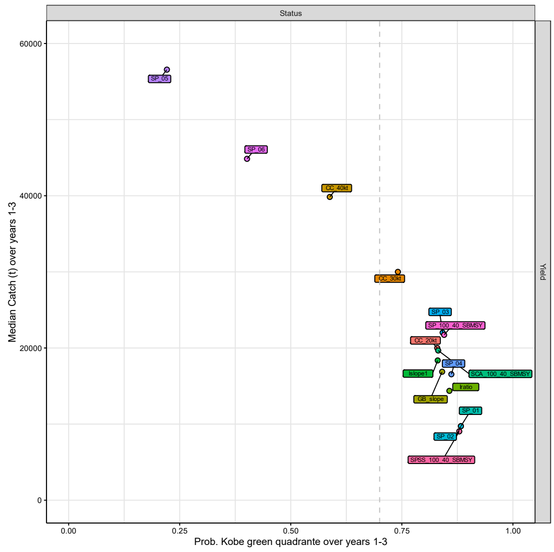
Figure 1. Harvest control rule (HCR) that will be applied in the MSE simulations for the assessment model-based MPs.

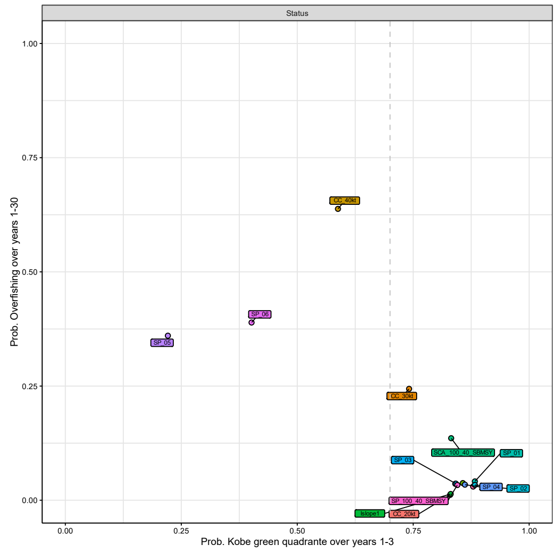

Status
Median Catch (t) over years 11-30
Prob. Kobe green quadrante over years 11-30


Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 11-30


Status
Yield
Median Catch (t) over years 4-10
Prob. Kobe green quadrante over years 4-10


Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 4-10


Status
Yield
Median Catch (t) over years 1-3
Prob. Kobe green quadrante over years 1-3


Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 1-3

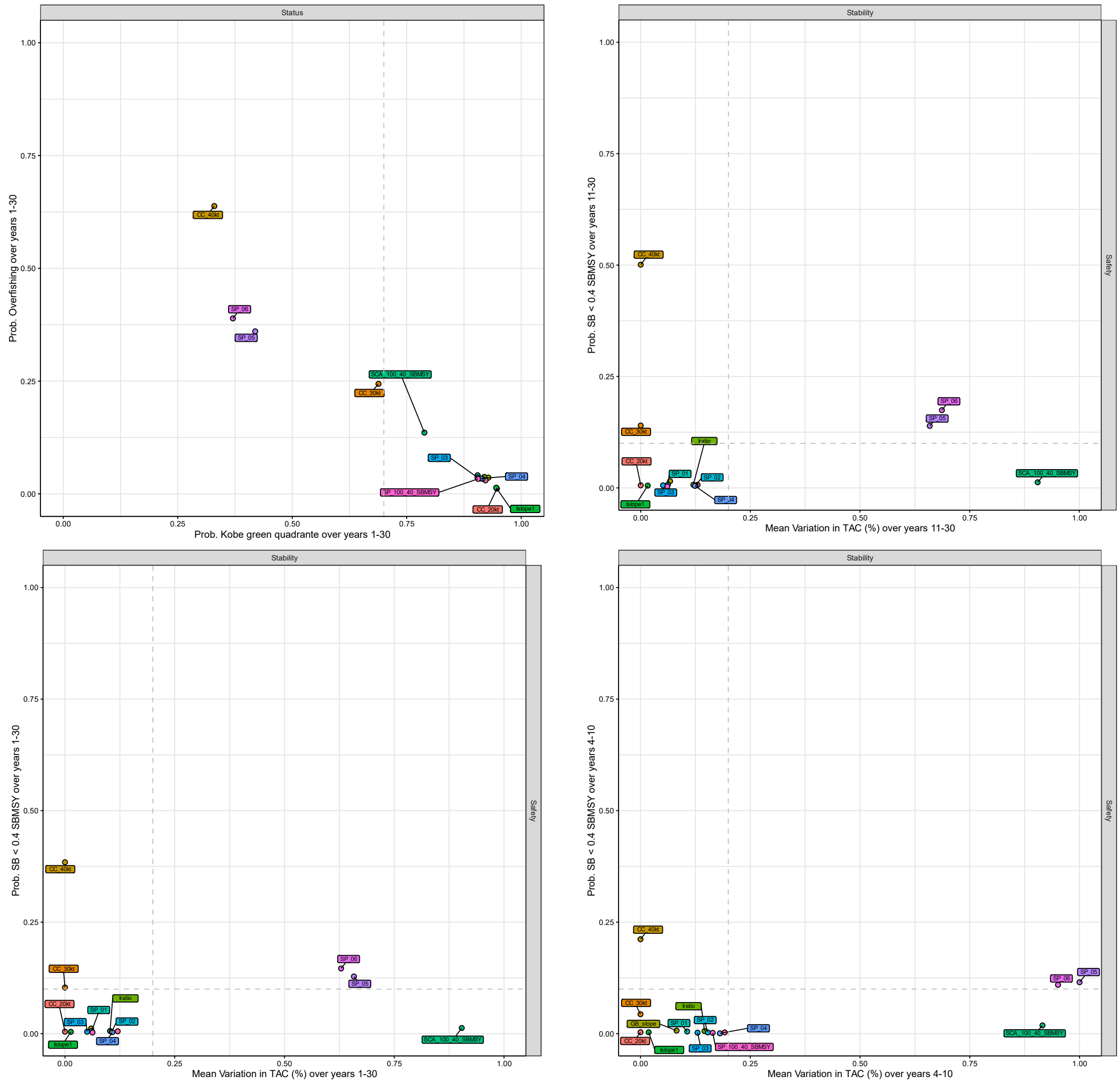
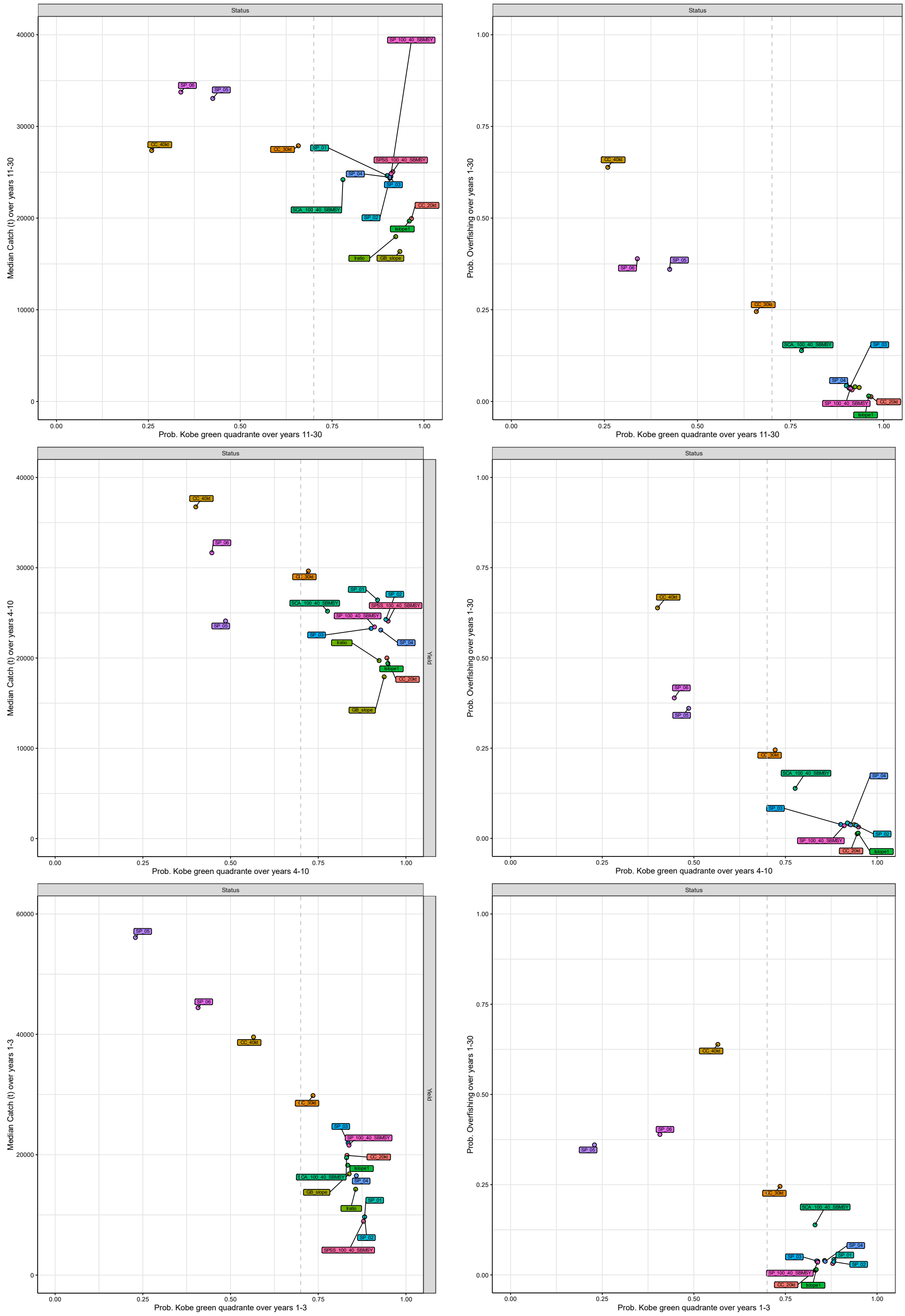


Figure 2. Trade-off plots showing the PM averaged statistics across the reference set of OMs with perfect TAC implementation (OMs 1-9) concerning safety, status, yield and stability for each MP.


Status
Median Catch (t) over years 11-30
Prob. Kobe green quadrante over years 11-30
Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 11-30
Status
Median Catch (t) over years 4-10
Prob. Kobe green quadrante over years 4-10
Yield
Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 4-10
Status
Median Catch (t) over years 1-3
Prob. Kobe green quadrante over years 1-3
Yield
Status
Prob. Overfishing over years 1-30
Prob. Kobe green quadrante over years 1-3

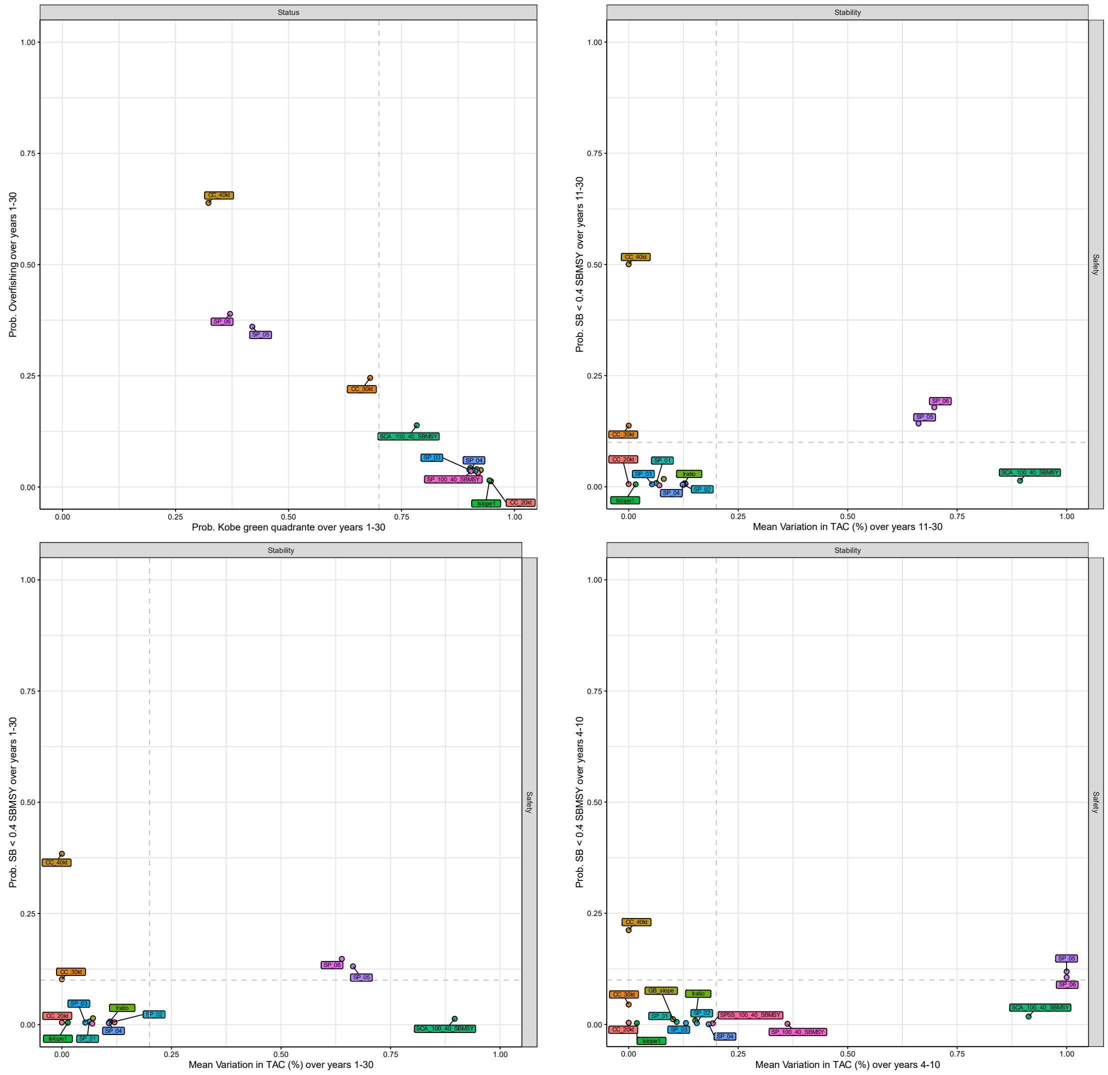
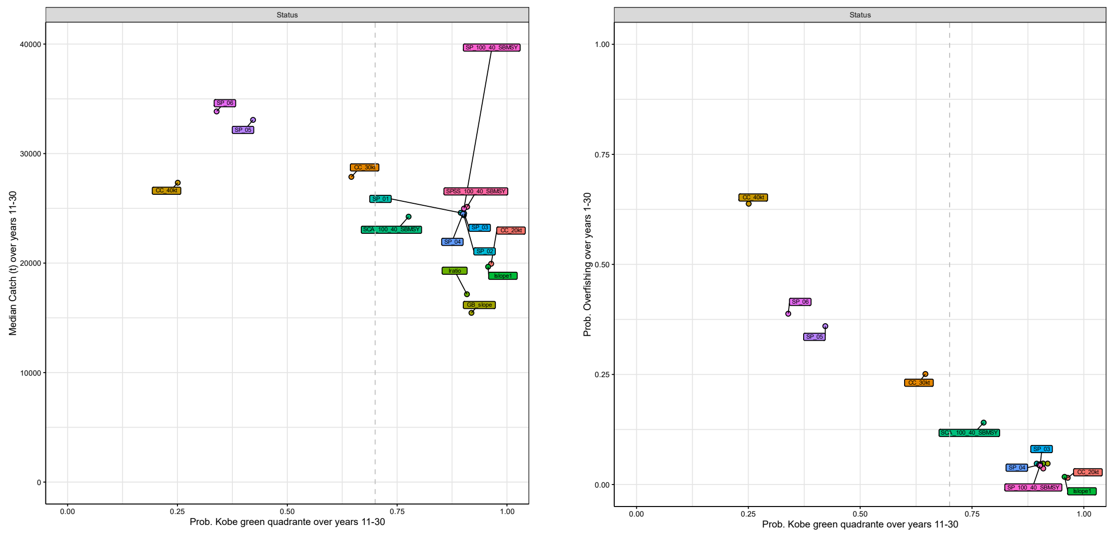
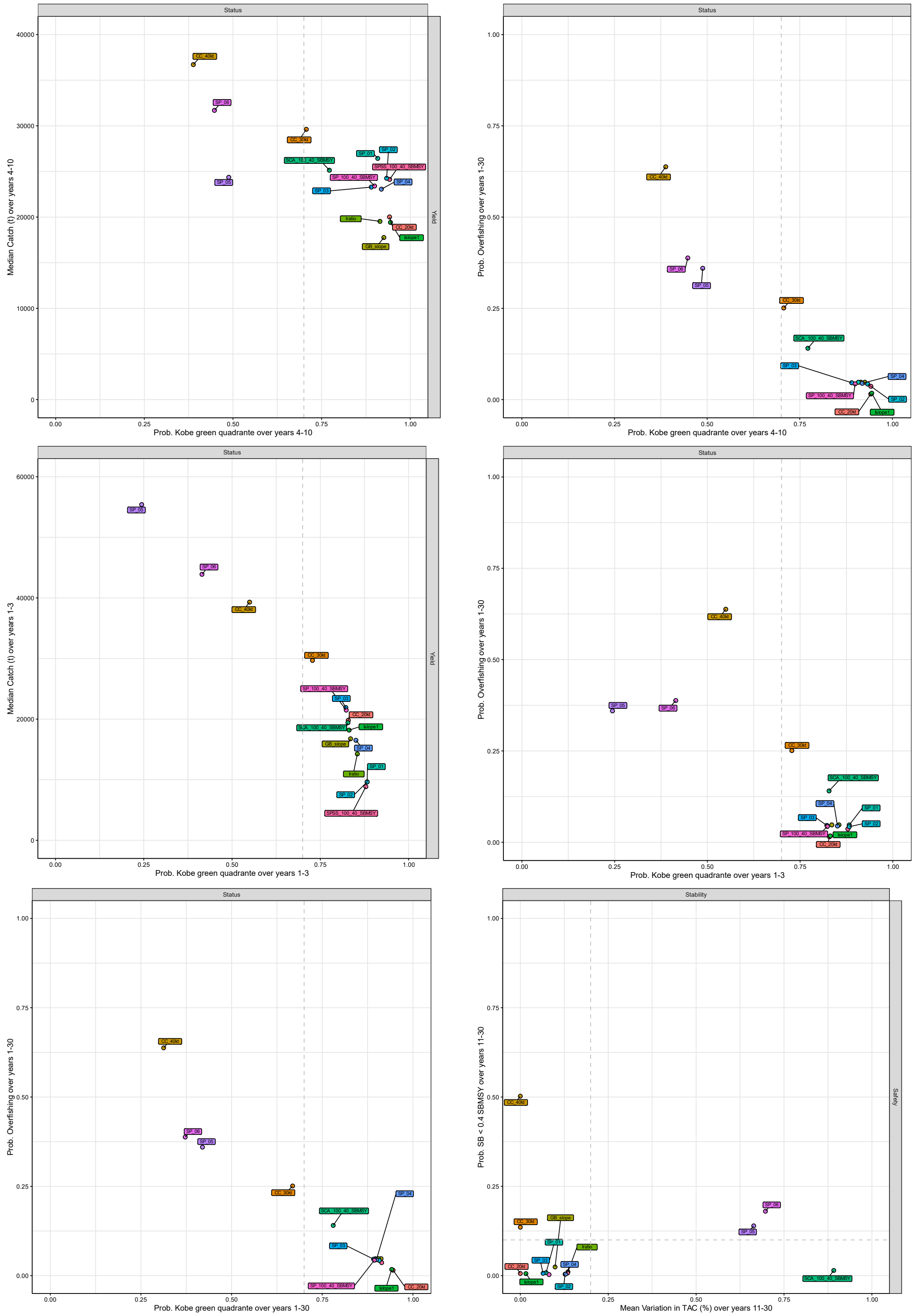


Figure 3. Trade-off plots showing the PM averaged statistics across the reference set of OMs with 10% TAC implementation error (OMs 10-18) concerning safety, status, yield and stability for each MP.




Status
Yield
Median Catch (t) over years 4-10
Prob. Kobe green quadrante over years 4-10
Prob. Overfishing over years 1-30
Median Catch (t) over years 1-3
Prob. Kobe green quadrante over years 1-3
Prob. Kobe green quadrante over years 1-30
Stability
Safety
Prob. SB < 0.4 SBMSY over years 11-30
Mean Variation in TAC (%) over years 11-30

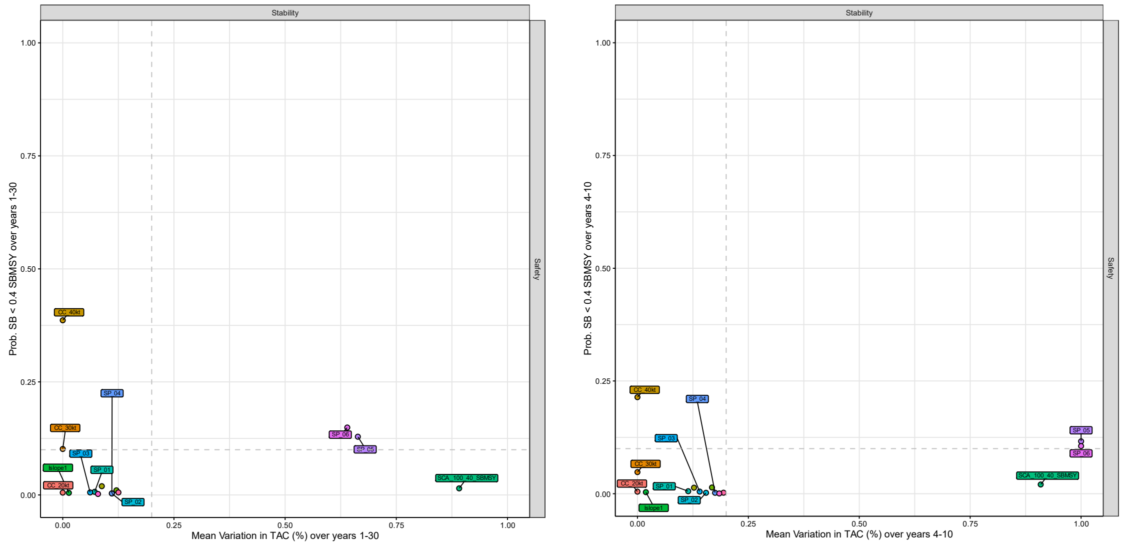


Figure 4. Trade-off plots showing the PM averaged statistics across the reference set of OMs with 20% TAC implementation error (OMs 19-27) concerning safety, status, yield and stability for each MP.

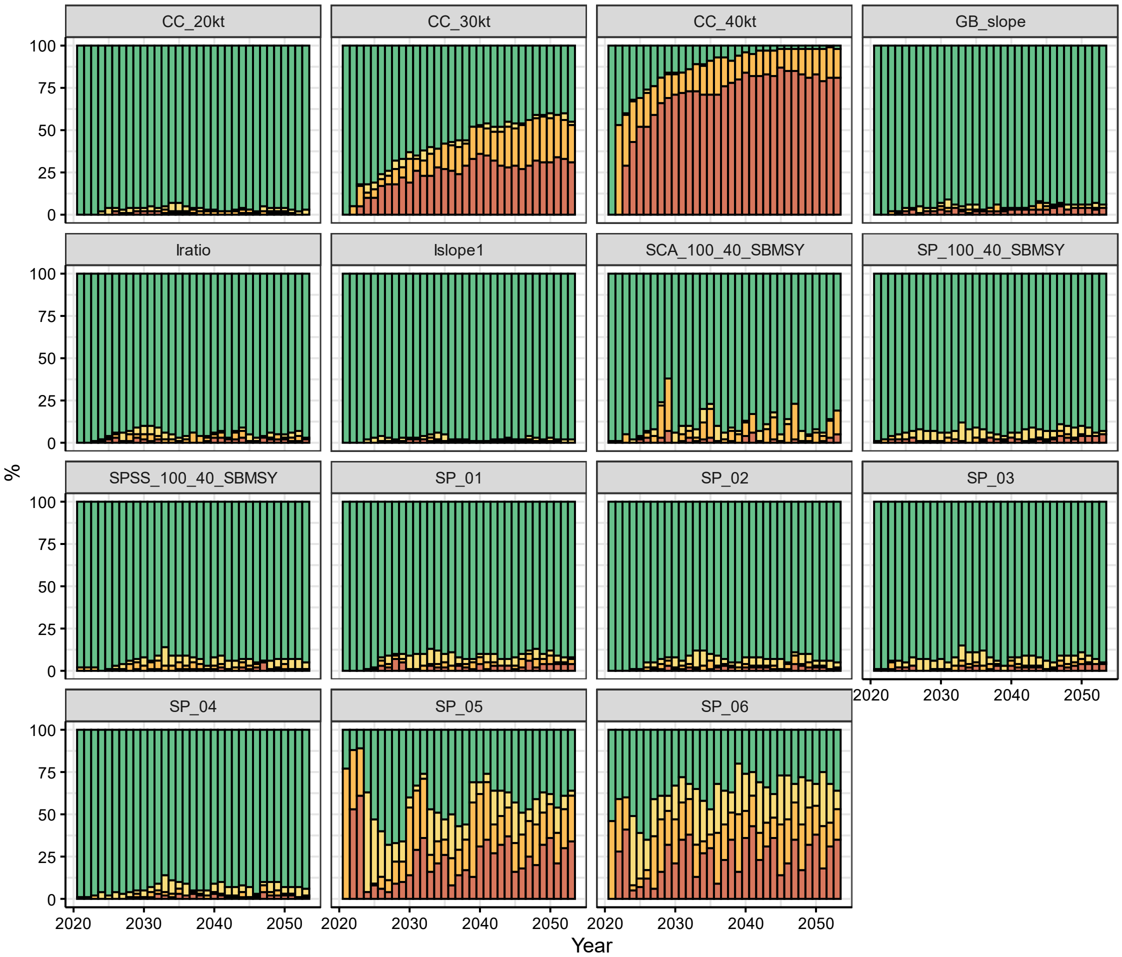


Figure 5. Probability of being in each of the Kobe plot quadrant through years across the reference set of OMs with perfect TAC implementation error (OMs 1-9).

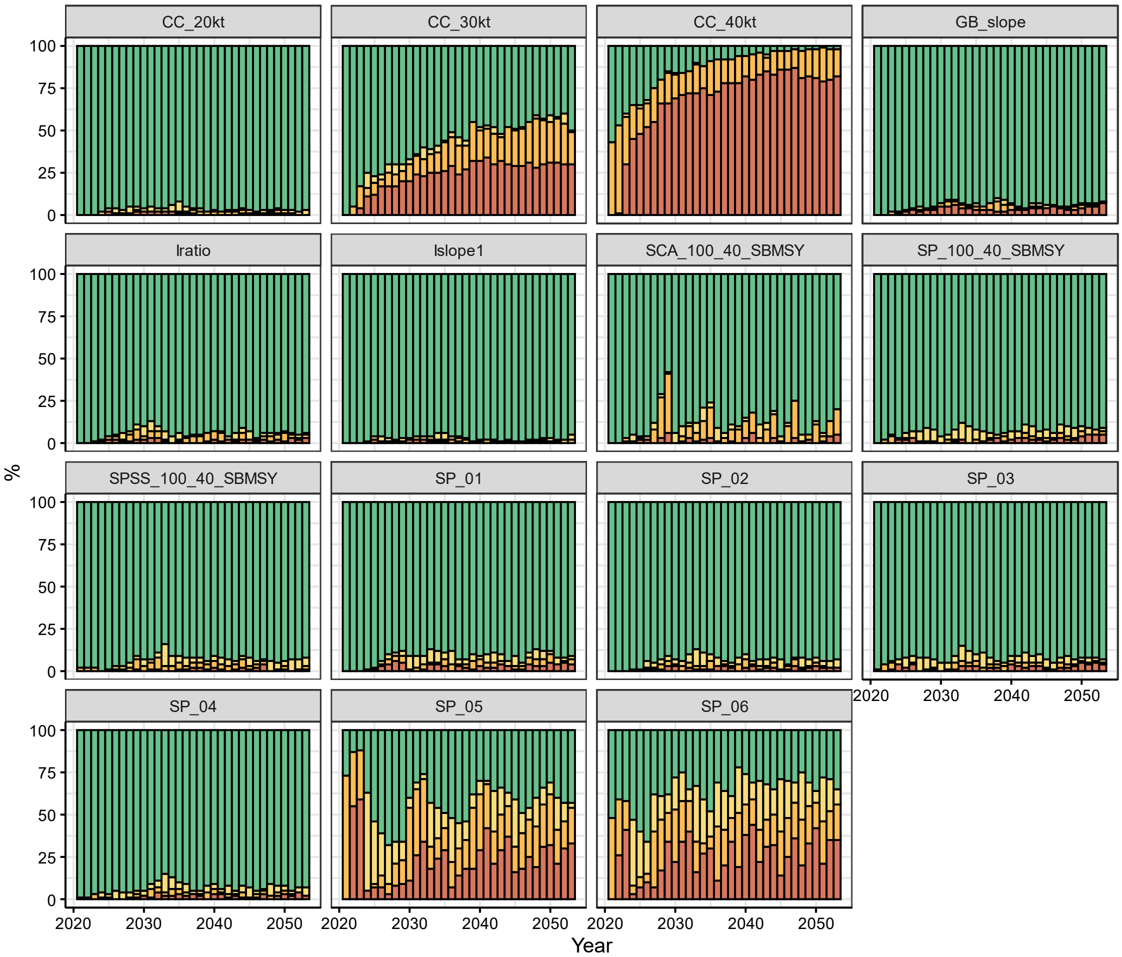


Figure 6. Probability of being in each of the Kobe plot quadrant through years across the reference set of OMs with 10% TAC implementation error (OMs 10-18).

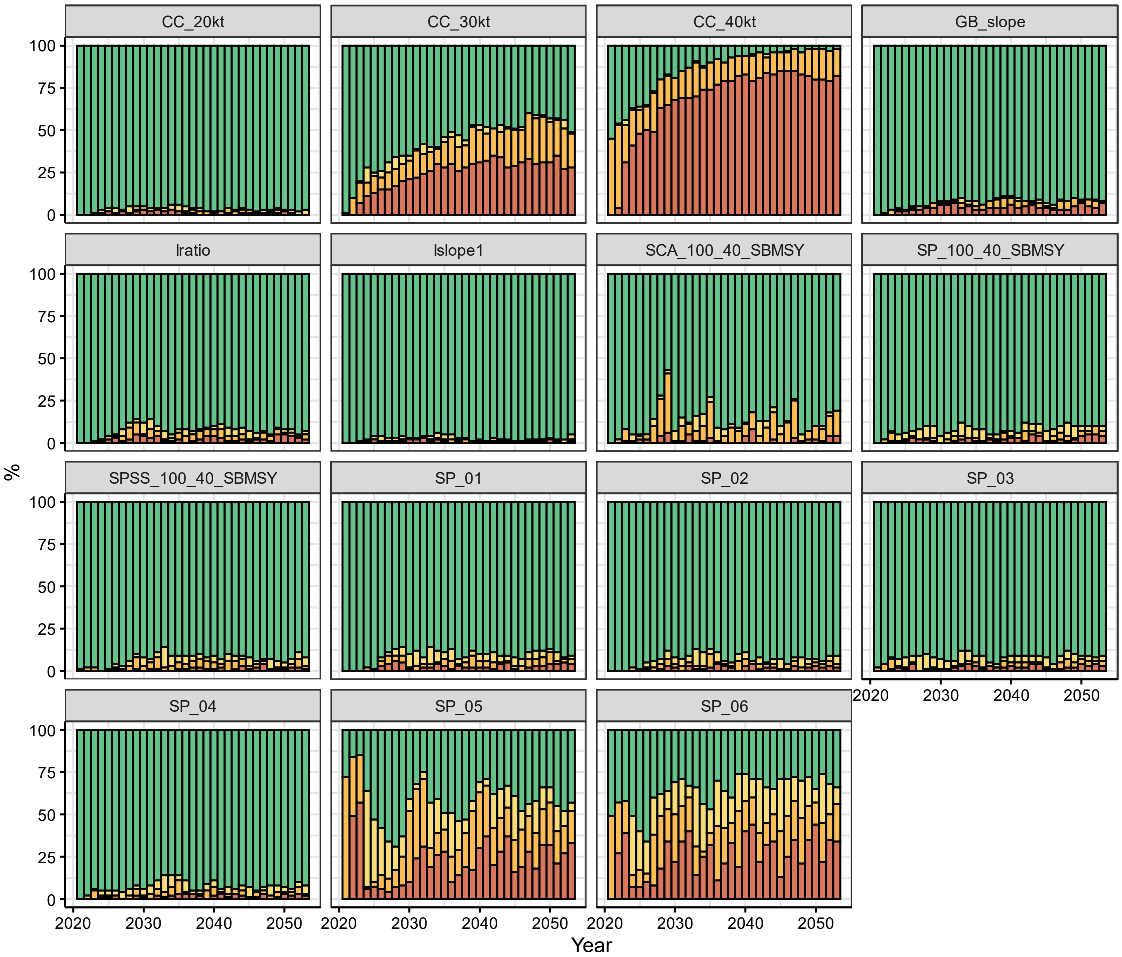


Figure 7. Probability of being in each of the Kobe plot quadrant through years across the reference set of OMs with 20% TAC implementation error (OMs 19-27).

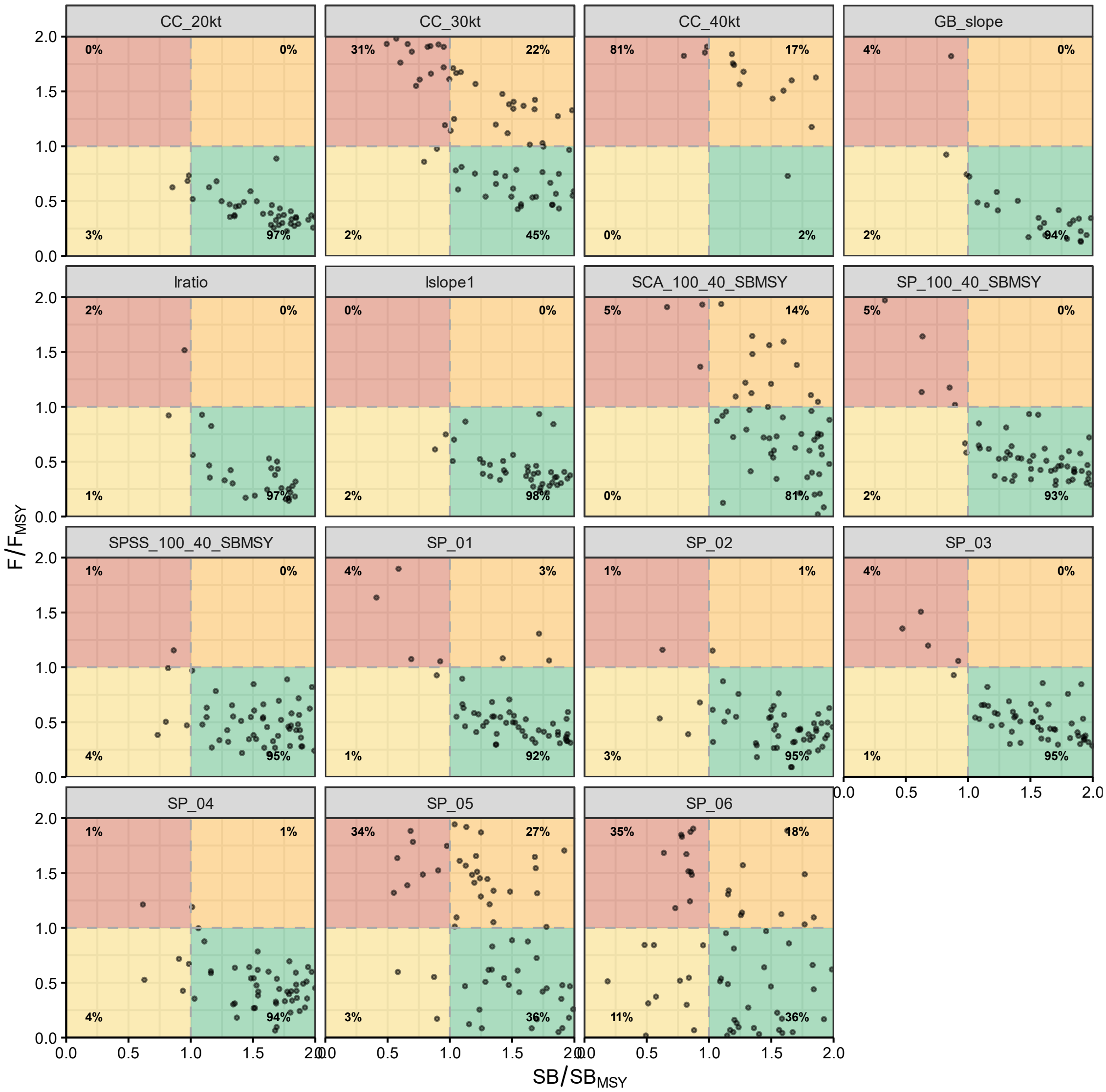


Figure 8. Probability of being in each of the Kobe plot quadrant in the last year across the reference set of OMs with perfect TAC implementation error (OMs 1-9).

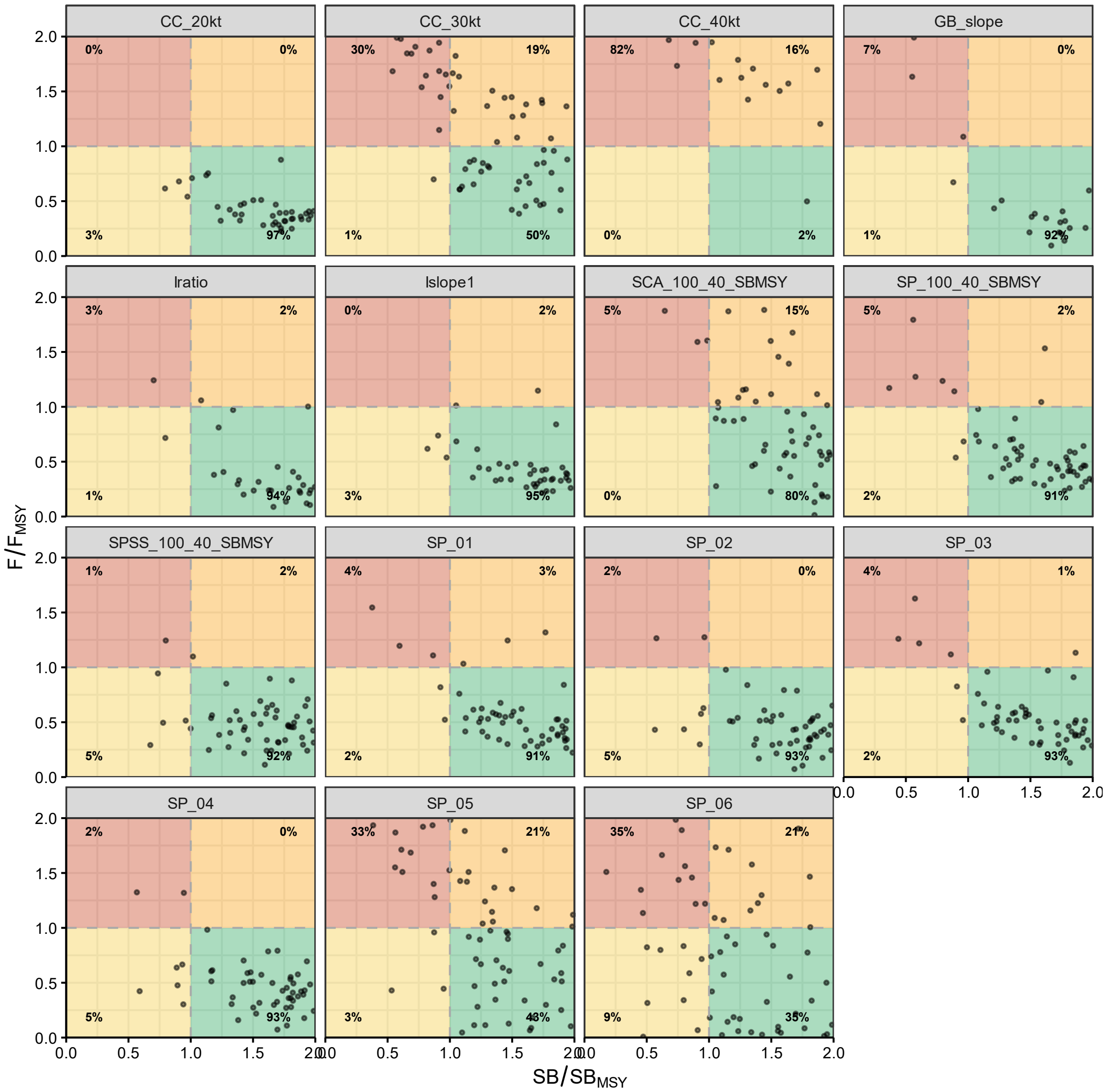


Figure 9. Probability of being in each of the Kobe plot in the last year across the reference set of OMs with 10% TAC implementation error (OMs 10-18).

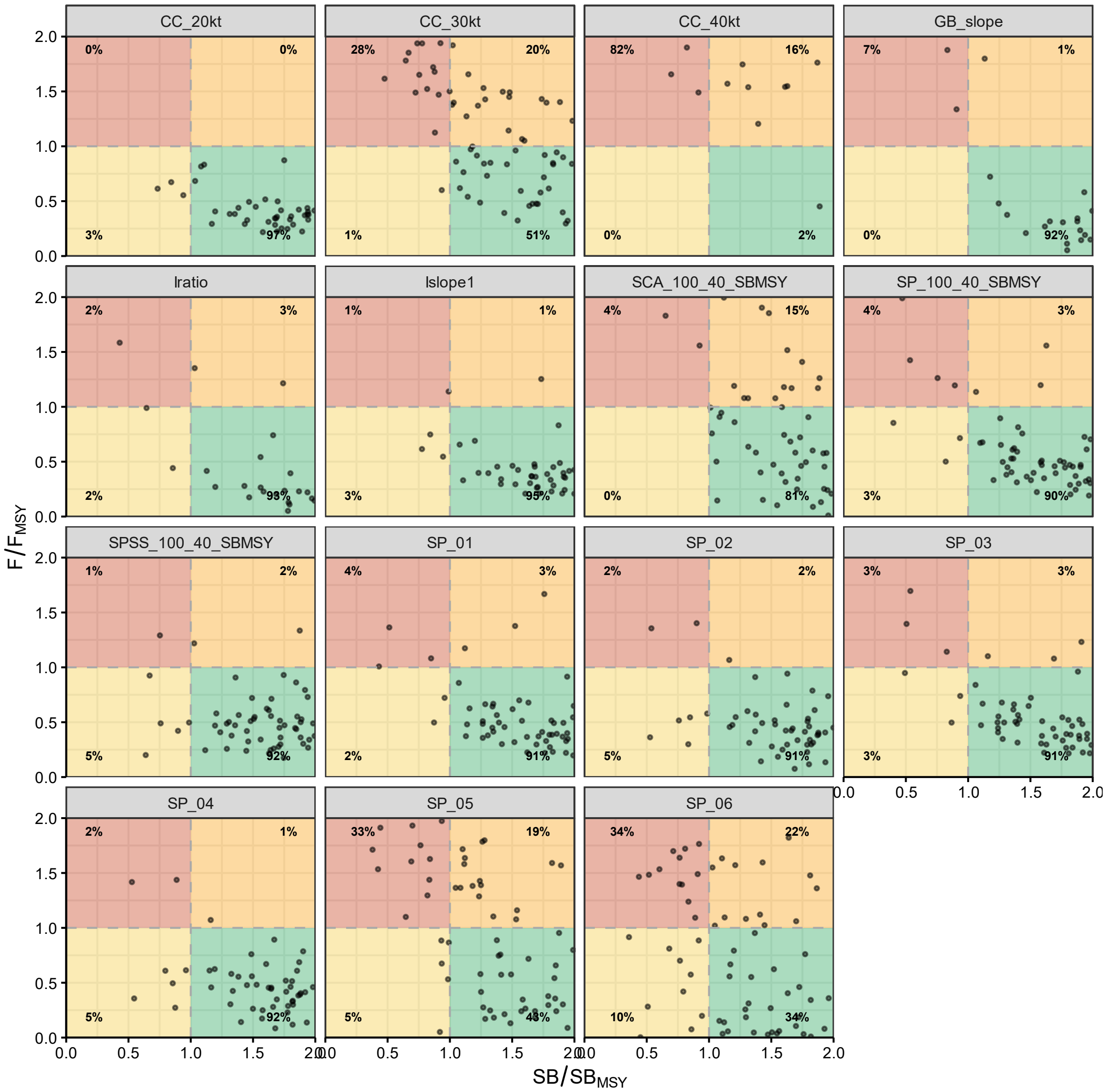
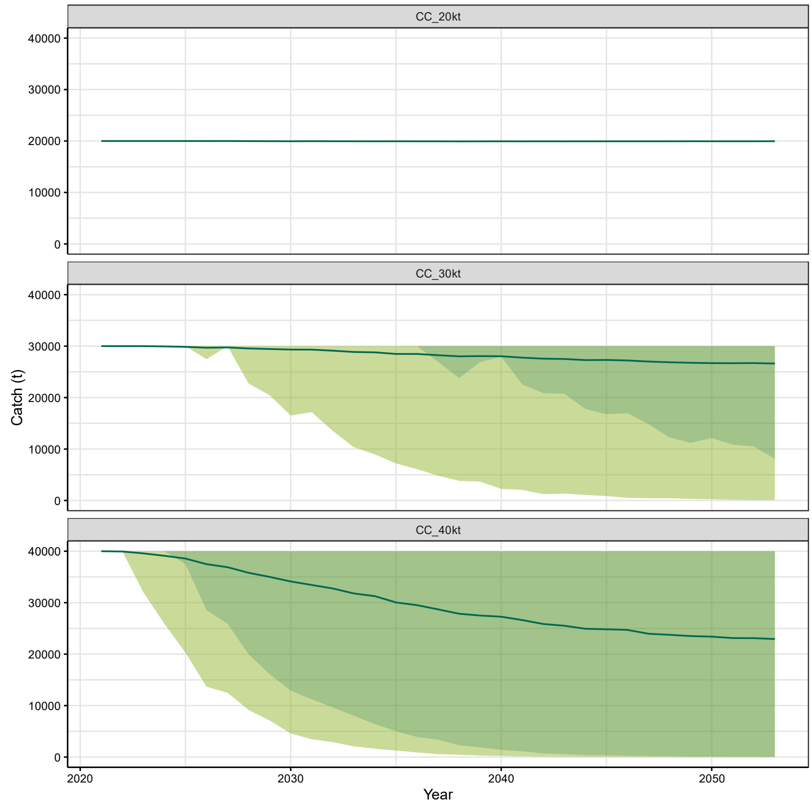
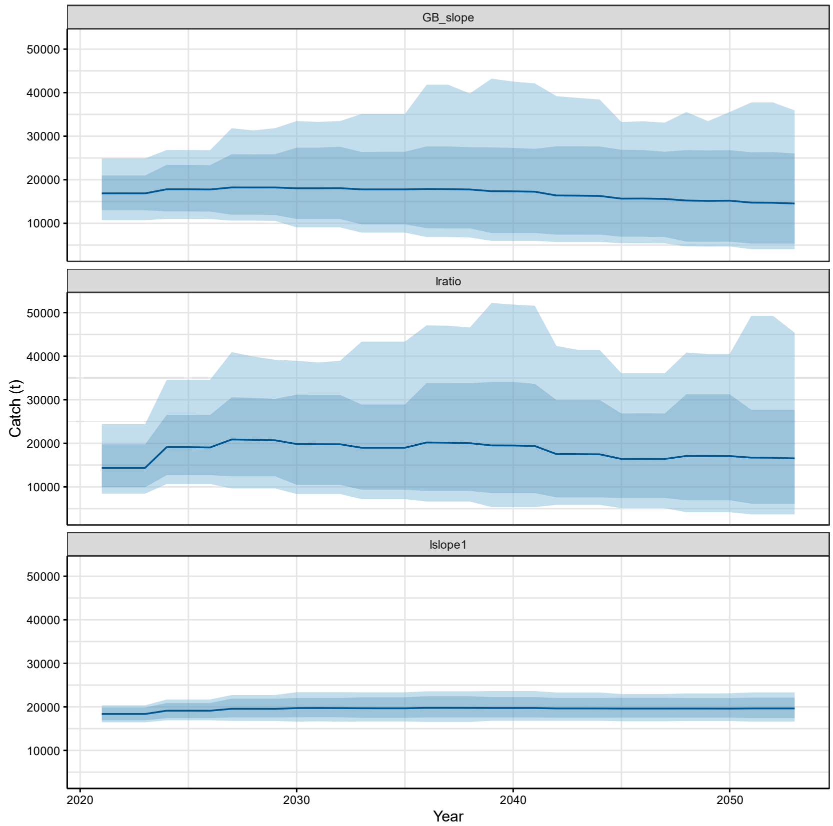


Figure 10. Probability of being in each of the Kobe plot in the last year across the reference set of OMs with 20% TAC implementation error (OMs 19-27).


CC_20kt
CC_30kt
CC_40kt
Catch (t)
Year
40000
30000
20000
10000
0
2020
2030
2040
2050


GB_slope
Iratio
Islope1
Catch (t)
Year
50000
40000
30000
20000
10000
2020
2030
2040
2050

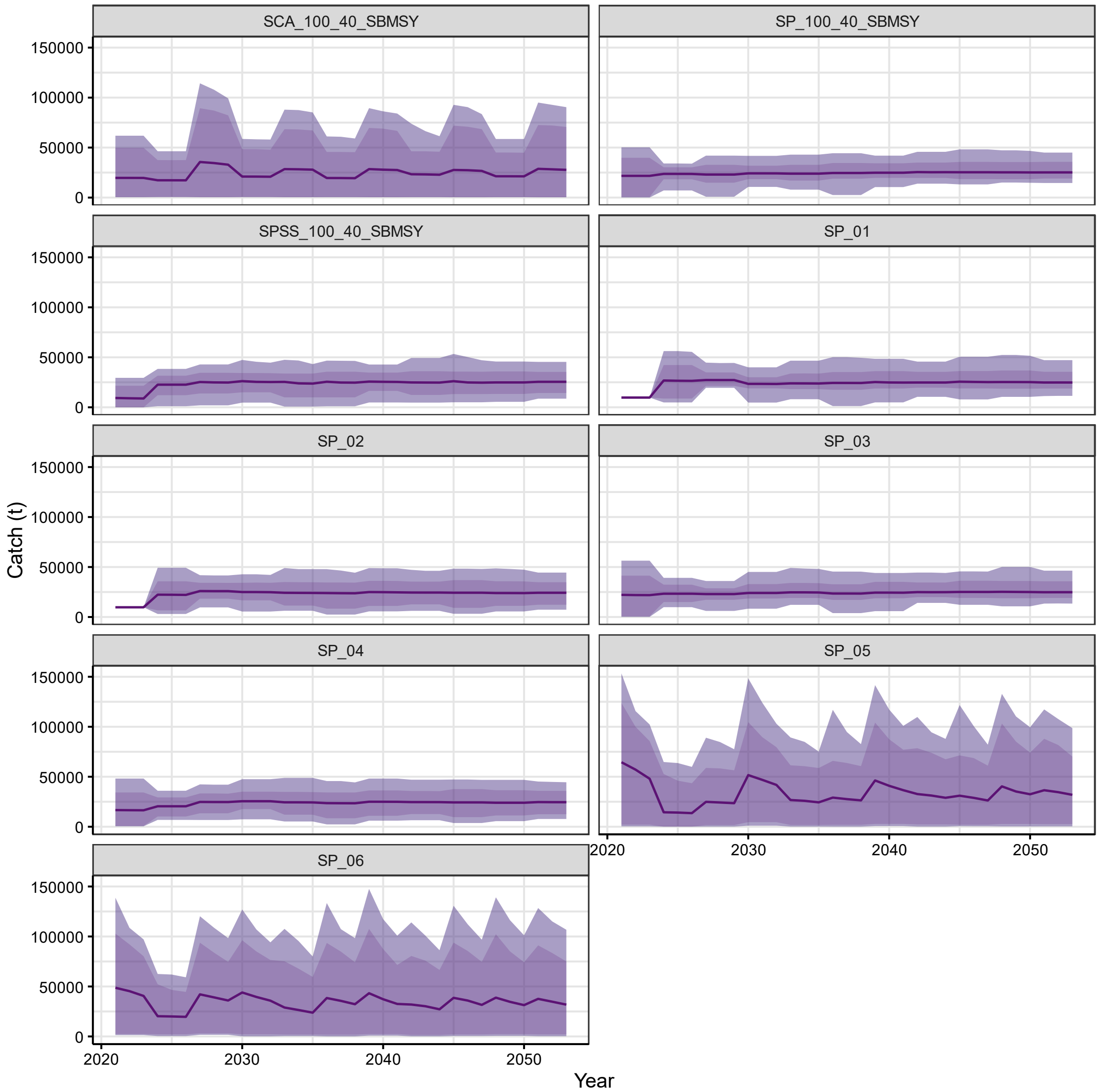
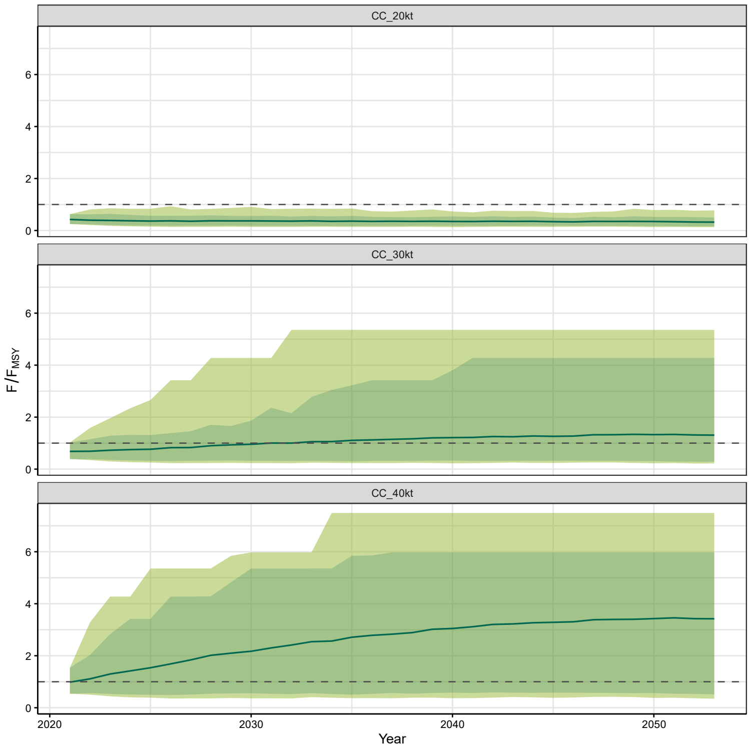
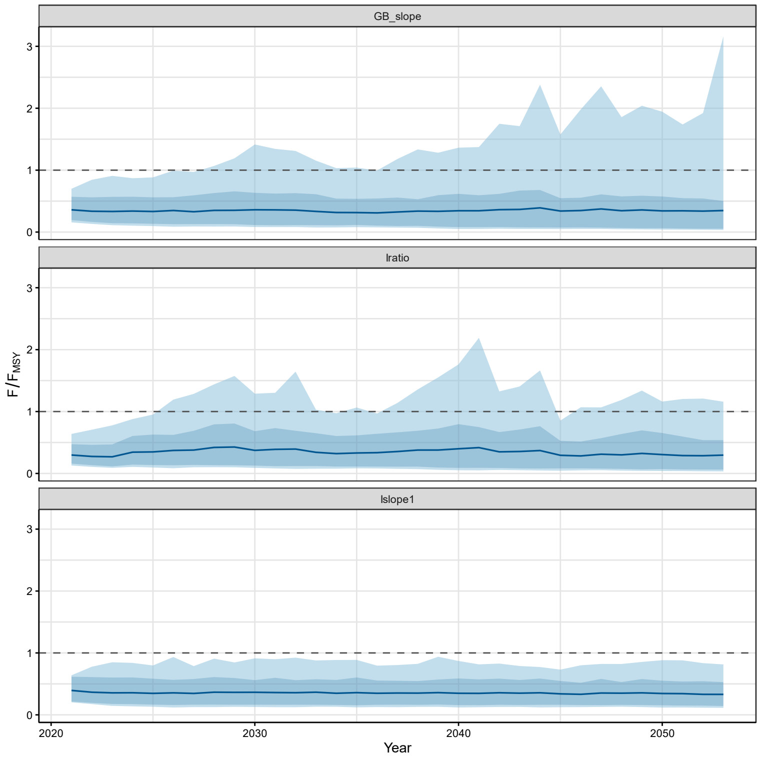


Figure 11. Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with perfect TAC implementation error (OMs 1-9).


CC_20kt
CC_30kt
CC_40kt
F/FMSY
0
2
4
6
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
F/FMSY
0
1
2
3
2020
2030
2040
2050
Year

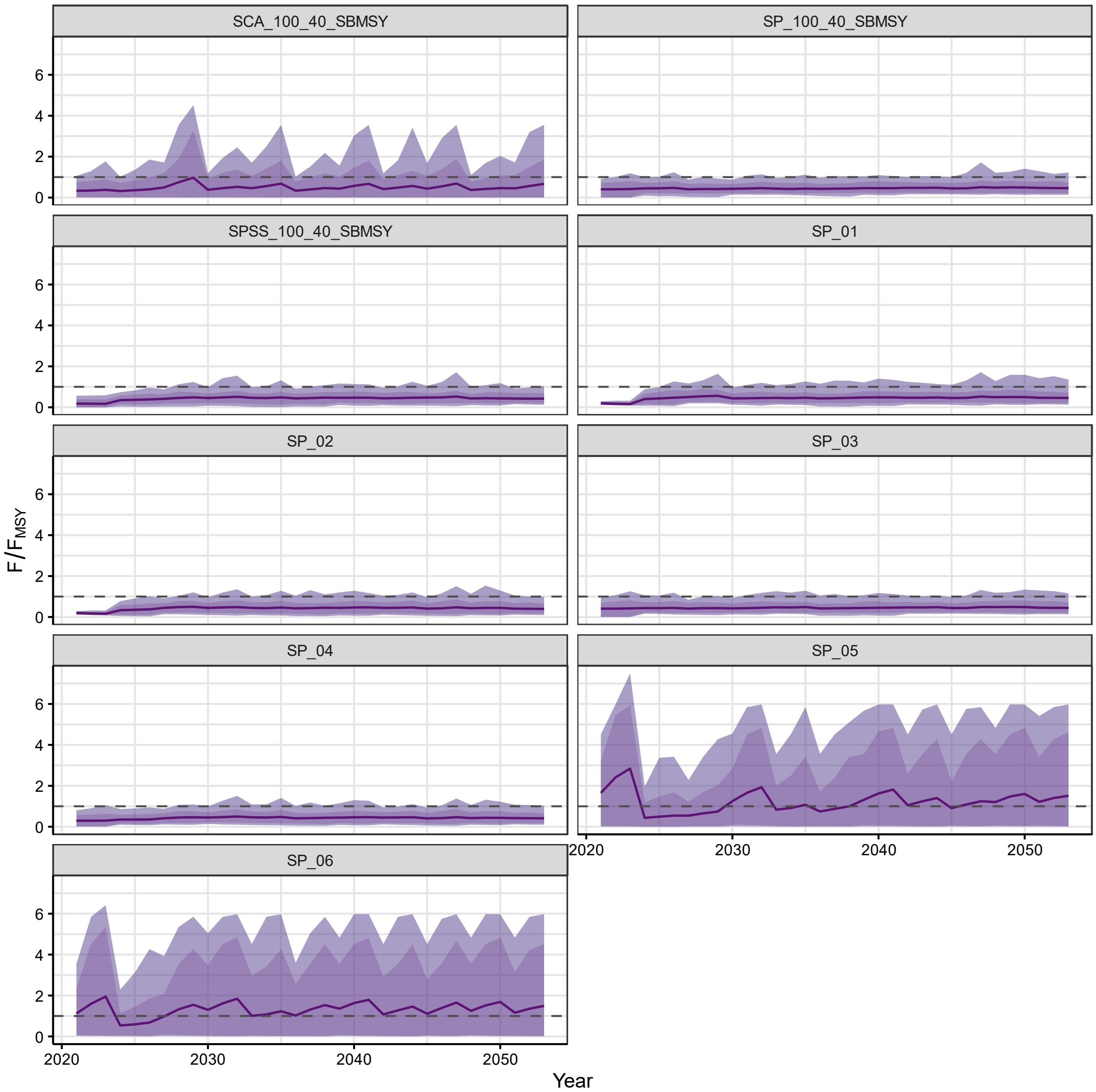
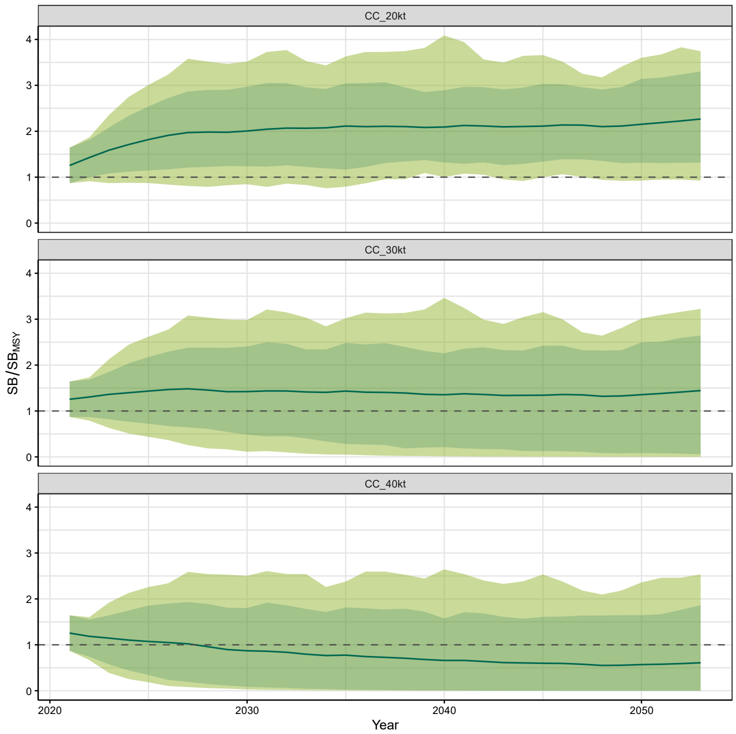
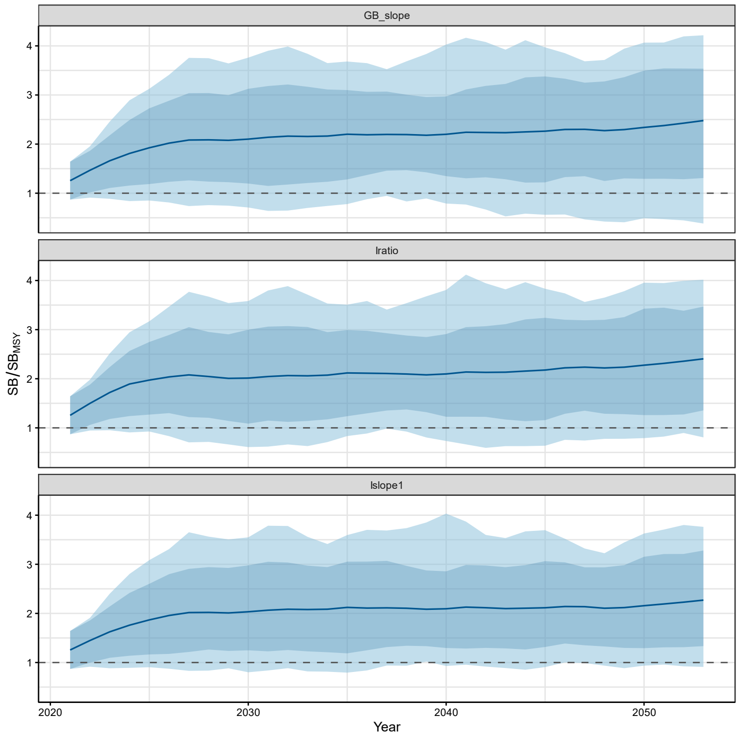


Figure 12. F/F_{MSY} from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with perfect TAC implementation error (OMs 1-9).


CC_20kt
CC_30kt
CC_40kt
SB/SB$_{MSY}$
0
1
2
3
4
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
SB/SB$_{MSY}$
1
2
3
4
2020
2030
2040
2050
Year

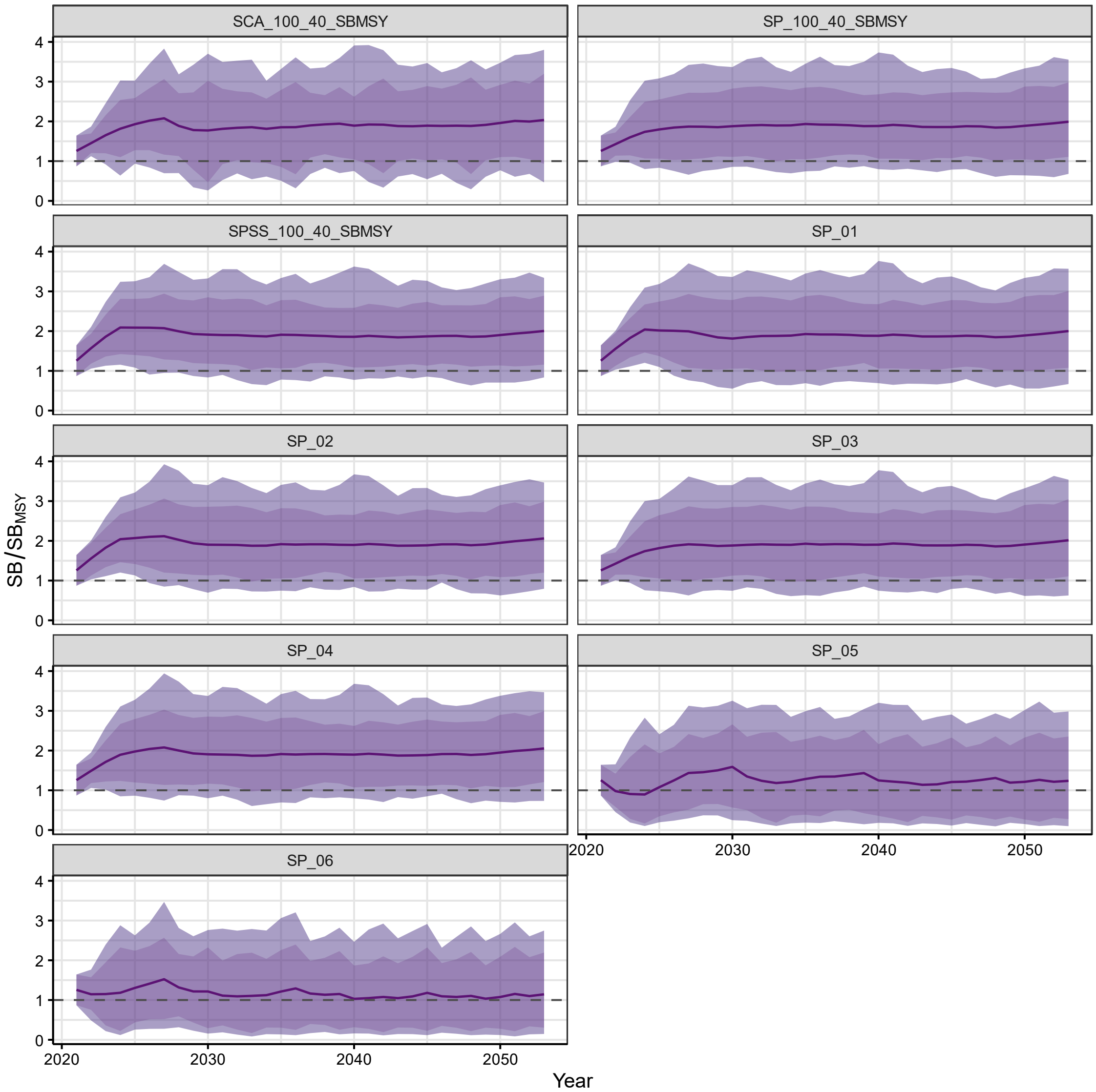
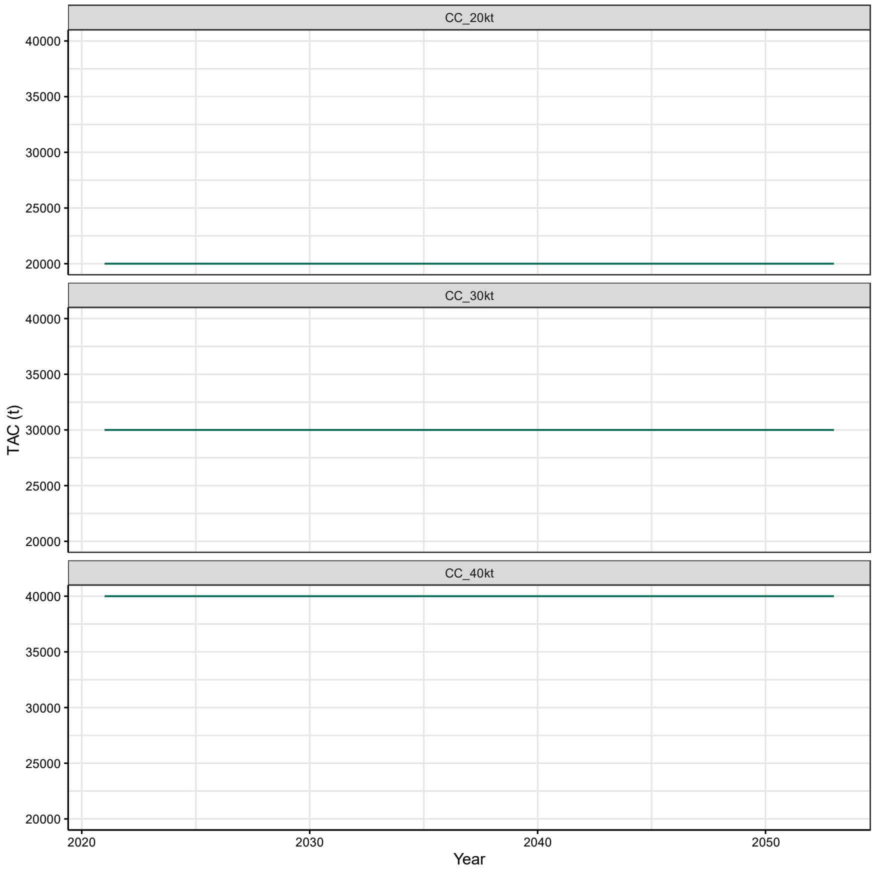
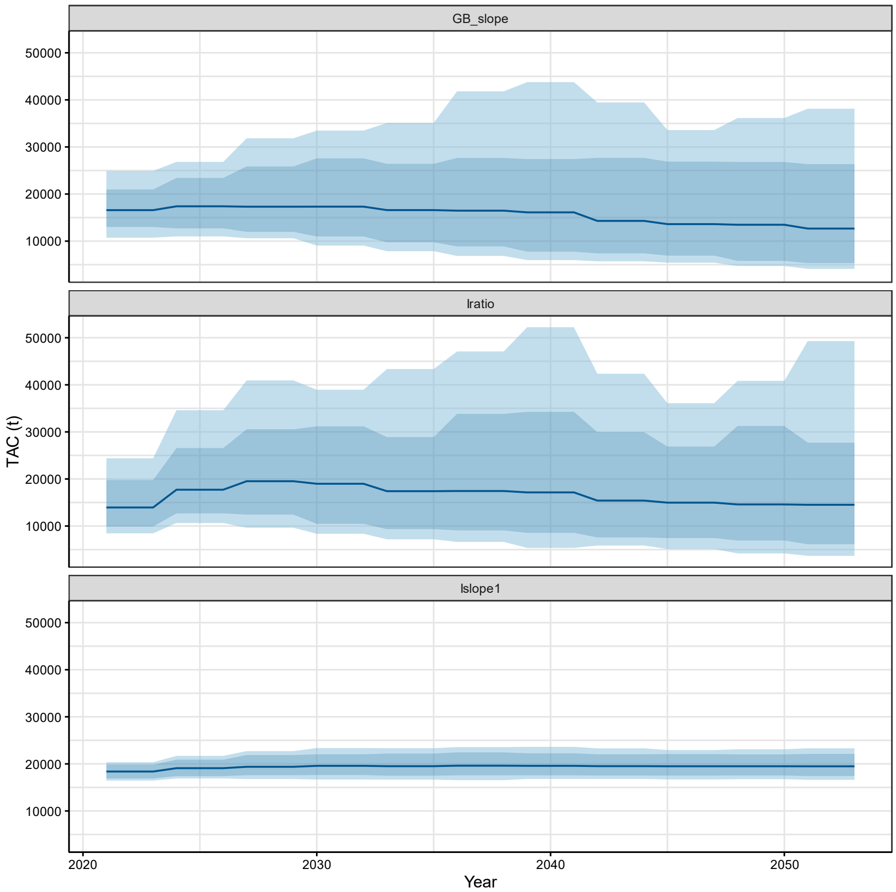


Figure 13. SB/SB_{MSY} from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with perfect TAC implementation error (OMs 1-9).


CC_20kt
CC_30kt
CC_40kt
TAC (t)
Year
20000
25000
30000
35000
40000
2020
2030
2040
2050


GB_slope
Iratio
Islope1
TAC (t)
Year
10000
20000
30000
40000
50000
2020
2030
2040
2050

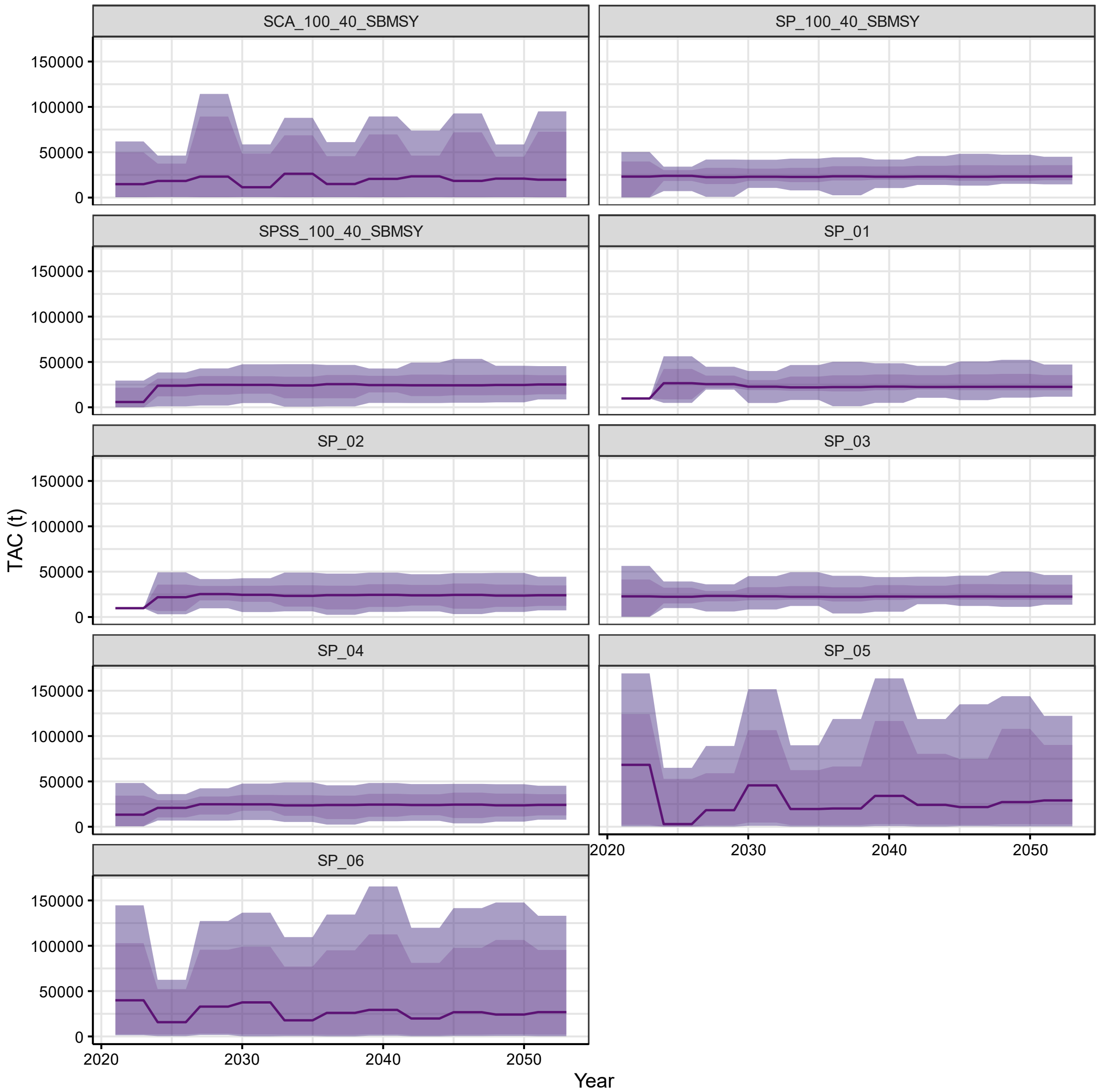
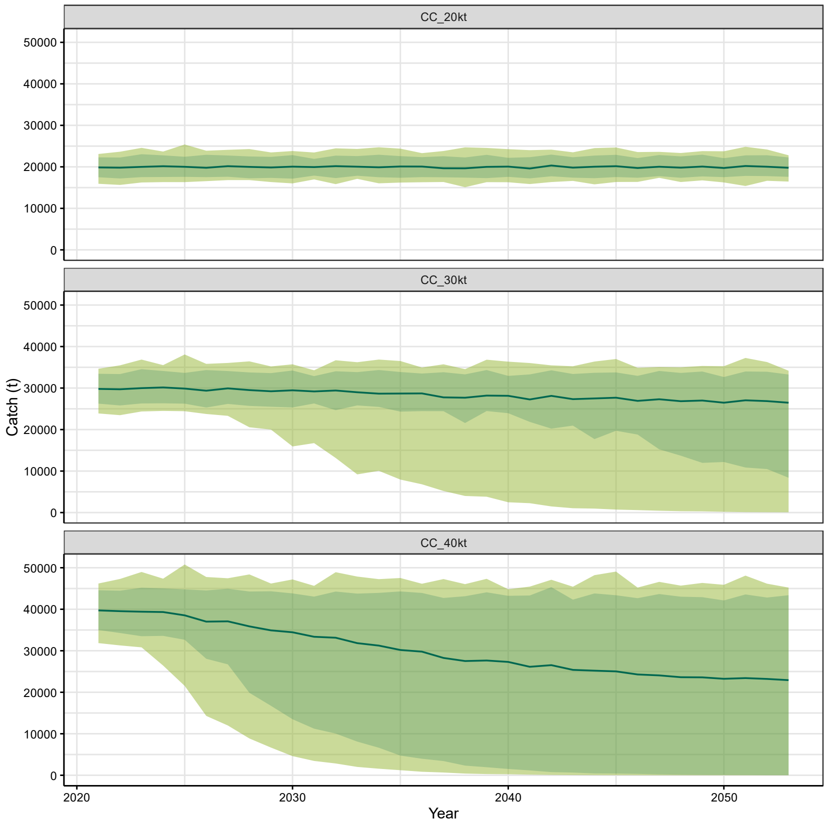
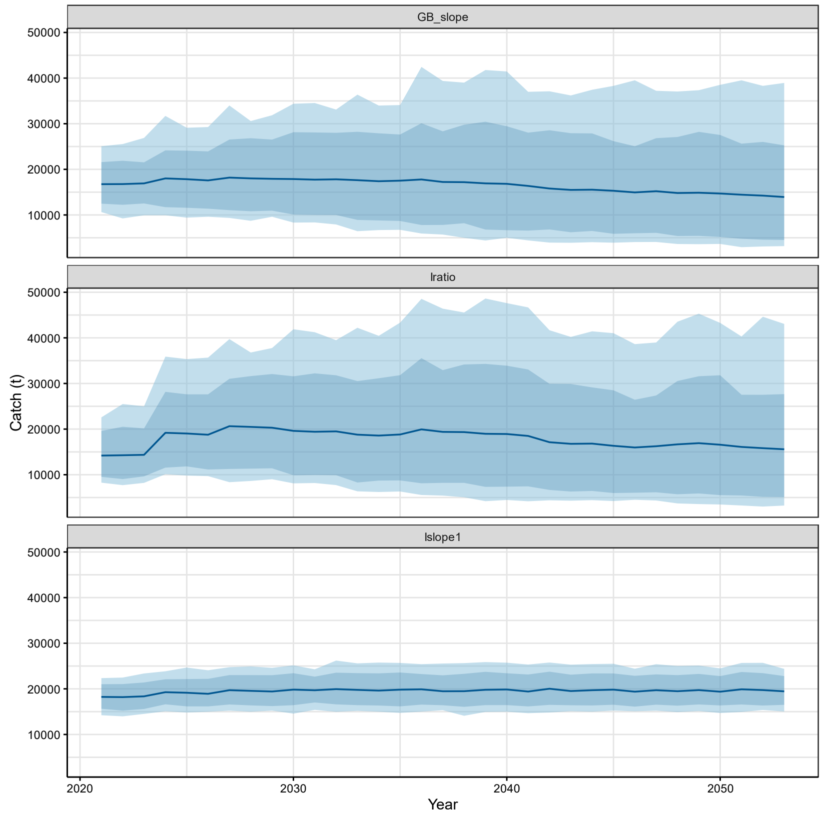


Figure 14. Total Allowable Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with perfect TAC implementation error (OMs 10-18).


CC_20kt
CC_30kt
CC_40kt
Catch (t)
Year
0
10000
20000
30000
40000
50000
2020
2030
2040
2050


GB_slope
Iratio
Islope1
Catch (t)
Year
10000
20000
30000
40000
50000
2020
2030
2040
2050

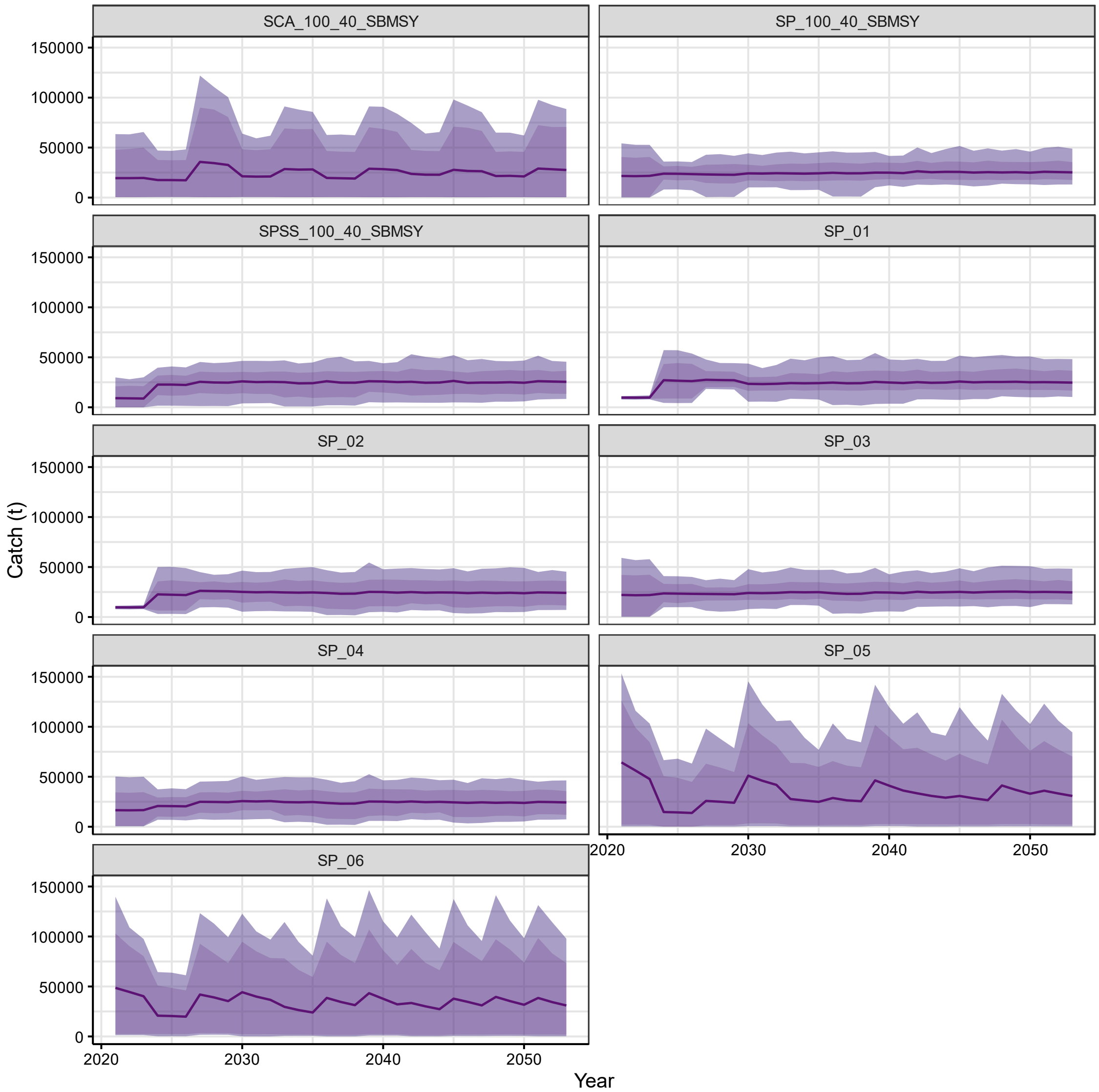
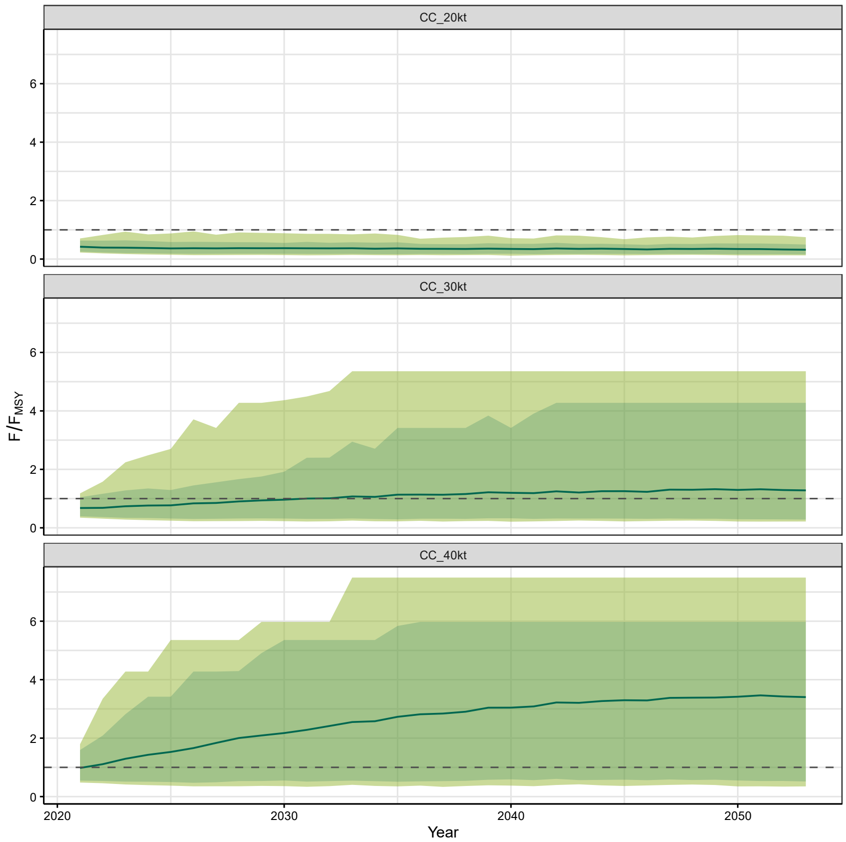
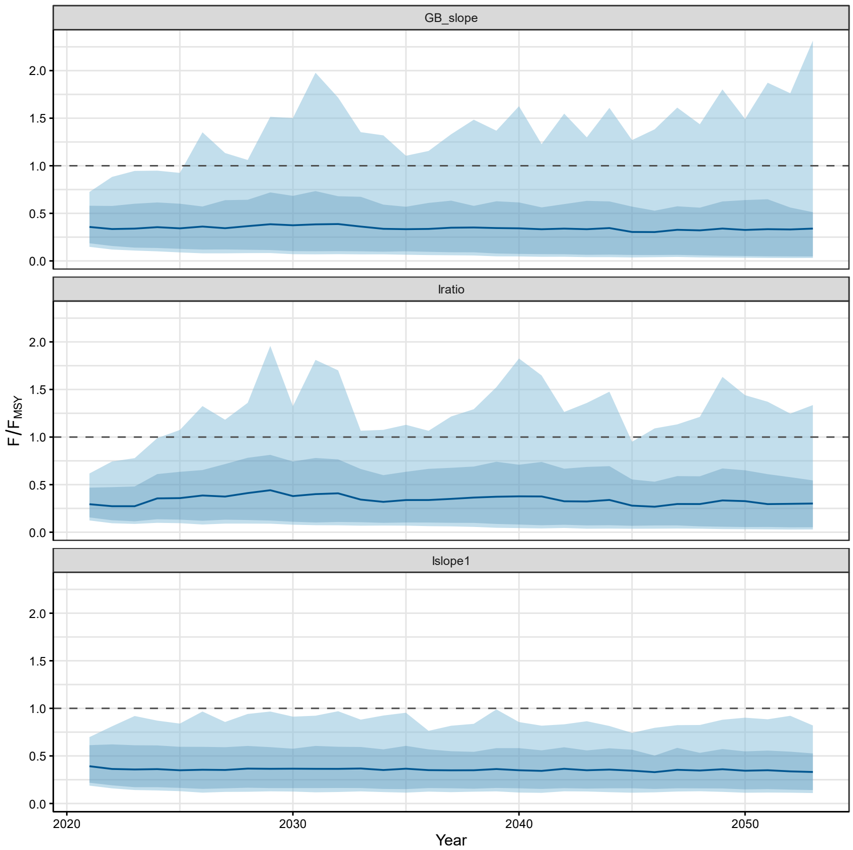


Figure 15. Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 10% of implementation error (OMs 10-18).


CC_20kt
CC_30kt
CC_40kt
F/F_MSY
Year
2020
2030
2040
2050
0
2
4
6


GB_slope
Iratio
Islope1
F/F_MSY
Year
2020
2030
2040
2050
0.0
0.5
1.0
1.5
2.0

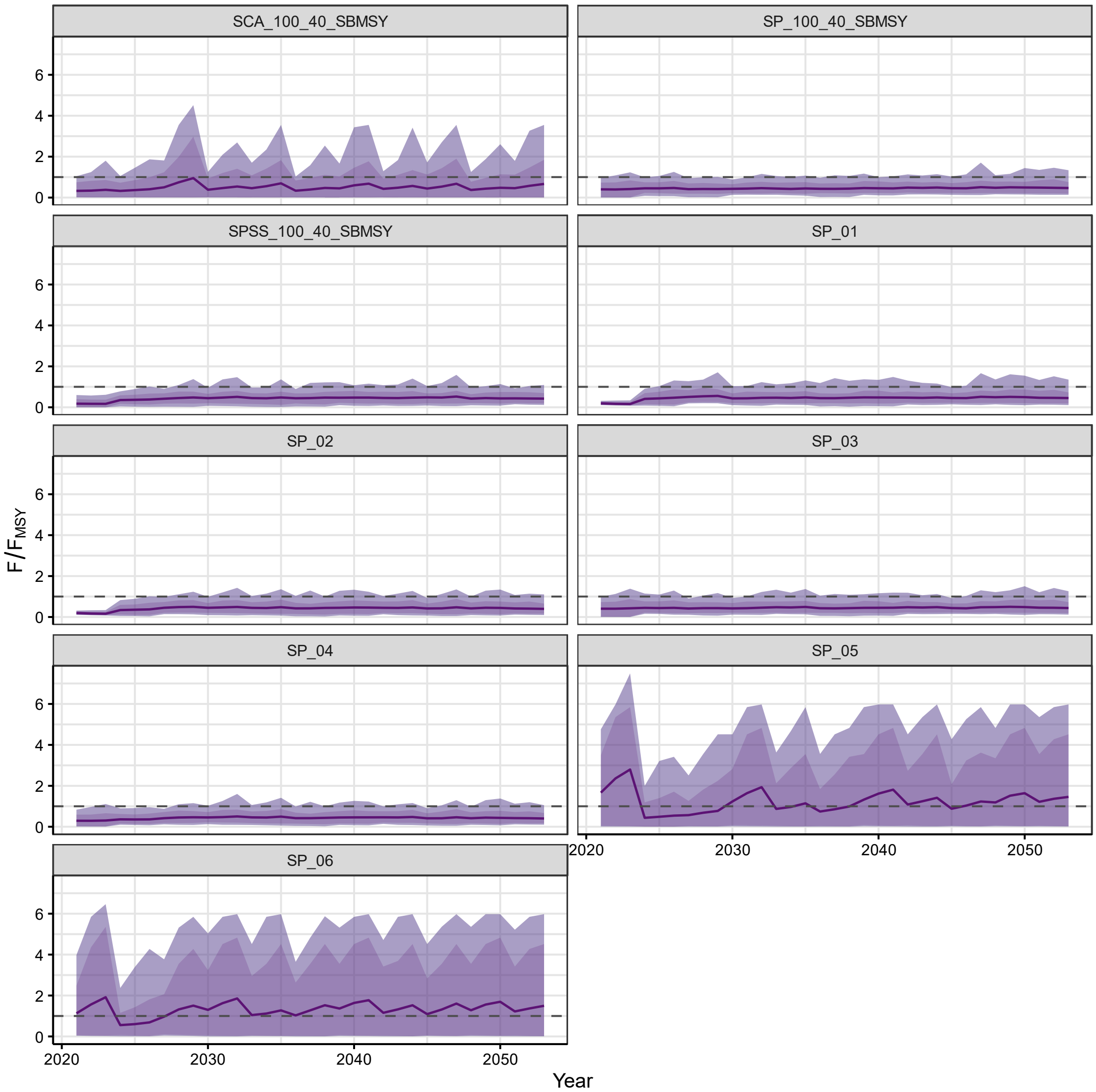
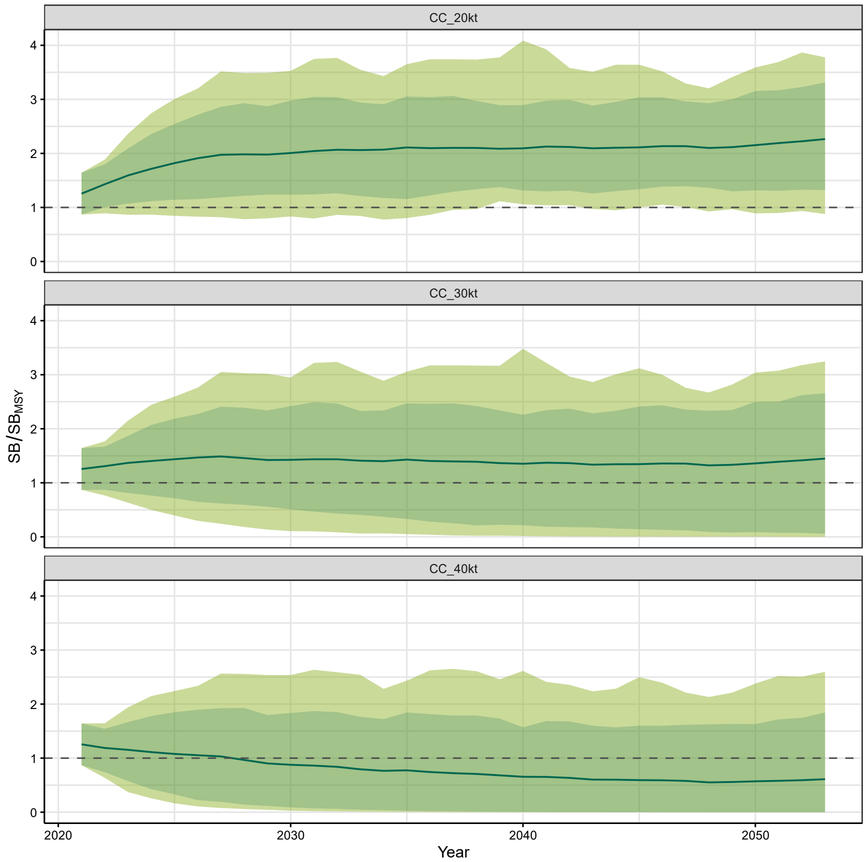
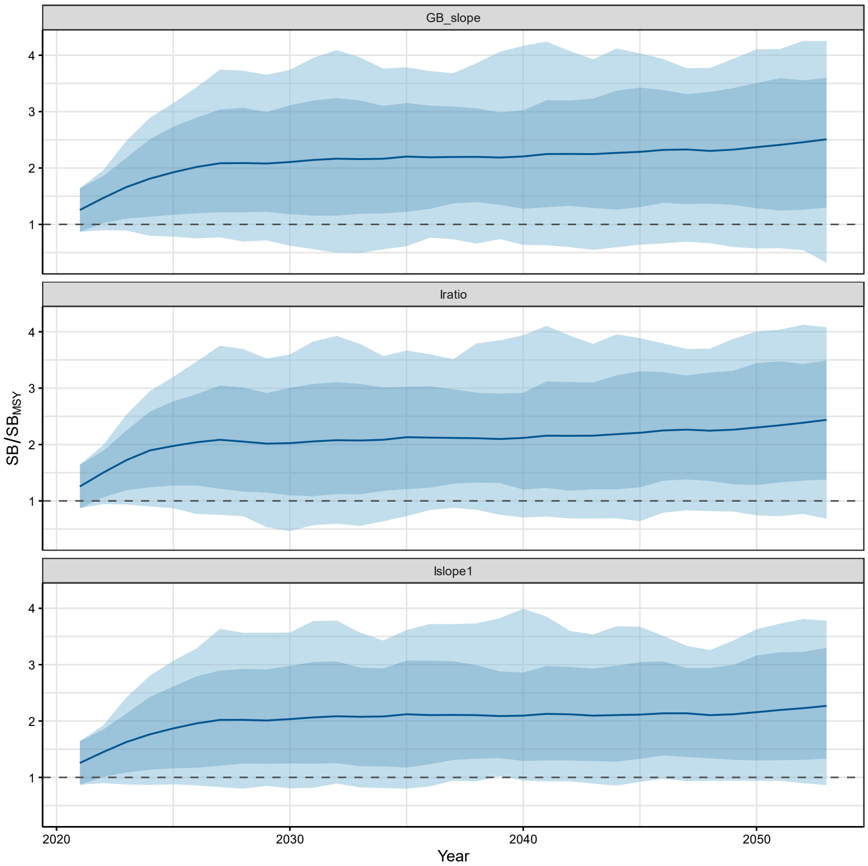


Figure 16. F/F_{MSY} from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 10% of implementation error (OMs 10-18).


CC_20kt
CC_30kt
CC_40kt
SB/SB$_{MSY}$
0
1
2
3
4
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
SB/SB$_{MSY}$
1
2
3
4
2020
2030
2040
2050
Year

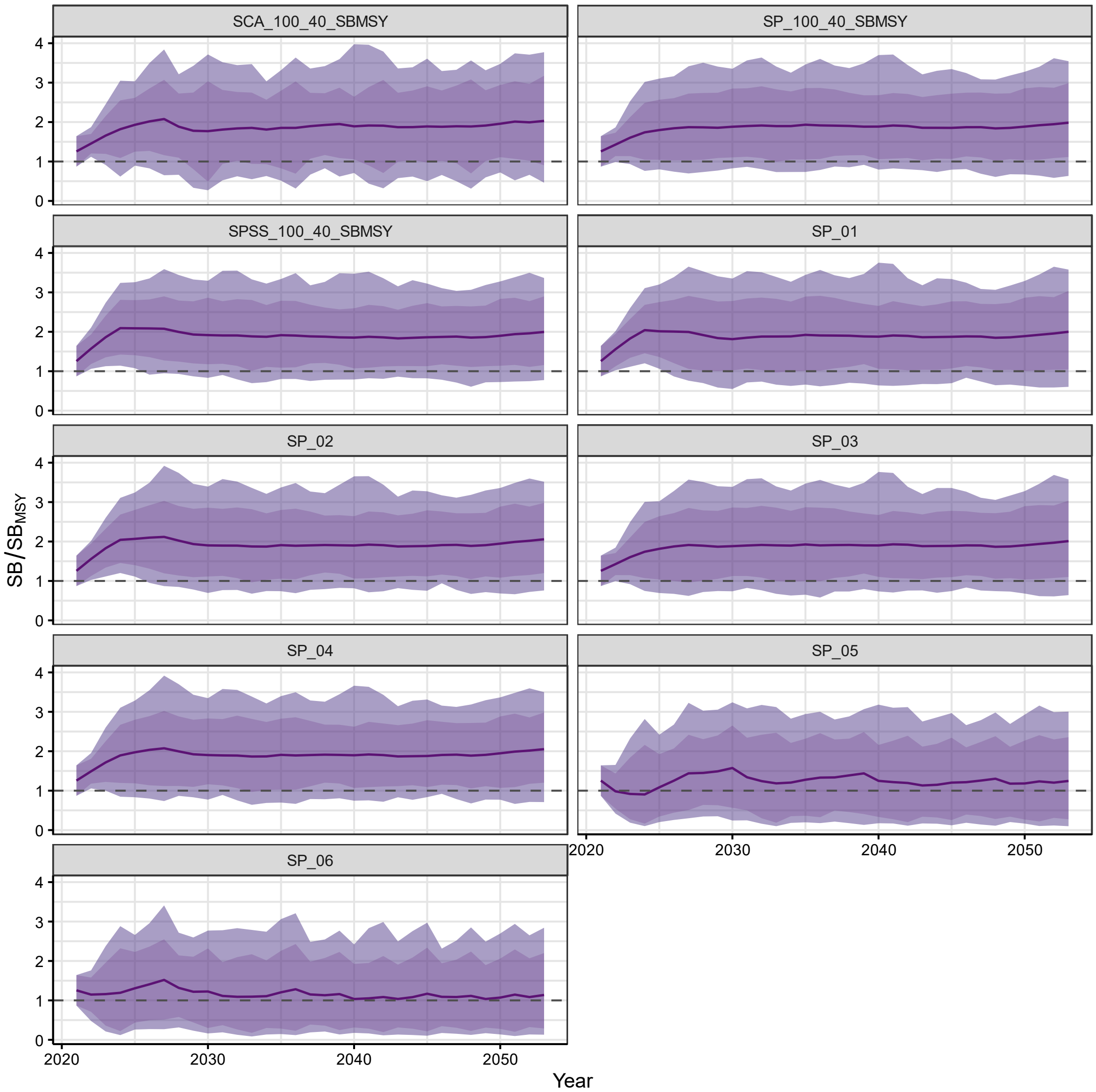
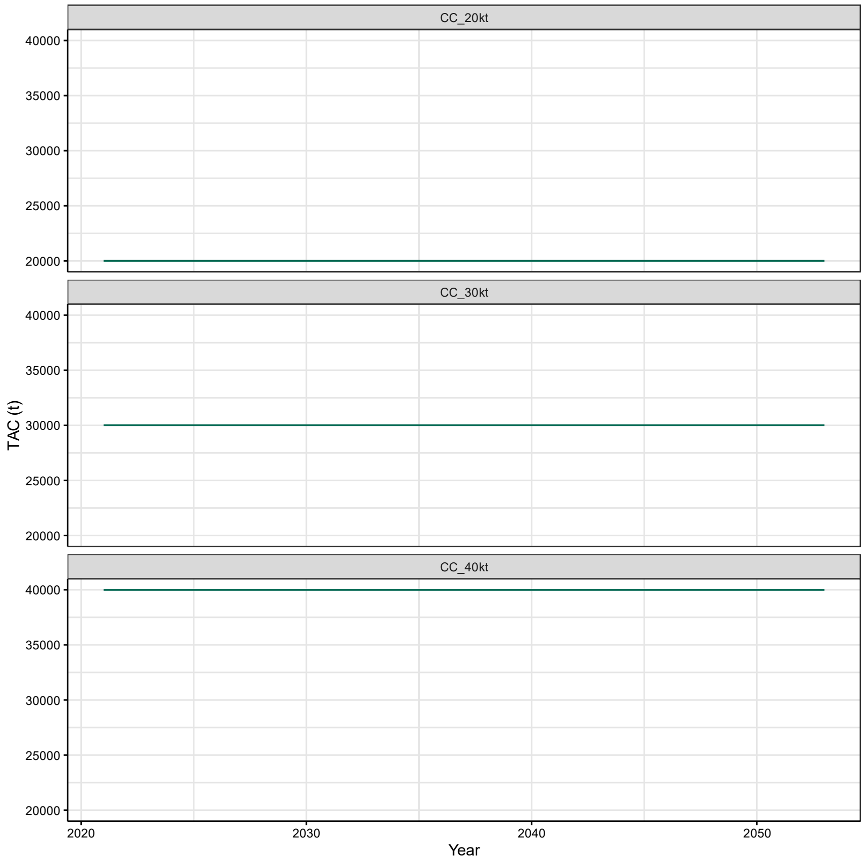
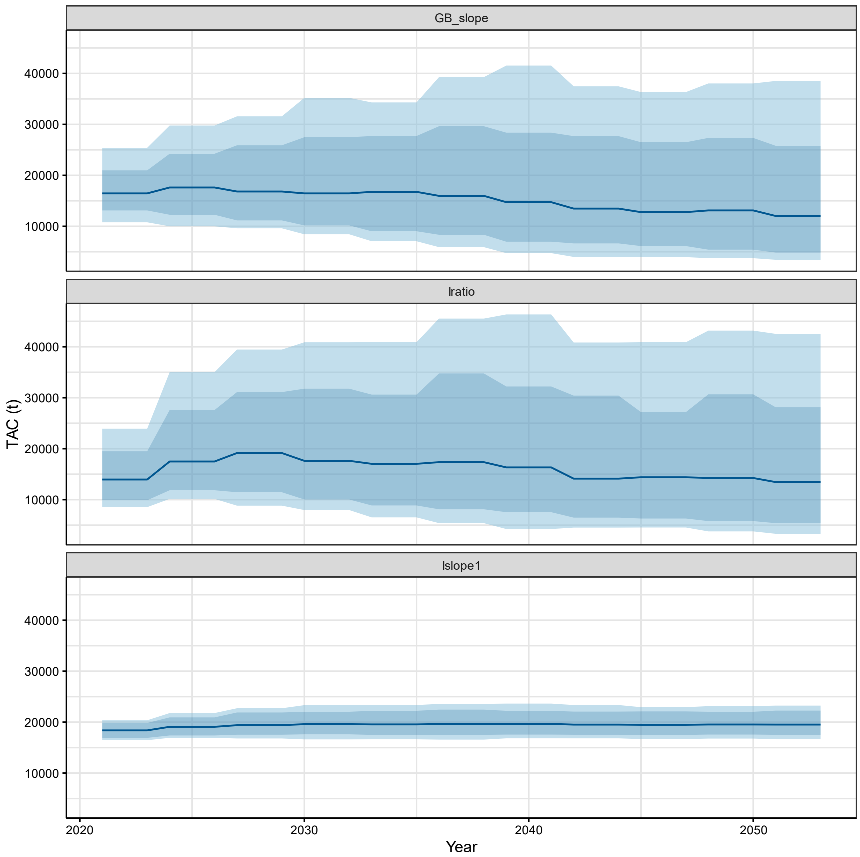


Figure 17. SB/SB_{MSY} from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 10% of implementation error (OMs 10-18).


CC_20kt
CC_30kt
CC_40kt
TAC (t)
40000
35000
30000
25000
20000
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
TAC (t)
40000
30000
20000
10000
2020
2030
2040
2050
Year

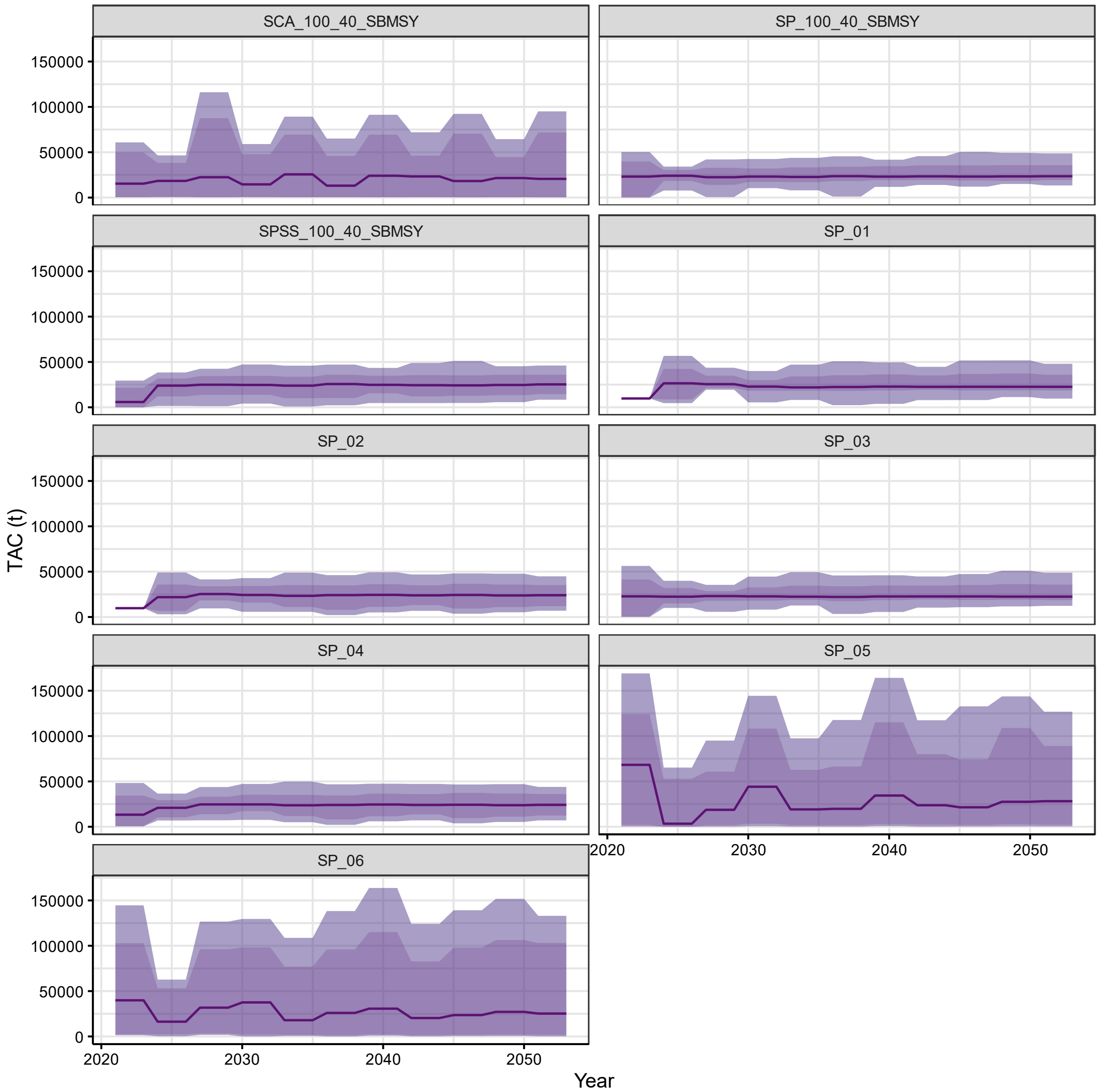
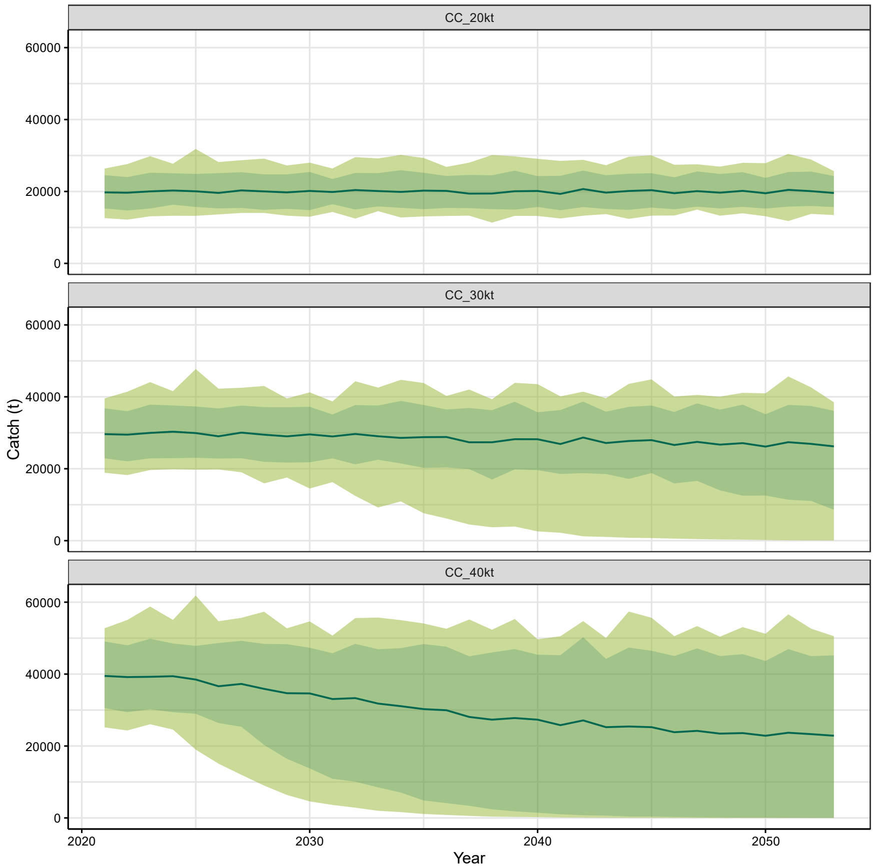
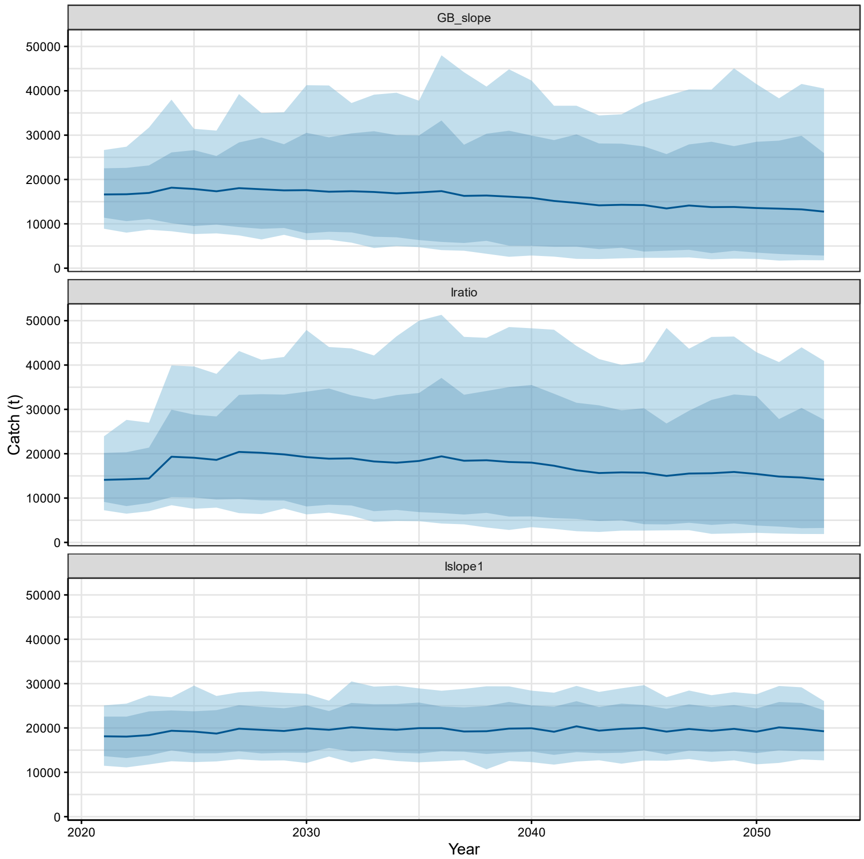


Figure 18. Total Allowable Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 10% of implementation error (OMs 10-18).



CC_20kt
CC_30kt
CC_40kt
Catch (t)
Year
60000
40000
20000
0
2020
2030
2040
2050



GB_slope
Iratio
Islope1
Catch (t)
Year
50000
40000
30000
20000
10000
0
2020
2030
2040
2050

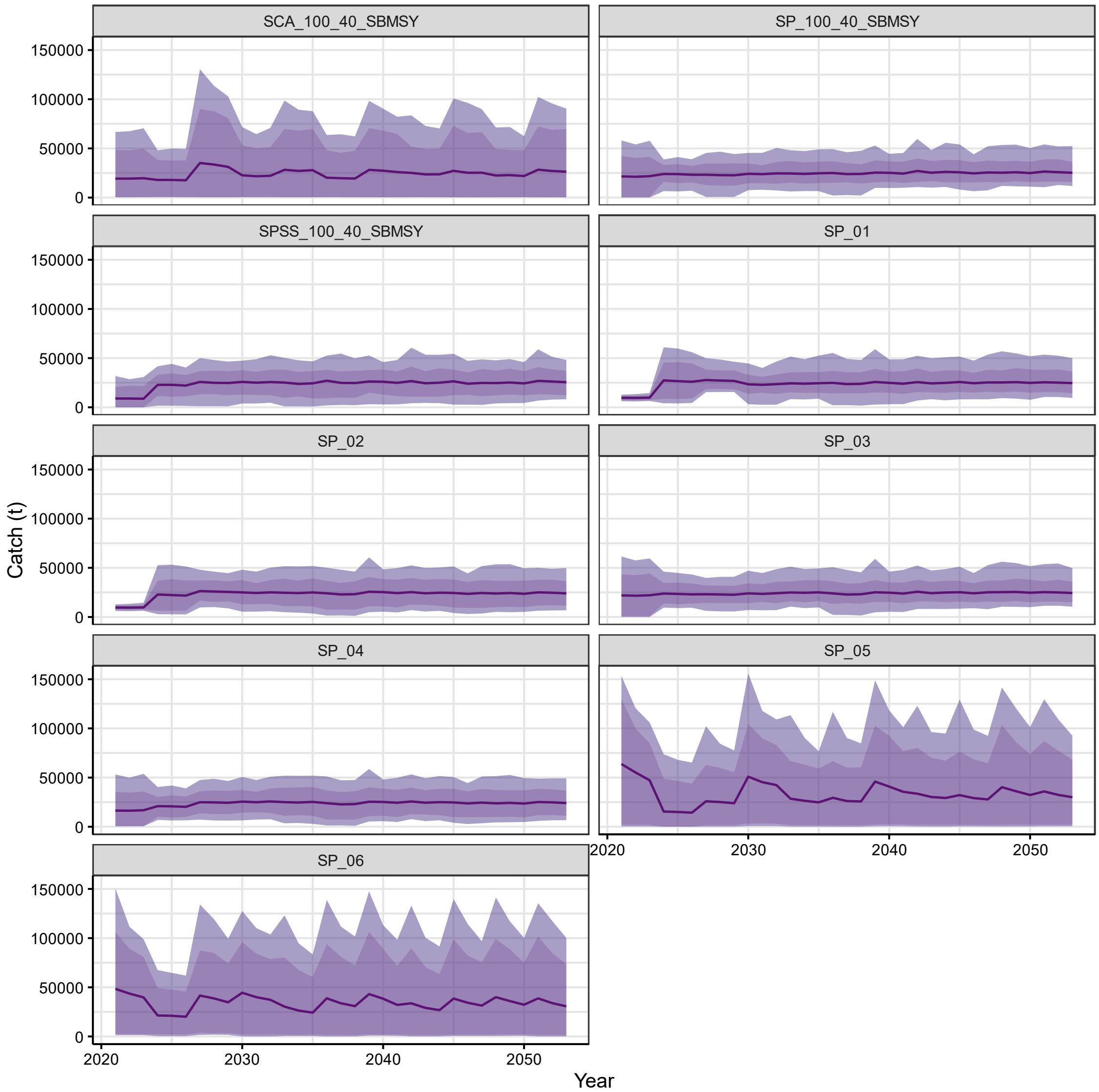
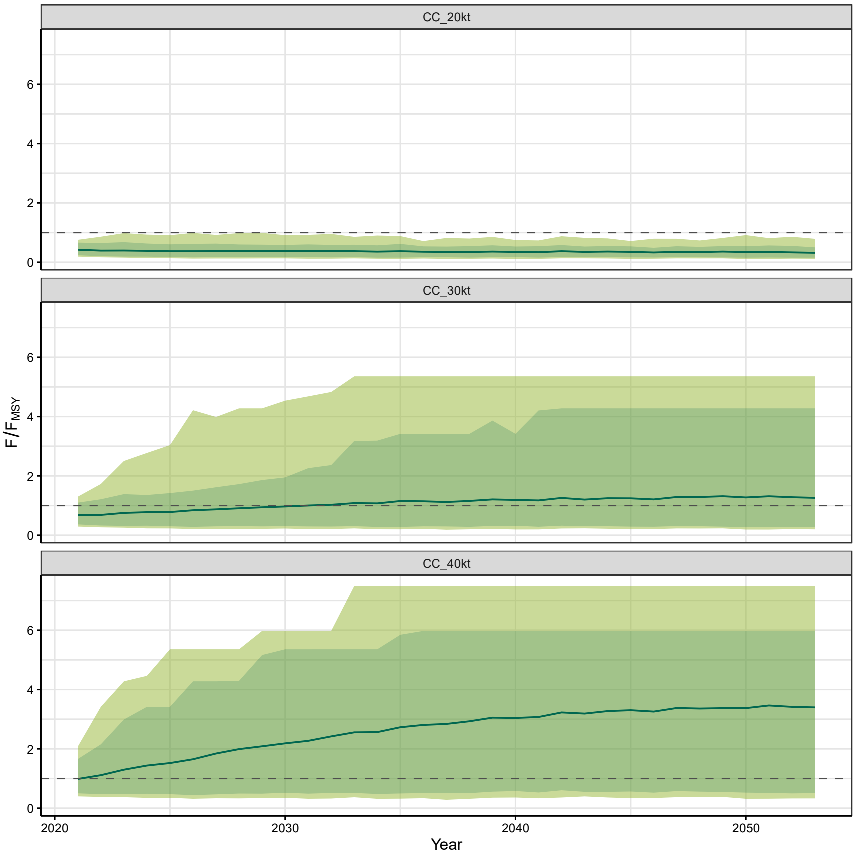
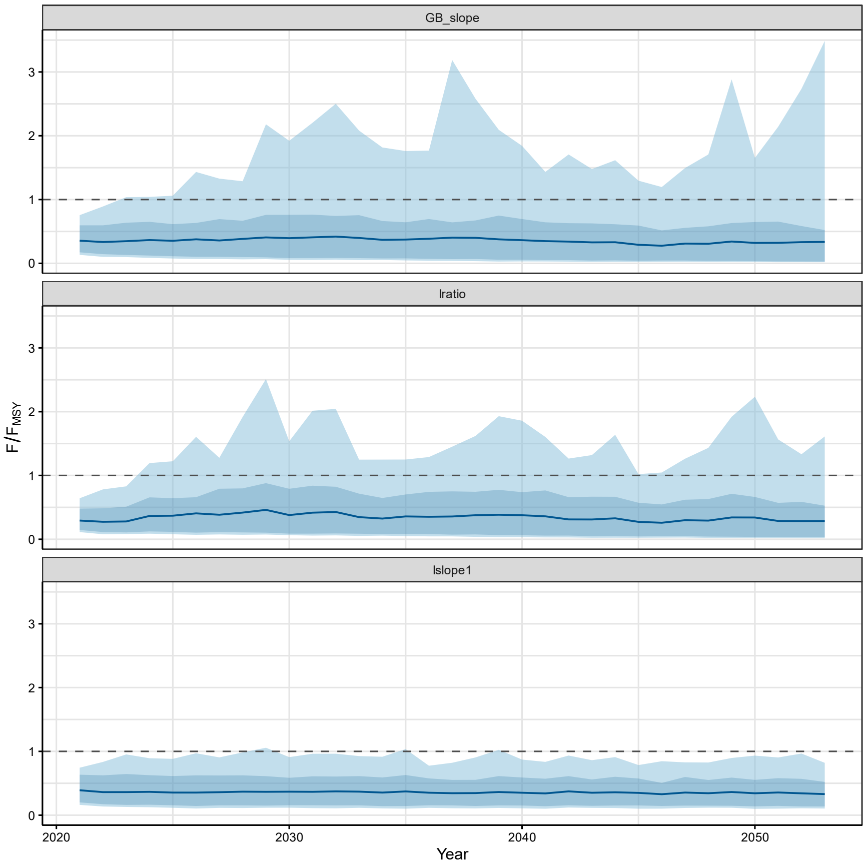


Figure 19. Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 20% of implementation error (OMs 19-27).



CC_20kt
CC_30kt
CC_40kt
F/F_MSY
0
2
4
6
2020
2030
2040
2050
Year



GB_slope
Iratio
Islope1
F/F_MSY
0
1
2
3
2020
2030
2040
2050
Year

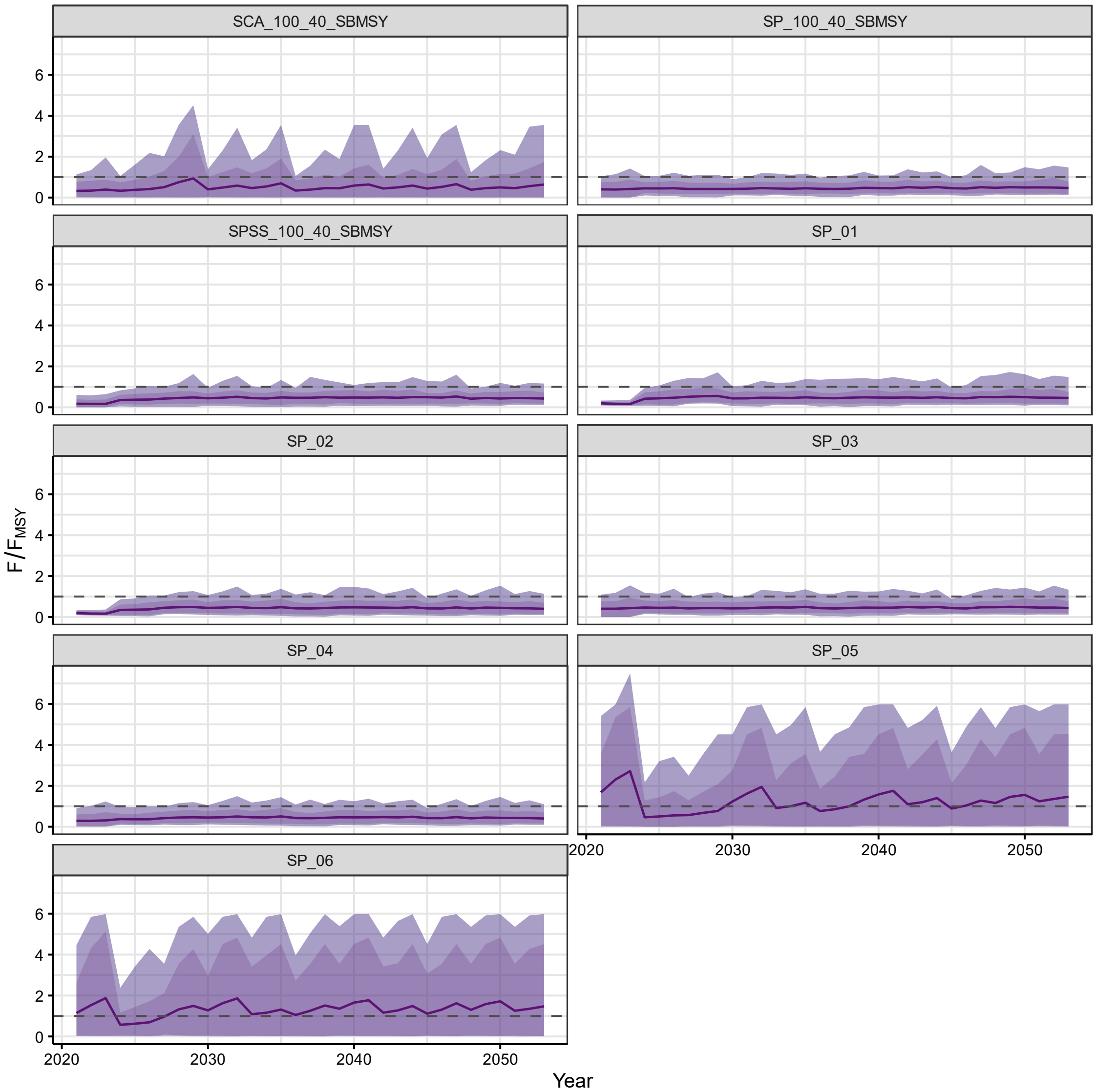
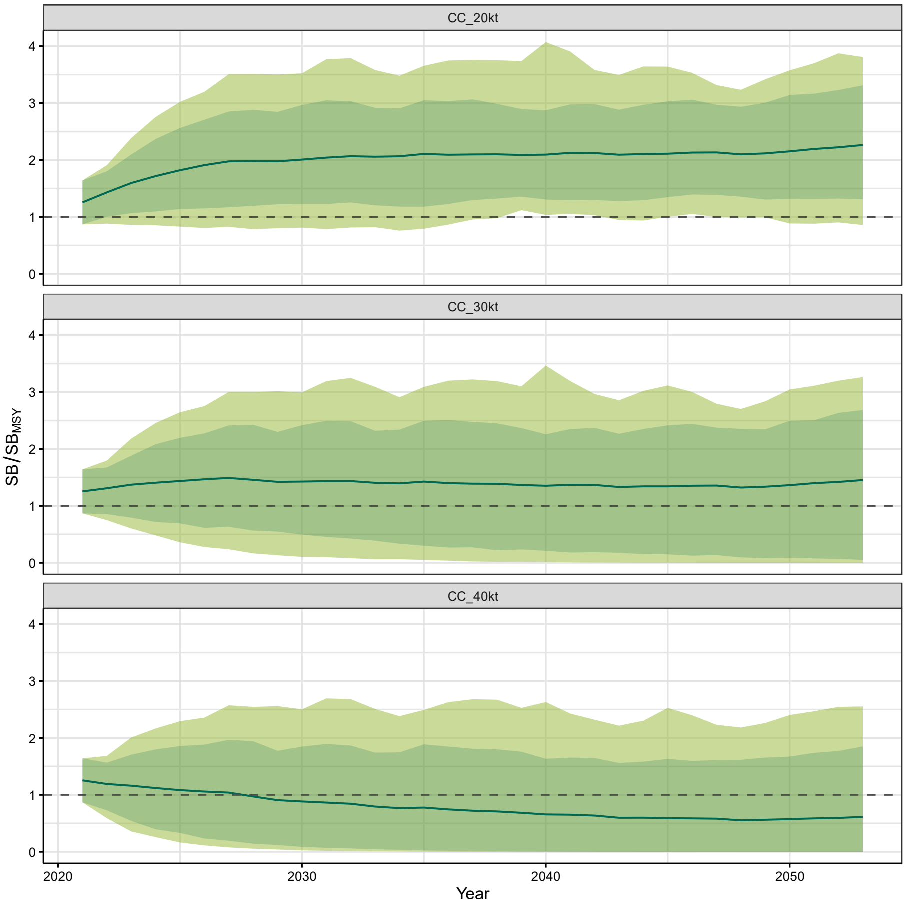
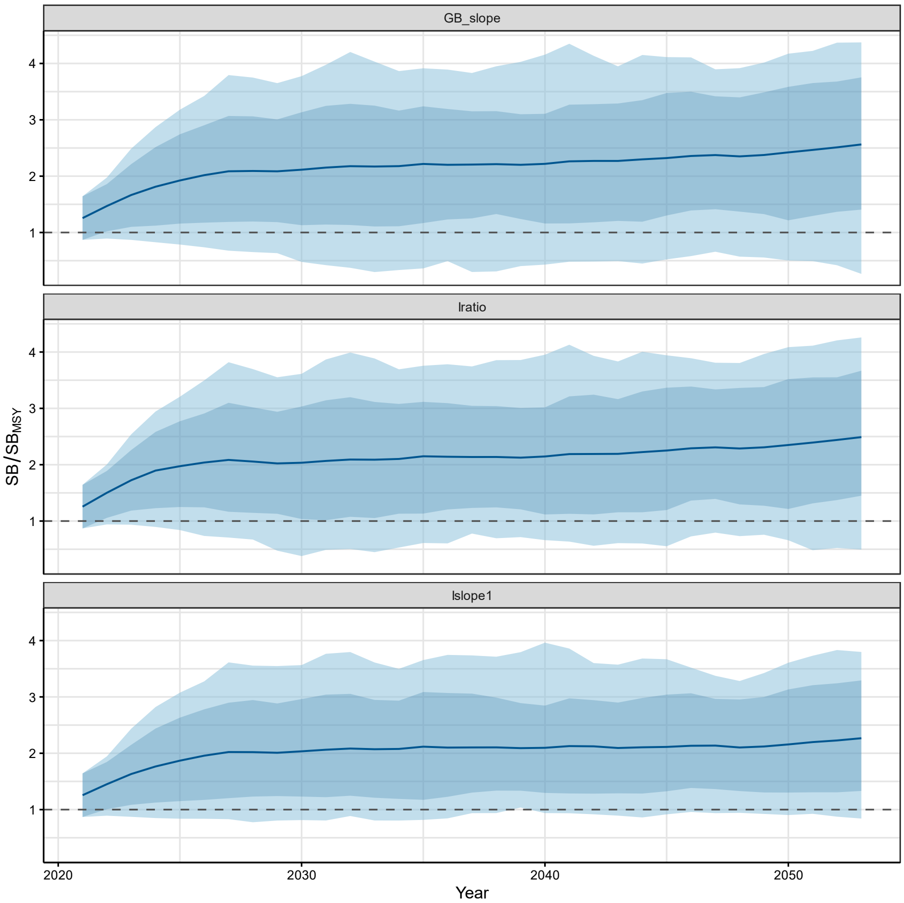


Figure 20. F/F_{MSY} from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 20% of implementation error (OMs 19-27).


CC_20kt
CC_30kt
CC_40kt
SB/SB_MSY
0
1
2
3
4
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
SB/SB_MSY
1
2
3
4
2020
2030
2040
2050
Year

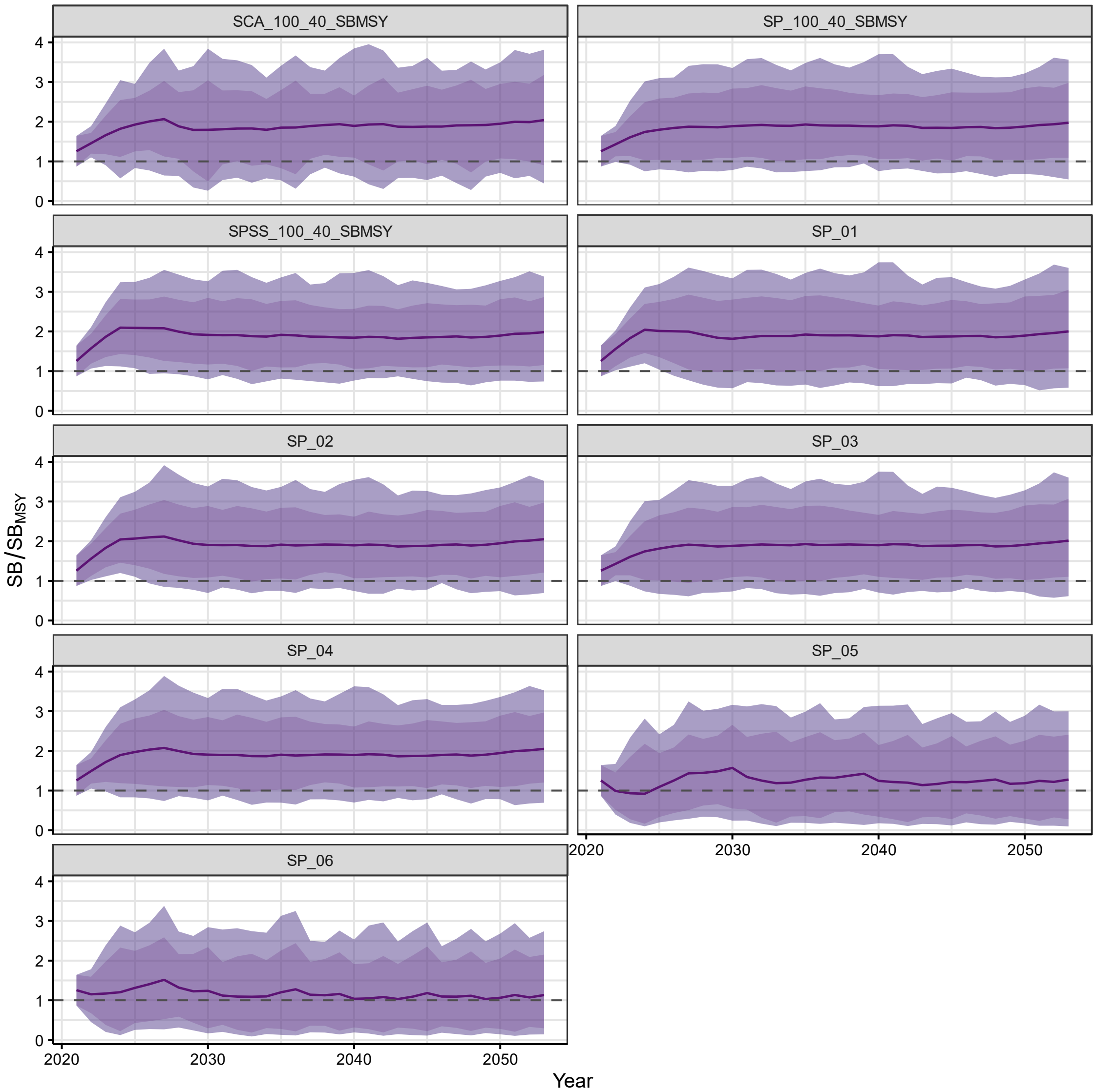
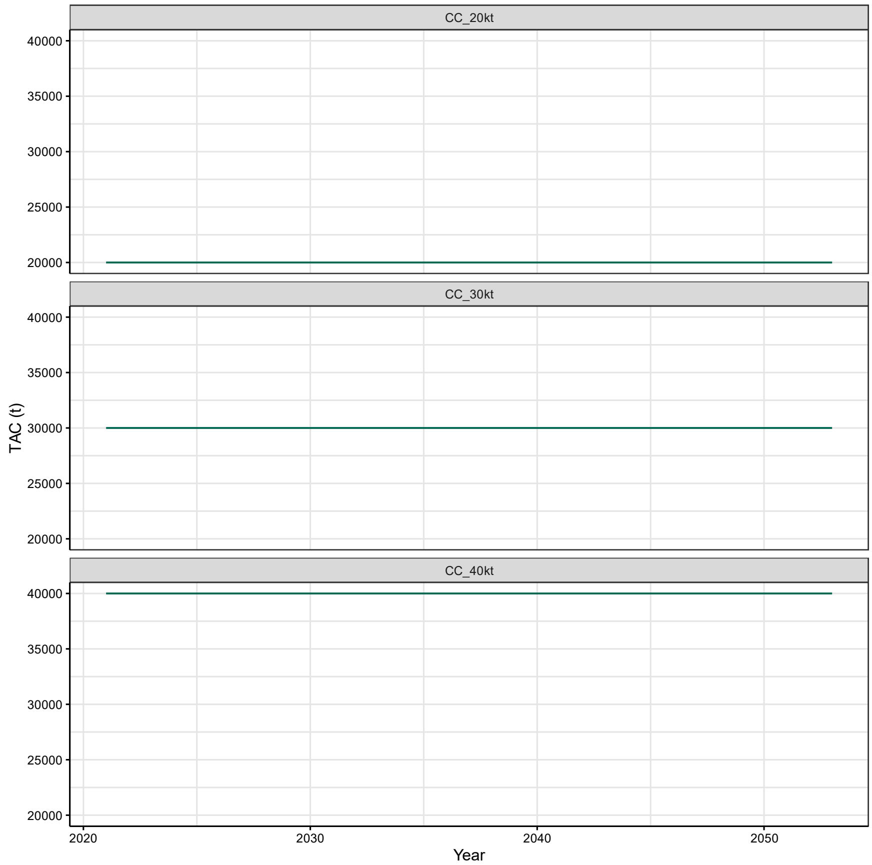
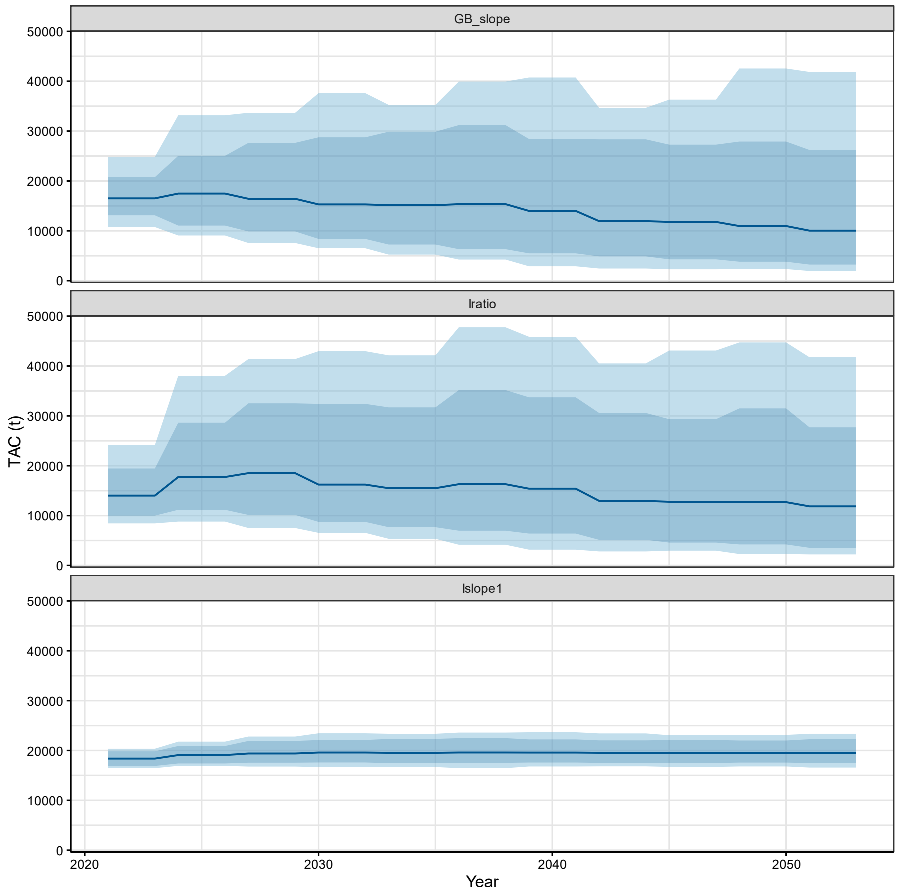


Figure 21. SB/SB$_{MSY}$ from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 20% of implementation error (OMs 19-27).


CC_20kt
CC_30kt
CC_40kt
TAC (t)
40000
35000
30000
25000
20000
2020
2030
2040
2050
Year


GB_slope
Iratio
Islope1
TAC (t)
50000
40000
30000
20000
10000
0
2020
2030
2040
2050
Year

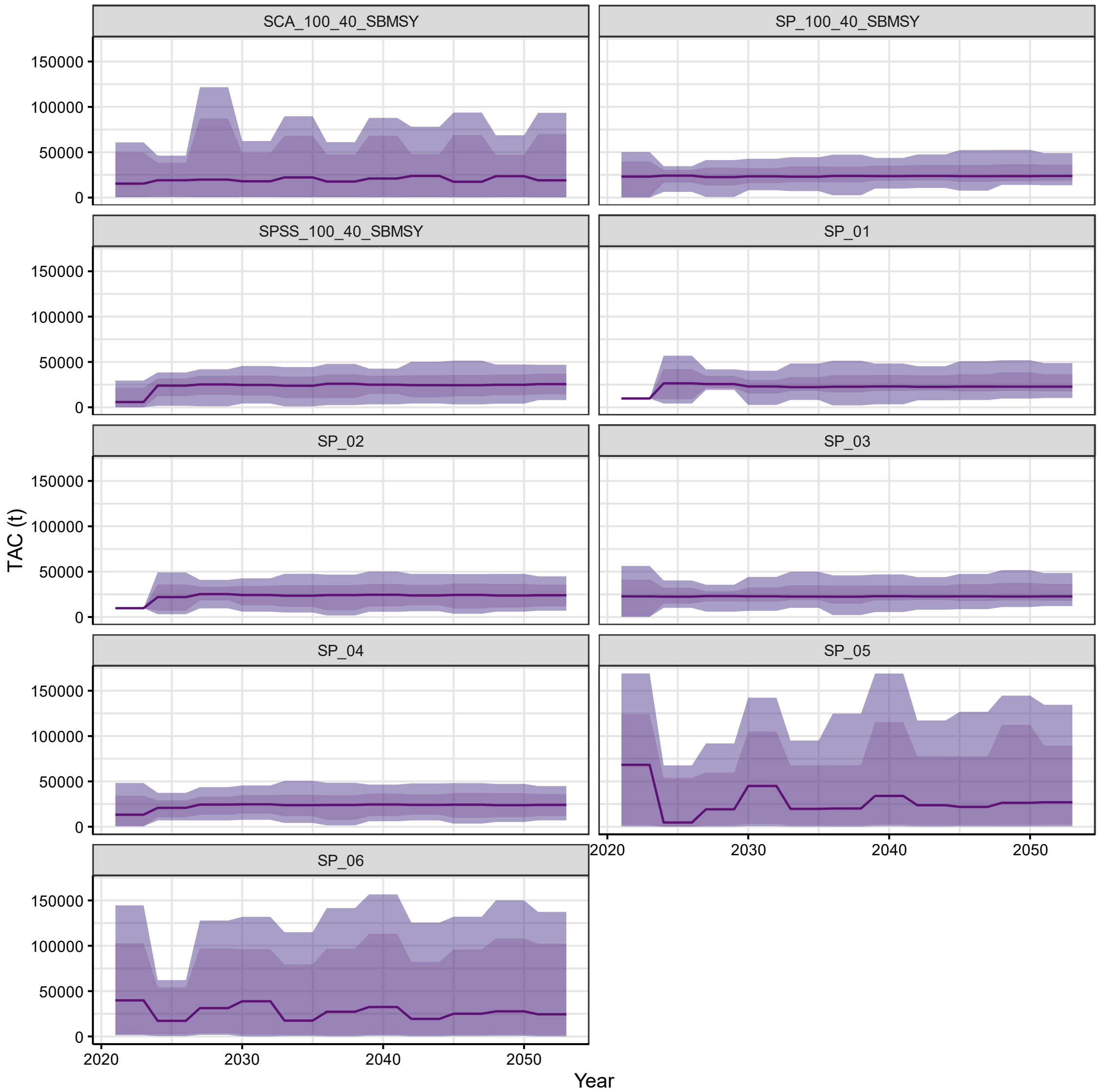


Figure 22. Total Allowable Catches from the closed-loop simulation for a selection of MPs (figure captions) for the OMs with 20% of implementation error (OMs 10-18).