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WESTERN SKIPJACK STOCK STATUS AND PROJECTIONS WITH THE STOCK SYNTHESIS ASSESSMENT MODEL

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SUMMARY

This document provides the final stock status and projection results for western skipjack using Stock Synthesis and assuming a multivariate lognormal distribution across a nine-model uncertainty grid. The Tropical Tuna Species Group reviewed preliminary projections during the stock assessment workshop, and agreed to finalize all results for adoption during a webinar on the 15 July 2022. All tables and figures followed the recommendation by the Stock Assessment Working Group on Methods (WGSAM), which included modification to the stock status plots to use 2020 end-of-year biomass for current status. The resulting Kobe plot based on the 9 Stock Synthesis runs of the uncertainty grid indicated that the current stock is likely not overfished (green quadrant; 90.9% probability) and overfishing is not occurring. The projections show that recent catch levels (around 20 thousand t) are sustainable in the near-term. Some model scenarios with higher constant TACs were predicted to be unsustainable in the long-term, with predicted SSB declining to less than 20% or 10% of SSB_{MSY}.

RÉSUMÉ

Ce document fournit les résultats finaux des projections et de l'état du stock du listao de l'Ouest en utilisant Stock Synthesis et en postulant une distribution lognormale multivariée dans une grille d'incertitude de neuf modèles. Le Groupe d'espèces sur les thonidés tropicaux a étudié les projections préliminaires lors de l'atelier d'évaluation du stock et a convenu de finaliser tous les résultats pour adoption au cours d'une webinaire le 15 juillet 2022. Tous les tableaux et figures suivaient la recommandation du Groupe de travail sur les méthodes d'évaluation des stocks (WGSAM), qui incluait la modification des graphiques de l'état du stock en vue d'utiliser la biomasse de la fin de l'année 2020 pour l'état actuel. Le diagramme de Kobe en résultant basé sur les 9 scénarios de Stock Synthesis de la grille d'incertitude indiquait que le stock actuel n'est probablement pas surexploité (quadrant vert: probabilité de 90,9%) et ne fait pas l'objet de surpêche. Les projections indiquent que les niveaux de captures actuels (environ 20.000 t) sont durables à court terme. Certains scénarios des modèles avec des TAC constants plus élevés ne semblaient pas durables à long terme, avec une SSB prédite reculant à moins de 20% ou 10% de la SSB_{PME}.

RESUMEN

Este documento proporciona el estado final del stock y los resultados de las proyecciones para el listado occidental utilizando Stock Synthesis y asumiendo una distribución lognormal multivariable a través de una matriz de incertidumbre de nueve modelos. El Grupo de especies de túnidos tropicales revisó las proyecciones preliminares durante el taller de evaluación de stock, y acordó finalizar todos los resultados para su adopción durante un webinario el 15 de julio de 2022. Todas las tablas y figuras siguieron la recomendación del Grupo de trabajo sobre métodos de evaluación de stock (WGSAM), que incluía la modificación de los diagramas del estado de los stocks para utilizar la biomasa del año final 2020 para el estado actual. El diagrama de Kobe resultante, basado en nuevos ensayos de Stock Synthesis de la matriz, indicó que es probable que el stock actual no esté sobrepescado (cuadrante verde; 90,9 % de probabilidad) y que no se esté produciendo sobrepesca. Las proyecciones muestran que los

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niveles recientes de capturas (alrededor de 20.000t) son sostenibles a corto plazo. Las predicciones de algunos escenarios de modelos con TAC constantes más elevados mostraron que eran insostenibles a largo plazo, con un descenso previsto de la SSB por debajo del 20 % o del 10 % de la SSB_{RMS}.

KEYWORDS

Projection, Stock Status, Stock Synthesis, Western Skipjack

1. Introduction

This document provides the final stock status and projection results with Stock Synthesis for western skipjack (W-SKJ). During the skipjack stock assessment meeting, due to the time constraints, the Tropical Tuna Species Group (TTSG) agreed to finalize the W-SKJ projection and confirm the results adopted in the stock assessment meeting report at the informal webinar on the 15th of July 2022.

After the skipjack stock assessment meeting, the Working Group of Stock Assessment Methods (WGSAM) at its meeting recommended that modelers be aware of what biomass (B) or spawning stock biomass (SSB) and fishing mortality (F) are reported in the SS results and ensure that biomass and fishing mortality corresponds to the correct reference year in both Kobe plots, matrices, and summary tables. The recommendation includes to generate the spawning stock biomass (SSB) at the end of the terminal year (beginning of the first forecast year) in order to account for landings in the terminal year of the model on biomass estimates. During the skipjack stock assessment meeting, the SSB trajectory and Kobe plot were produced with SSB at the beginning of years. Following the WGSAM recommendation, those figures were updated using the SSB at the end of each year.

2. Data and methods

The TTSG recommended that final management advice be developed from the joint distribution of the projections for the 9 Stock Synthesis runs (combination of *h* (0.6, 0.7, or 0.8) and growth (25, 50, or 75th regression quantiles)) of the uncertainty grid with Stock Synthesis (version 3.30.18) (Cardoso et al. 2022, Appendix I).

Following the agreement on the projection specifications during the skipjack stock assessment meeting, the stock was projected over 2021-2040 with constant F_{MSY} and 16 constant catch scenarios (0t, 16,000 to 32,000 t in 2,000 t intervals, 33,000 to 36,000 t in 1,000 t intervals, 38,000 t and 40,000 t). Deterministic projections were conducted with all catch scenarios and stochastic projections were provided using the Monte-Carlo multivariate lognormal (MVLN) described in Walter and Winker (2019) with 200,000 iterations except F_{MSY} and 0t.

The 2021 and 2022 catch in the projection are fixed at 18,859 t, equivalent to the 2020 reported catch. Future recruitment was predicted based on the estimated stock recruitment relationship, with no recruitment deviations. Selectivity and relative contribution of fleets to catches were fixed at recent years' (2018-2020) averages. The fleet catch proportions were also calculated using the average of the last three years (2018-2020).

We present a summary of the following: SSB trajectory, Fishing mortality trajectory, Kobe plot by individual uncertainty grid run, Kobe plot for all grid runs, Kobe 2 matrix, and the probabilities of SSB falling below 10% or 20% SSB_{MSY}. Following the recommendation by the WGSAM, all figures were produced with SSB at the end of the year *t* that is equal to the beginning of the year *t*+1.

3. Results and conclusions

The general pattern in the time series of mediansSSB/SSB_{MSY} (**Figure 1**) and F/F_{MSY} (**Figure 2**) were similar for all nine runs, although the absolute magnitude of the estimates varied notably. After the SSB/SSB_{MSY} declined significantly between the late 1970s and the mid-1980s, the SSB/SSB_{MSY} showed slight increase or remained at the similar level to the one in the mid-1980s by the mid-2010s, except a noticeable drop in 1994. Since mid-2010s, the SSB/SSB_{MSY} decreased to the historical lowest level in 2019 but showed a slight increase in the last year of the stock assessment (2020). However, the SSB for all grid runs were mostly above SSB_{MSY} level over the assessment period, with annual F never exceeding F_{MSY}. **Table 1** provides the estimates of MSY, F_{MSY}, virgin SSB, and SSB_{MSY} for each deterministic grid run.

A Kobe plot for the 9 Stock Synthesis deterministic runs (**Figure 3**) was produced to represent the uncertainty across the different Stock Synthesis runs in the uncertainty grid. The three grid runs with the lowest assumed M at age (Qnt75) were the least optimistic with regards to stock condition in the most recent year, and produced median SSB estimates in 2020 below the level that supports MSY (SSB_{2020}/SSB_{MSY} ranging from 0.93 to 1.18, **Table 2**). Members of the grid produced the median SSB in 2020 above SSB_{MSY} (SSB_{2020}/SSB_{MSY}) ranging from 0.93 to 2.58. No grid run indicated that the median F in 2020 was above F_{MSY} (median F_{2020}/F_{MSY} ranged from 0.22 to 0.81). The overall average MSY estimate produced from the uncertainty grid was 35,277 t. Individual grid run estimates ranged from 28,444 t to 46,340 t.

To incorporate the cross-model uncertainty in stock status, a Kobe plot based on multivariate log normal (MVLN) approximation (Walter and Winker, 2019) of the posterior density across the 9 Stock Synthesis model uncertainty grid was produced representing the 2020 values of relative fishing mortality and relative spawning stock biomass (**Figure 4**). During the stock assessment meeting, Kobe plot was produced with SSB at the beginning of the year 2020, and this was updated using the SSB at the end of the year 2020 that is the beginning of the year 2021. The number of iterations of multivariate log normal (MVLN) approximation was also increased from 10000 to 200000.

Table 2 shows the median and 95% credibility intervals of the Stock Synthesis-uncertainty grid estimates (across all 9 runs, 200,000 iterations) of spawning stock biomass relative to SSB_{MSY}(SSB/SSB_{MSY}) and fishing mortality relative to F_{MSY} (F/F_{MSY}) for all years from 1952 to 2020. For the year 2020 (**Table 3** and **Figure 4**), the joint-model results indicated that the stock is estimated to be in healthy condition with 91% probability of being in the green quadrant of the Kobe plot, and that the stock is not overfished (SSB_{2020}/SSB_{MSY} = 1.60) nor undergoing overfishing (F_{2020}/F_{MSY} = 0.41). There was a relatively low estimated probability that the stock is either overfished (yellow quadrant; 6.2%) or both overfished and undergoing overfishing (red quadrant; 2.9%).

Deterministic projections were conducted with constant F_{MSY} and 16 constant catch scenarios, and the means of SSB/SSB_{MSY} and F/F_{MSY} by all 9 grid runs were provided in **Figures 5** and **6**. As a result of the assumptions made of the catches in 2021 and 2022 and gradual decrease in catch after 2017, the SSB/SSB_{MSY} increases and F/F_{MSY} declines in the period 2021-2022. Results of the individual grid runs produced SSB trajectories close to zero over the projection years in the four of the nine grid runs, when growth Qnt75 and Qnt50 with steepness 0.6 and 0.7 were assumed (**Figure 7**). These runs also showed extreme F/F_{MSY} values (**Figure 8**), and especially undesirable projection behavior in F/F_{MSY} related to the extremely low SSB/SSB_{MSY} were observed at the 38000 t constant catch in the two grid runs with Qnt75 with steepness 0.6 and 0.7. The future catch trajectories (**Figure 9**) showed that the biomass in the grid runs with Qnt75 would not be able to support the constant catch more than 32000 t in the projection years.

Stochastic projections were provided using MVLN approximation. Beginning in 2023 catches of 30,000 or more lead to a decline in the spawning stock (**Figures 10**) and to an increase in fishing mortality (**Figures 11**). In this projection, the median of SSB/SSB_{MSY} would remain above 1.0 at the range of the considered catch scenarios by 2032. However, the TTSG reiterated that the uncertainty of the projections increases substantially as time increases and that long-term (e.g. 5+ years) projections are highly uncertain.

In the stochastic projections, the histograms of SSB/SSB_{MSY} and F/F_{MSY} showed very small probability of SSB/SSB_{MSY} close to zero or high F/F_{MSY} for most TAC scenarios (**Figures 12** and **13**). The probabilities to fall SSB below 10% or 20% SSB_{MSY} (corresponding to 1.8 – 2.8 % or 3.4 – 5.6 % of virgin biomass, **Table 1**) for the 9 grid runs were investigated. For some of the projections, the modeled stock could not sustain some of the constant high TACs in the long term, as SSB was predicted to decline below a safe threshold (**Table 4**). This threshold is an indicator of very low SSBs that may compromise the fishery or rebuilding ability of a stock. The value of 20% SSB is used by the SCRS for both yellowfin and bigeye tunas.

The catch advice is provided in the form of Kobe 2 Strategic Matrices including with probabilities that overfishing is not occurring ($F<=F_{MSY}$), stock is not overfished ($SSB>=SSB_{MSY}$) and the joint probability of being in the green quadrant of the Kobe plot (i.e. $F<= F_{MSY}$ and $SSB>= SSB_{MSY}$) (**Table 5**). Future constant catches of 20,000 t, close to the current catch (18,859 t in 2020) are expected to continue to remain in the green quadrant. The average MSY across the 9 grid runs was 35,277 t (**Table1**). Future constant catches of 35,000 t are expected to prevent overfishing ($F>F_{MSY}$) and overfished ($SSB<SSB_{MSY}$) with greater than 59% for the entire projection period. However, it should be noted that a few percentages to fall SSB below 10% or 20% of SSB_{MSY} were observed with the constant catch of the average MSY level (**Table 4**).

During the stock assessment meeting, the TTSG pointed out that recent catches have been below previous catches and below MSY, and that such decline is mostly due to lower catches by the Brazilian fleets. The projections indicate that recent catch levels are sustainable and are predicted to increase the stock size if recruitment is at the levels near those predicted by the stock-recruitment relationship. This document supported the recommendation by TTSG that catches should not be allowed to exceed MSY.

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Table 1. Estimates of MSY, F_{MSY}, Virgin SSB, SSB_{MSY}, $10\%SSB_{MSY}$, $20\%SSB_{MSY}$ for the deterministic 9 grid runs.

Grid runs							$10\%SSB_{MSY}$		$20\%SSB_{MSY}$
Qnt	h	MSY	F_{MSY}	virgin SSB	SSB_{MSY}	$10\%SSB_{MSY}$	% virgin SSB	$20\%SSB_{MSY}$	% virgin SSB
25	0.6	41003	0.500	199582	54466	5447	2.7%	10893	5.5%
25	0.7	42401	0.701	166437	37316	3732	2.2%	7463	4.5%
25	0.8	46340	1.002	148743	25599	2560	1.7%	5120	3.4%
50	0.6	32342	0.377	250229	69702	6970	2.8%	13940	5.6%
50	0.7	33497	0.536	210495	48736	4874	2.3%	9747	4.6%
50	0.8	35906	0.787	185962	33293	3329	1.8%	6659	3.6%
75	0.6	28313	0.310	294861	82172	8217	2.8%	16434	5.6%
75	0.7	28444	0.451	238811	55306	5531	2.3%	11061	4.6%
75	0.8	29244	0.697	200524	35381	3538	1.8%	7076	3.5%

Table 2. Stock Synthesis uncertainty grid deterministic estimates (individual 9 runs) of spawning stock biomass relative to SSB_{MSY} and fishing mortality relative to F_{MSY} between 1952 and 2020 for the western Atlantic skipjack stock.

	B/B_{MSY}									F/F_{MSY}								
	Qnt25h6	Qnt25h7	Qnt25h8	Qnt50h6	Qnt50h7	Qnt50h8	Qnt75h6	Qnt75h7	Qnt75h8	Qnt25h6	Qnt25h7	Qnt25h8	Qnt50h6	Qnt50h7	Qnt50h8	Qnt75h6	Qnt75h7	Qnt75h8
1952	3.65	4.43	5.77	3.57	4.29	5.55	3.57	4.29	5.62	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1953	3.63	4.42	5.75	3.56	4.27	5.51	3.55	4.26	5.58	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1954	3.62	4.40	5.72	3.54	4.25	5.49	3.53	4.24	5.55	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1955	3.61	4.39	5.71	3.53	4.24	5.47	3.52	4.22	5.52	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1956	3.61	4.38	5.70	3.52	4.23	5.45	3.51	4.21	5.50	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
1957	3.60	4.36	5.67	3.51	4.21	5.43	3.50	4.19	5.47	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1958	3.59	4.36	5.67	3.50	4.20	5.42	3.49	4.18	5.45	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.01
1959	3.59	4.35	5.66	3.50	4.19	5.41	3.48	4.17	5.44	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1960	3.56	4.32	5.61	3.47	4.16	5.35	3.45	4.12	5.37	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.03	0.02
1961	3.55	4.29	5.57	3.45	4.13	5.31	3.43	4.09	5.32	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.03	0.02
1962	3.55	4.30	5.59	3.45	4.13	5.32	3.43	4.09	5.33	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1963	3.52	4.27	5.54	3.42	4.09	5.26	3.39	4.04	5.26	0.03	0.03	0.02	0.04	0.03	0.03	0.04	0.04	0.03
1964	3.49	4.21	5.46	3.38	4.03	5.18	3.34	3.97	5.15	0.04	0.04	0.03	0.05	0.04	0.03	0.06	0.05	0.04
1965	3.52	4.25	5.52	3.40	4.07	5.23	3.37	4.02	5.22	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01
1966	3.53	4.28	5.57	3.42	4.10	5.28	3.39	4.05	5.28	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1967	3.53	4.28	5.57	3.43	4.10	5.28	3.40	4.05	5.28	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.02
1968	3.53	4.28	5.57	3.43	4.10	5.29	3.40	4.06	5.29	0.02	0.02	0.01	0.03	0.02	0.02	0.03	0.02	0.02
1969	3.55	4.30	5.59	3.44	4.12	5.32	3.41	4.08	5.32	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1970	3.55	4.30	5.60	3.44	4.13	5.32	3.42	4.09	5.33	0.02	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.02
1971	3.56	4.31	5.61	3.45	4.14	5.34	3.43	4.10	5.35	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1972	3.56	4.32	5.62	3.46	4.15	5.36	3.44	4.11	5.37	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
1973	3.56	4.32	5.62	3.46	4.15	5.35	3.44	4.11	5.37	0.02	0.02	0.01	0.03	0.02	0.02	0.03	0.02	0.02
1974	3.54	4.30	5.59	3.44	4.13	5.32	3.42	4.09	5.33	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.03	0.02
1975	3.53	4.28	5.56	3.43	4.11	5.29	3.41	4.07	5.29	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.03	0.02
1976	3.52	4.26	5.53	3.41	4.08	5.26	3.39	4.04	5.25	0.03	0.03	0.02	0.04	0.03	0.02	0.04	0.04	0.03
1977	3.52	4.26	5.53	3.41	4.08	5.25	3.38	4.03	5.24	0.03	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.02
1978	3.50	4.23	5.49	3.39	4.05	5.20	3.35	3.99	5.18	0.04	0.03	0.03	0.05	0.04	0.03	0.05	0.04	0.03
1979	3.47	4.19	5.43	3.35	4.00	5.14	3.32	3.94	5.10	0.05	0.04	0.03	0.05	0.05	0.04	0.06	0.05	0.04
1980	3.35	4.01	5.18	3.22	3.81	4.87	3.17	3.72	4.77	0.11	0.09	0.07	0.13	0.11	0.08	0.14	0.12	0.09
1981	3.11	3.67	4.69	2.95	3.44	4.32	2.87	3.28	4.10	0.20	0.18	0.14	0.24	0.21	0.16	0.27	0.24	0.19
1982	2.81	3.24	4.07	2.60	2.94	3.62	2.47	2.71	3.23	0.30	0.27	0.21	0.37	0.32	0.26	0.42	0.37	0.30
1983	2.62	2.98	3.70	2.36	2.62	3.16	2.18	2.31	2.65	0.31	0.28	0.23	0.40	0.35	0.28	0.46	0.42	0.36
1984	2.51	2.84	3.52	2.20	2.42	2.90	1.99	2.06	2.30	0.31	0.28	0.23	0.40	0.36	0.30	0.48	0.46	0.40
1985	2.29	2.55	3.13	1.94	2.08	2.44	1.69	1.66	1.74	0.43	0.39	0.32	0.58	0.52	0.43	0.70	0.69	0.61
1986	2.23	2.47	3.04	1.84	1.96	2.30	1.55	1.49	1.53	0.39	0.35	0.29	0.54	0.50	0.42	0.68	0.70	0.66
1987	2.27	2.56	3.19	1.86	2.01	2.40	1.55	1.51	1.60	0.30	0.28	0.22	0.43	0.40	0.33	0.56	0.58	0.56
1988	2.30	2.62	3.31	1.88	2.06	2.51	1.57	1.55	1.69	0.29	0.26	0.21	0.42	0.38	0.31	0.55	0.57	0.53
1989	2.30	2.62	3.32	1.87	2.06	2.53	1.54	1.53	1.68	0.32	0.29	0.23	0.46	0.42	0.34	0.61	0.62	0.56
1990	2.29	2.63	3.34	1.86	2.06	2.55	1.52	1.52	1.69	0.32	0.28	0.23	0.46	0.41	0.33	0.61	0.62	0.56
1991	2.22	2.53	3.20	1.77	1.95	2.40	1.41	1.38	1.49	0.39	0.35	0.27	0.56	0.50	0.40	0.75	0.76	0.68
1992	2.19	2.50	3.16	1.73	1.90	2.34	1.36	1.31	1.42	0.36	0.33	0.26	0.53	0.48	0.39	0.74	0.76	0.69
1993	2.11	2.39	3.01	1.63	1.78	2.17	1.21	1.13	1.20	0.41	0.37	0.30	0.62	0.56	0.44	0.87	0.90	0.82
1994	2.06	2.32	2.90	1.52	1.65	1.99	1.02	0.92	0.96	0.39	0.36	0.29	0.60	0.54	0.44	0.89	0.94	0.87
1995	2.24	2.56	3.22	1.67	1.84	2.25	1.21	1.16	1.29	0.29	0.26	0.21	0.48	0.44	0.36	0.78	0.86	0.81
1996	2.53	2.91	3.68	2.02	2.26	2.79	1.42	1.40	1.58	0.32	0.29	0.23	0.50	0.45	0.36	0.78	0.81	0.72
1997	2.74	3.14	3.97	2.10	2.34	2.88	1.56	1.54	1.74	0.33	0.30	0.24	0.51	0.46	0.36	0.80	0.81	0.71
1998	2.75	3.14	3.96	2.19	2.44	3.01	1.55	1.52	1.71	0.30	0.27	0.21	0.44	0.39	0.31	0.65	0.66	0.58
1999	2.75	3.15	3.98	2.10	2.33	2.87	1.46	1.41	1.56	0.28	0.25	0.20	0.42	0.38	0.30	0.65	0.67	0.59
2000	2.75	3.15	3.99	2.15	2.40	2.98	1.46	1.42	1.60	0.30	0.27	0.21	0.45	0.40	0.32	0.71	0.74	0.66
2001	2.55	2.91	3.66	2.02	2.24	2.77	1.35	1.28	1.42	0.33	0.29	0.23	0.48	0.43	0.34	0.77	0.80	0.70
2002	2.42	2.76	3.49	1.96	2.19	2.72	1.31	1.26	1.42	0.25	0.22	0.18	0.35	0.32	0.25	0.58	0.61	0.54
2003	2.40	2.75	3.47	1.85	2.06	2.55	1.27	1.23	1.39	0.29	0.26	0.21	0.43	0.38	0.30	0.69	0.71	0.63
2004	2.49	2.85	3.61	1.95	2.19	2.72	1.31	1.28	1.46	0.32	0.28	0.23	0.48	0.43	0.34	0.77	0.79	0.69
2005	2.99	3.45	4.38	2.14	2.40	3.00	1.43	1.40	1.60	0.29	0.26	0.21	0.47	0.42	0.33	0.77	0.79	0.69
2006	2.90	3.33	4.22	2.28	2.57	3.21	1.49	1.46	1.67	0.26	0.23	0.18	0.39	0.35	0.28	0.65	0.67	0.58
2007	2.76	3.17	4.01	2.16	2.42	3.02	1.43	1.39	1.56	0.25	0.23	0.18	0.38	0.33	0.26	0.62	0.63	0.55
2008	2.72	3.14	3.98	2.16	2.43	3.03	1.47	1.44	1.64	0.23	0.20	0.16	0.34	0.30	0.24	0.56	0.57	0.51
2009	2.46	2.80	3.53	2.04	2.28	2.84	1.35	1.31	1.48	0.28	0.25	0.20	0.39	0.35	0.28	0.63	0.65	0.57
2010	2.71	3.11	3.93	2.04	2.28	2.84	1.40	1.36	1.56	0.28	0.25	0.20	0.43	0.38	0.31	0.70	0.72	0.64
2011	2.88	3.33	4.24	2.24	2.52	3.15	1.47	1.45	1.66	0.32	0.29	0.23	0.49	0.43	0.34	0.81	0.83	0.72
2012	2.55	2.92	3.70	2.07	2.32	2.88	1.41	1.38	1.58	0.34	0.30	0.24	0.49	0.43	0.34	0.80	0.81	0.70
2013	2.35	2.67	3.37	1.89	2.10	2.59	1.26	1.21	1.35	0.40	0.35	0.28	0.55	0.49	0.39	0.88	0.90	0.78
2014	3.17	3.67	4.68	2.09	2.35	2.93	1.47	1.44	1.65	0.27	0.24	0.19	0.47	0.42	0.34	0.77	0.80	0.71
2015	3.00	3.47	4.43	2.46	2.80	3.53	1.60	1.60	1.84	0.19	0.17	0.14	0.30	0.26	0.21	0.49	0.50	0.43
2016	2.27	2.58	3.25	2.02	2.27	2.83	1.30	1.26	1.41	0.23	0.20	0.16	0.30	0.26	0.21	0.49	0.50	0.43
2017	1.73	1.94	2.42	1.51	1.65	2.03	0.96	0.88	0.96	0.32	0.29	0.23	0.40	0.36	0.28	0.66	0.69	0.61
2018	1.63	1.86	2.34	1.26	1.38	1.70	0.79	0.73	0.79	0.35	0.31	0.25	0.48	0.43	0.35	0.81	0.88	0.80
2019	1.56	1.78	2.25	1.25	1.39	1.73	0.81	0.78	0.90	0.33	0.30	0.24	0.50	0.45	0.36	0.86	0.94	0.85
2020	1.70	2.00	2.58	1.39	1.60	2.06	0.93	0.94	1.18	0.31	0.28	0.22	0.46	0.41	0.32	0.78	0.81	0.69

Table 3. Stock Synthesis uncertainty grid estimates (across all 9 runs) of spawning stock biomass relative to SSB_{MSY} and fishing mortality relative to F_{MSY} between 1952 and 2020 for the western Atlantic skipjack stock. The median and 90% credibility intervals provided are based on 200000 iterations of the MVLN approximation.

	B/B_{MSY}			F/F_{MSY}		
	Median	Lower CI*	Upper CI*	Median	Lower CI*	Upper CI*
1952	4.29	3.11	5.94	0.01	0.01	0.01
1953	4.27	3.09	5.89	0.01	0.01	0.01
1954	4.25	3.08	5.87	0.01	0.01	0.02
1955	4.24	3.07	5.84	0.01	0.01	0.02
1956	4.22	3.06	5.82	0.01	0.01	0.02
1957	4.21	3.05	5.80	0.02	0.01	0.02
1958	4.20	3.04	5.78	0.01	0.01	0.02
1959	4.19	3.05	5.78	0.02	0.01	0.02
1960	4.15	3.02	5.72	0.03	0.02	0.04
1961	4.12	3.00	5.66	0.03	0.02	0.04
1962	4.13	3.01	5.68	0.02	0.01	0.02
1963	4.09	2.98	5.62	0.03	0.02	0.05
1964	4.03	2.94	5.52	0.04	0.03	0.06
1965	4.07	2.96	5.58	0.01	0.01	0.02
1966	4.10	2.98	5.65	0.02	0.01	0.02
1967	4.10	2.98	5.63	0.02	0.02	0.03
1968	4.11	2.98	5.66	0.02	0.02	0.03
1969	4.13	2.99	5.68	0.02	0.01	0.02
1970	4.13	3.00	5.68	0.02	0.01	0.03
1971	4.14	3.00	5.71	0.02	0.01	0.02
1972	4.15	3.01	5.72	0.02	0.01	0.02
1973	4.15	3.02	5.72	0.02	0.02	0.03
1974	4.13	2.99	5.69	0.03	0.02	0.04
1975	4.11	2.99	5.65	0.03	0.02	0.04
1976	4.08	2.97	5.61	0.03	0.02	0.04
1977	4.08	2.97	5.60	0.03	0.02	0.04
1978	4.04	2.95	5.54	0.04	0.03	0.05
1979	4.00	2.92	5.48	0.05	0.03	0.07
1980	3.81	2.81	5.17	0.11	0.07	0.15
1981	3.44	2.58	4.57	0.20	0.14	0.29
1982	2.95	2.25	3.85	0.30	0.21	0.43
1983	2.62	1.98	3.45	0.35	0.24	0.51
1984	2.42	1.79	3.27	0.36	0.24	0.55
1985	2.08	1.46	2.97	0.52	0.33	0.82
1986	1.96	1.31	2.92	0.50	0.30	0.84
1987	2.01	1.32	3.05	0.40	0.23	0.70
1988	2.06	1.35	3.15	0.38	0.21	0.68
1989	2.06	1.33	3.19	0.42	0.23	0.74
1990	2.06	1.32	3.22	0.41	0.23	0.74
1991	1.95	1.21	3.14	0.50	0.28	0.91
1992	1.90	1.15	3.15	0.48	0.25	0.91
1993	1.78	1.01	3.12	0.56	0.29	1.08
1994	1.65	0.83	3.25	0.54	0.26	1.10
1995	1.84	1.02	3.32	0.44	0.19	1.04
1996	2.25	1.29	3.95	0.45	0.21	0.94
1997	2.34	1.36	4.03	0.46	0.22	0.95
1998	2.44	1.40	4.27	0.39	0.20	0.77
1999	2.33	1.27	4.26	0.38	0.18	0.77
2000	2.40	1.31	4.39	0.40	0.19	0.85
2001	2.24	1.21	4.16	0.43	0.21	0.90
2002	2.19	1.21	3.97	0.32	0.15	0.66
2003	2.06	1.12	3.77	0.38	0.18	0.81
2004	2.19	1.19	4.01	0.43	0.20	0.91
2005	2.40	1.23	4.69	0.42	0.18	0.94
2006	2.57	1.38	4.81	0.35	0.16	0.76
2007	2.43	1.30	4.51	0.33	0.16	0.71
2008	2.43	1.34	4.40	0.30	0.14	0.65
2009	2.29	1.27	4.11	0.35	0.17	0.70
2010	2.29	1.23	4.23	0.38	0.18	0.83
2011	2.52	1.34	4.75	0.43	0.20	0.95
2012	2.32	1.31	4.12	0.43	0.21	0.91
2013	2.10	1.15	3.86	0.49	0.24	0.98
2014	2.35	1.19	4.68	0.42	0.18	1.00
2015	2.80	1.53	5.12	0.26	0.12	0.58
2016	2.26	1.28	4.02	0.26	0.13	0.52
2017	1.66	0.90	3.04	0.36	0.18	0.70
2018	1.39	0.69	2.78	0.43	0.20	0.93
2019	1.39	0.75	2.58	0.45	0.20	1.04
2020	1.60	0.90	2.87	0.41	0.19	0.89

* 90% credibility interval

Table 4. Percent of the model runs based on 200000 iterations of the MVLN approximation that resulted in SSB levels <= 10% or 20% of SSB_{MSY} during the projection period for a given catch level (in 1000 t) for the western Atlantic skipjack stock.

Probability of Stock Depletion (SSB < 10% of SSB_{MSY})

TAC (1000s mt)	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
20	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
22	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
33	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
34	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
35	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
36	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
38	0%	0%	0%	0%	0%	0%	0%	1%	2%	2%
40	0%	0%	0%	0%	0%	0%	1%	2%	3%	4%

Probability of Stock Depletion (SSB < 20% of SSB_{MSY})

TAC (1000s mt)	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
20	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
22	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
33	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
34	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
35	0%	0%	0%	0%	0%	0%	0%	1%	2%	3%
36	0%	0%	0%	0%	0%	0%	1%	2%	3%	5%
38	0%	0%	0%	0%	0%	1%	2%	5%	7%	9%
40	0%	0%	0%	0%	1%	3%	5%	8%	10%	13%

Table 5. Estimated probabilities of the western Atlantic skipjack stock being below F_{MSY} (overfishing not occurring), above B_{MSY} (not overfished) and above B_{MSY} and below F_{MSY} (green zone) in a given year for a given catch level ('000 t), based on 200000 iterations of the MVLN approximation.

Probability $F<=F_{MSY}$

TAC (1000s mt)	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
16	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
18	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
22	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
24	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%
26	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%
28	97%	97%	97%	97%	97%	97%	97%	97%	97%	96%
30	96%	95%	94%	93%	93%	92%	91%	91%	90%	89%
32	94%	92%	91%	89%	87%	85%	83%	81%	79%	77%
33	93%	91%	88%	86%	83%	80%	78%	75%	73%	70%
34	92%	89%	86%	82%	79%	75%	72%	69%	66%	64%
35	91%	87%	83%	78%	74%	70%	67%	63%	61%	59%
36	90%	85%	80%	75%	70%	65%	61%	59%	56%	55%
38	88%	81%	74%	67%	61%	56%	53%	50%	47%	44%
40	85%	76%	67%	59%	53%	48%	44%	40%	36%	31%

Probability $SSB>=SSB_{MSY}$

TAC (1000s mt)	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
16	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
18	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
22	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
24	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%
26	98%	99%	99%	99%	99%	99%	99%	99%	100%	100%
28	98%	98%	98%	98%	98%	98%	98%	98%	98%	98%
30	98%	97%	96%	96%	95%	94%	94%	93%	92%	91%
32	97%	96%	94%	92%	90%	88%	86%	84%	82%	79%
33	97%	95%	93%	90%	87%	84%	81%	78%	74%	71%
34	96%	94%	91%	87%	83%	79%	75%	71%	67%	64%
35	96%	93%	89%	84%	79%	74%	69%	65%	62%	59%
36	96%	92%	87%	81%	75%	69%	64%	61%	58%	56%
38	95%	89%	82%	73%	66%	60%	56%	53%	50%	48%
40	94%	86%	76%	66%	59%	53%	48%	45%	41%	37%

Probability $F<=F_{MSY}$ and $SSB>=SSB_{MSY}$

TAC (1000s mt)	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
16	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
18	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
22	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
24	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%
26	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%
28	97%	97%	97%	97%	97%	97%	97%	96%	96%	96%
30	96%	95%	94%	93%	93%	92%	91%	91%	90%	89%
32	94%	92%	91%	89%	87%	85%	83%	81%	79%	77%
33	93%	91%	88%	86%	83%	80%	77%	75%	72%	70%
34	92%	89%	86%	82%	79%	75%	72%	68%	65%	63%
35	91%	87%	83%	78%	74%	70%	66%	63%	60%	57%
36	90%	85%	80%	75%	70%	65%	61%	58%	55%	53%
38	88%	81%	74%	67%	61%	56%	52%	49%	46%	43%
40	85%	76%	67%	59%	53%	48%	43%	39%	35%	31%

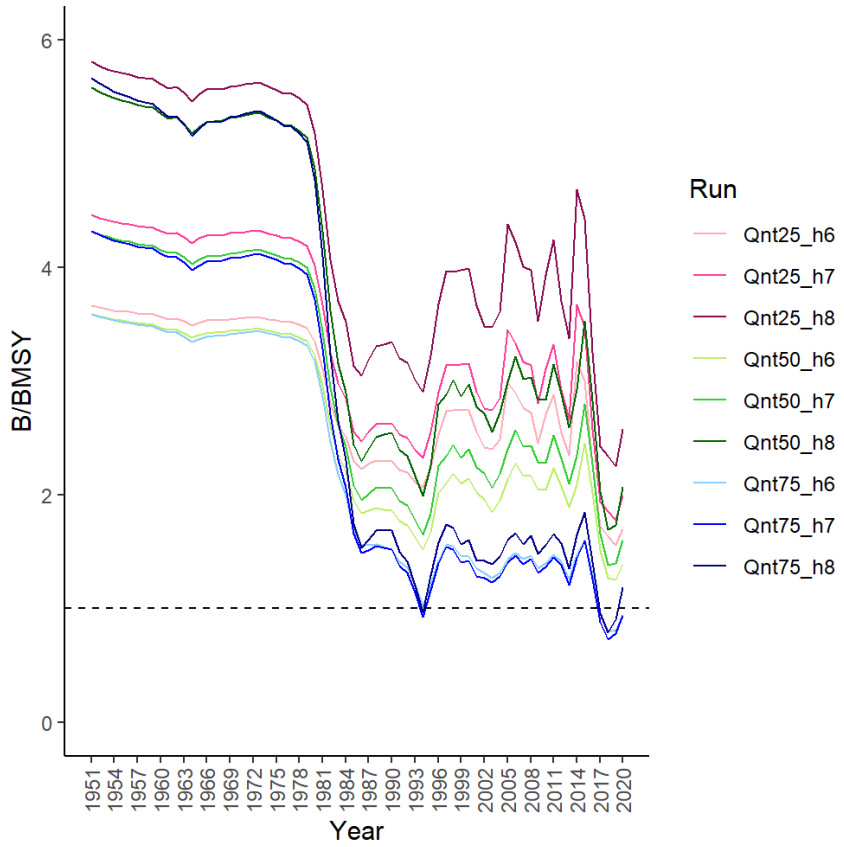

Figure 1. Annual estimates of the median SSB at the end of years from nine Stock Synthesis uncertainty grid runs, exploring uncertainty in natural mortality (M) and stock productivity (steepness, h).

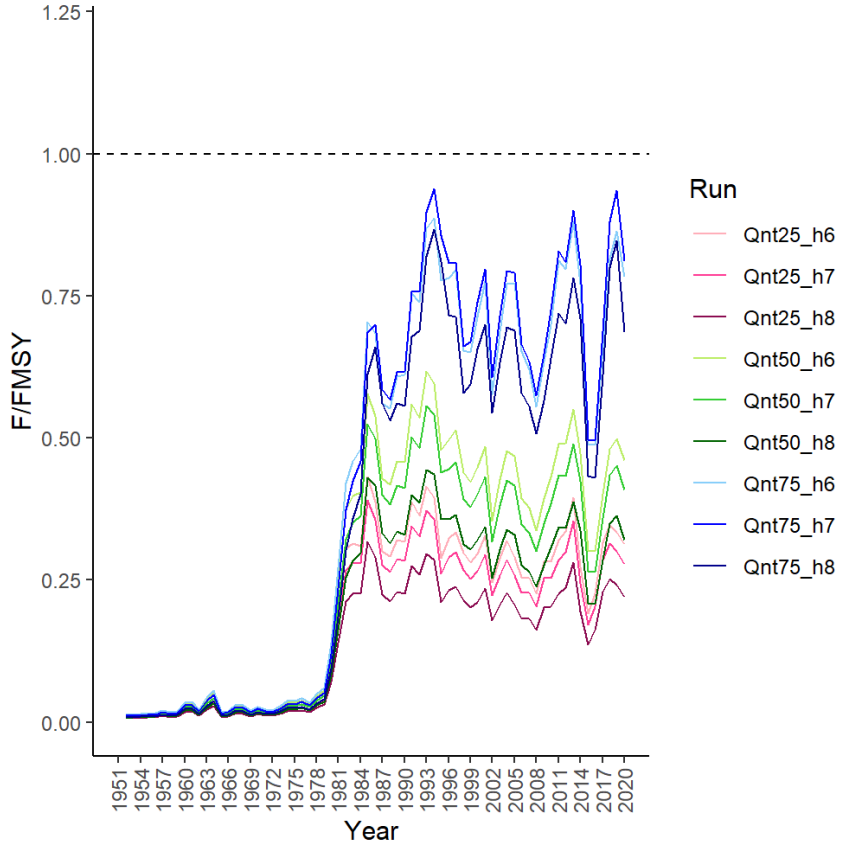

Figure 2. Annual estimates of the median F from nine Stock Synthesis uncertainty grid runs, exploring uncertainty in natural mortality (M) and stock productivity (steepness, h).

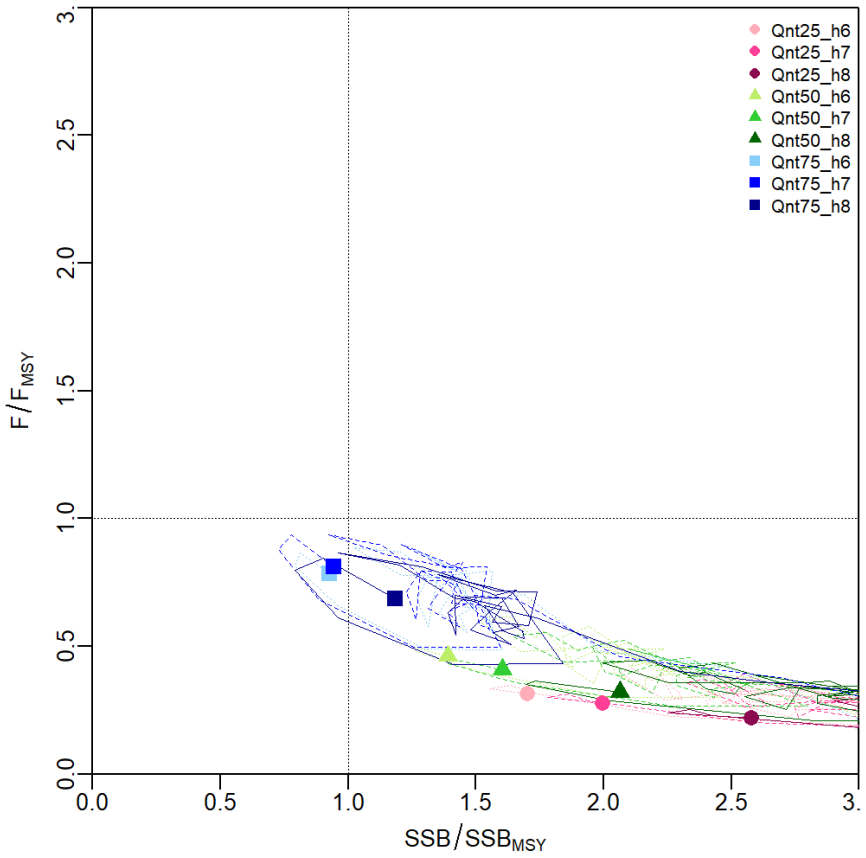

Figure 3. Kobe phase plot for the deterministic runs of the 9 Stock Synthesis uncertainty grid runs for the western Atlantic skipjack stock. For each run the benchmarks are calculated from the year-specific selectivity and fleet allocations. Symbols represent the estimates of relative fishing mortality and relative spawning stock biomass for 2020. Lines represent the historical evolution of the deterministic estimates.

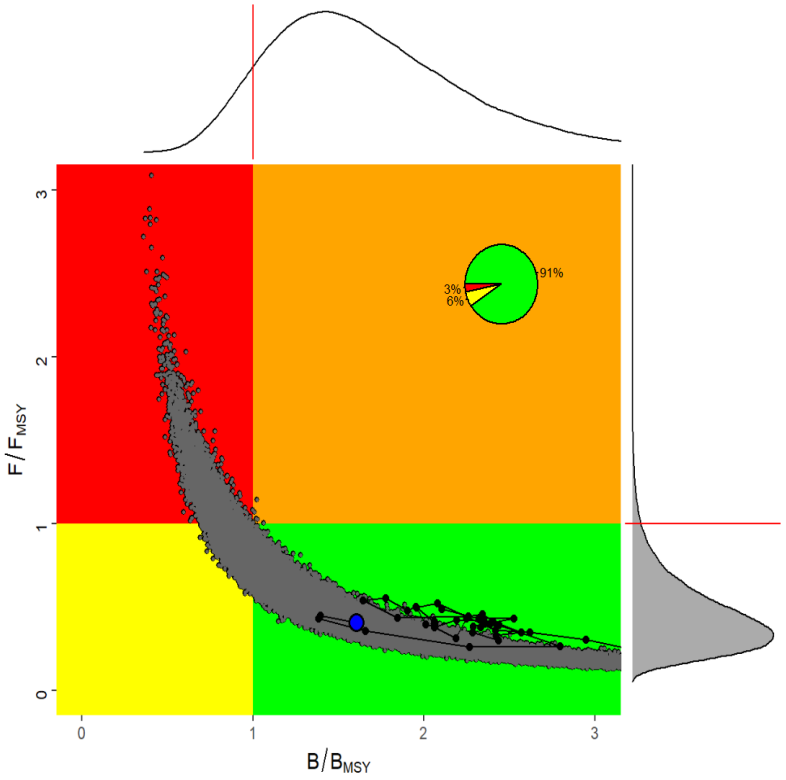

Figure 4a. Kobe phase plot for the 9 Stock Synthesis uncertainty grid runs for the western Atlantic skipjack stock. For each run the benchmarks are calculated from the year-specific selectivity and fleet allocations, and based on 200000 MVLN iterations. The blue point shows the median of 200,000 iterations for SSB_{2020}/SSB_{MSY} and F_{2020}/F_{MSY} for the entire set of runs in the grid. Black line with black symbols represents the historical evolution of the median of all runs. Grey points represent the 2020 estimates of relative fishing mortality and relative spawning stock biomass for 2020 for each of the 270,000 iterations. The upper graph represents the smoothed frequency distribution of SSB/SSB_{MSY} estimates for 2020. The right graph represents the smoothed frequency distribution of F/F_{MSY} estimates for 2020. The inserted pie graph represents the percentage of each 2020 estimate that fall in each quadrant of the Kobe plot. All SSB showed the values at the end of years.

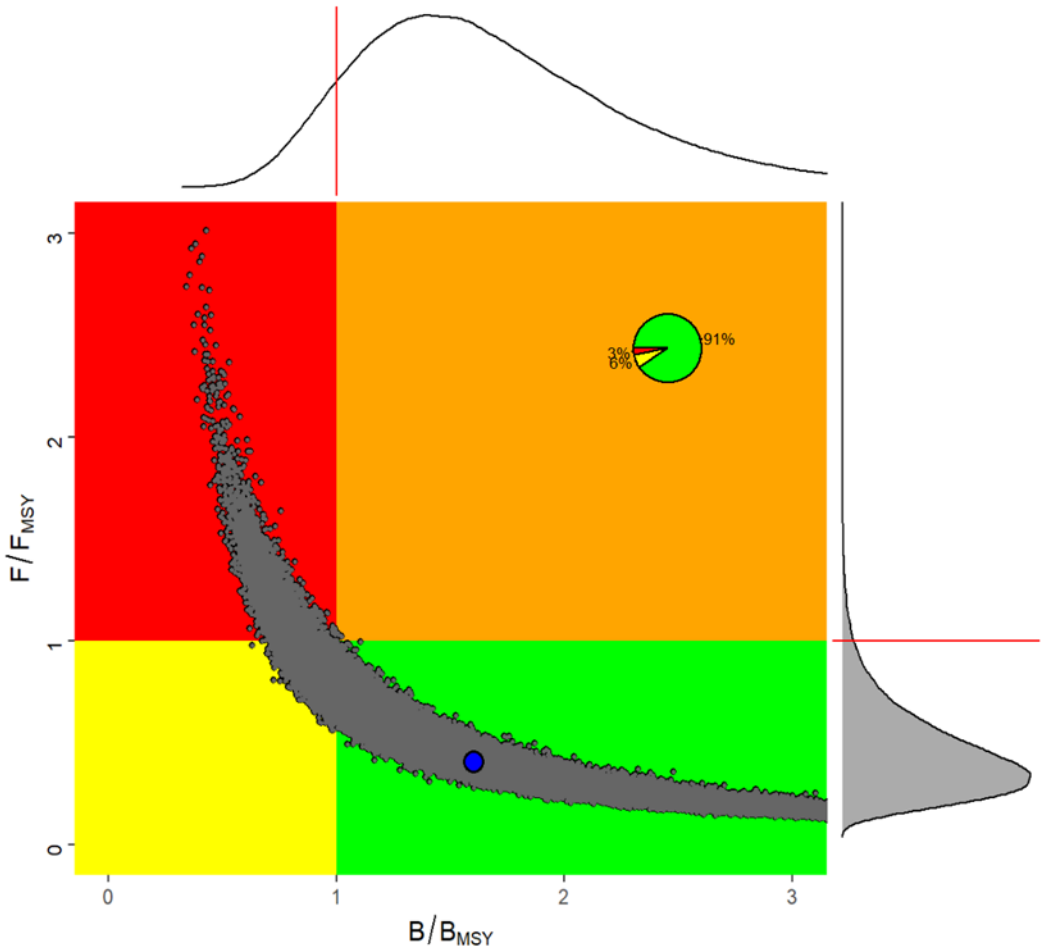

Figure 4b. Kobe phase plot for the 9 Stock Synthesis uncertainty grid runs for the western Atlantic skipjack stock without the historical trajectory.

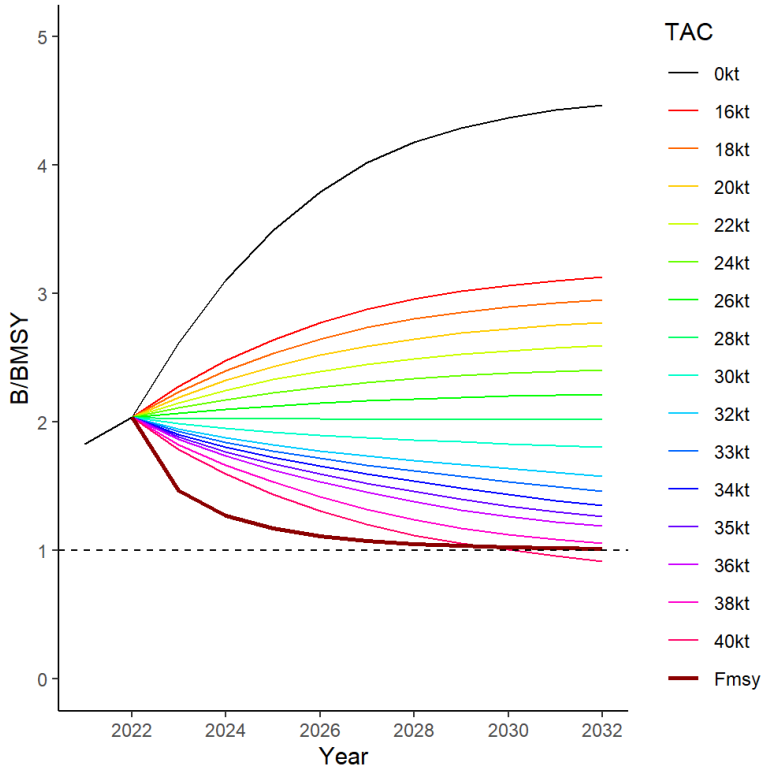

Figure 5. Deterministic projections of SSB/SSB_{MSY} for the 9 Stock Synthesis uncertainty grid runs at 0, 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock. The lines are the mean of 9 grid runs.

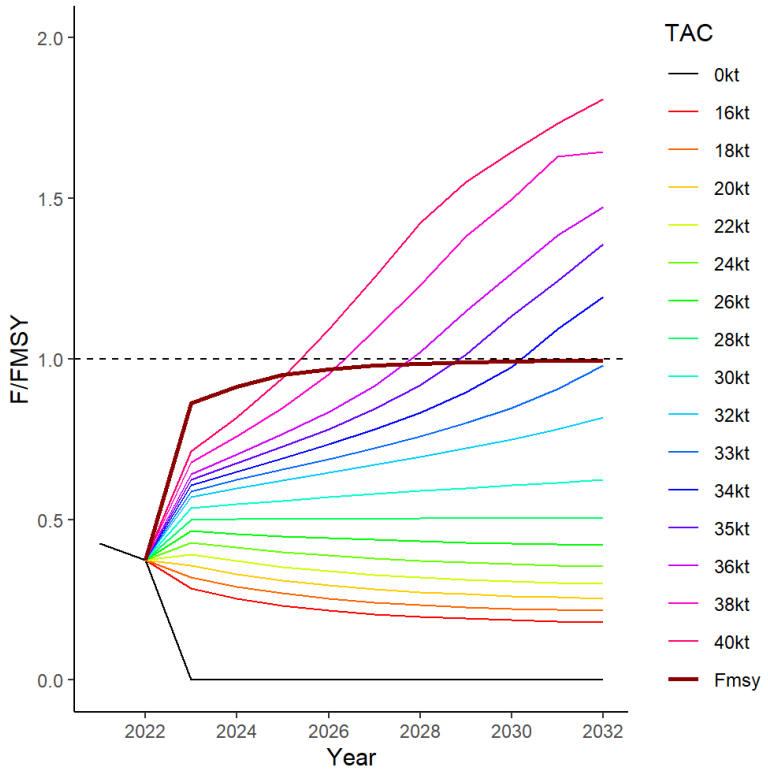

Figure 6. Deterministic projections of F/F_{MSY} for the 9 Stock Synthesis uncertainty grid runs at 0, 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock. The lines are the mean of 9 grid runs.

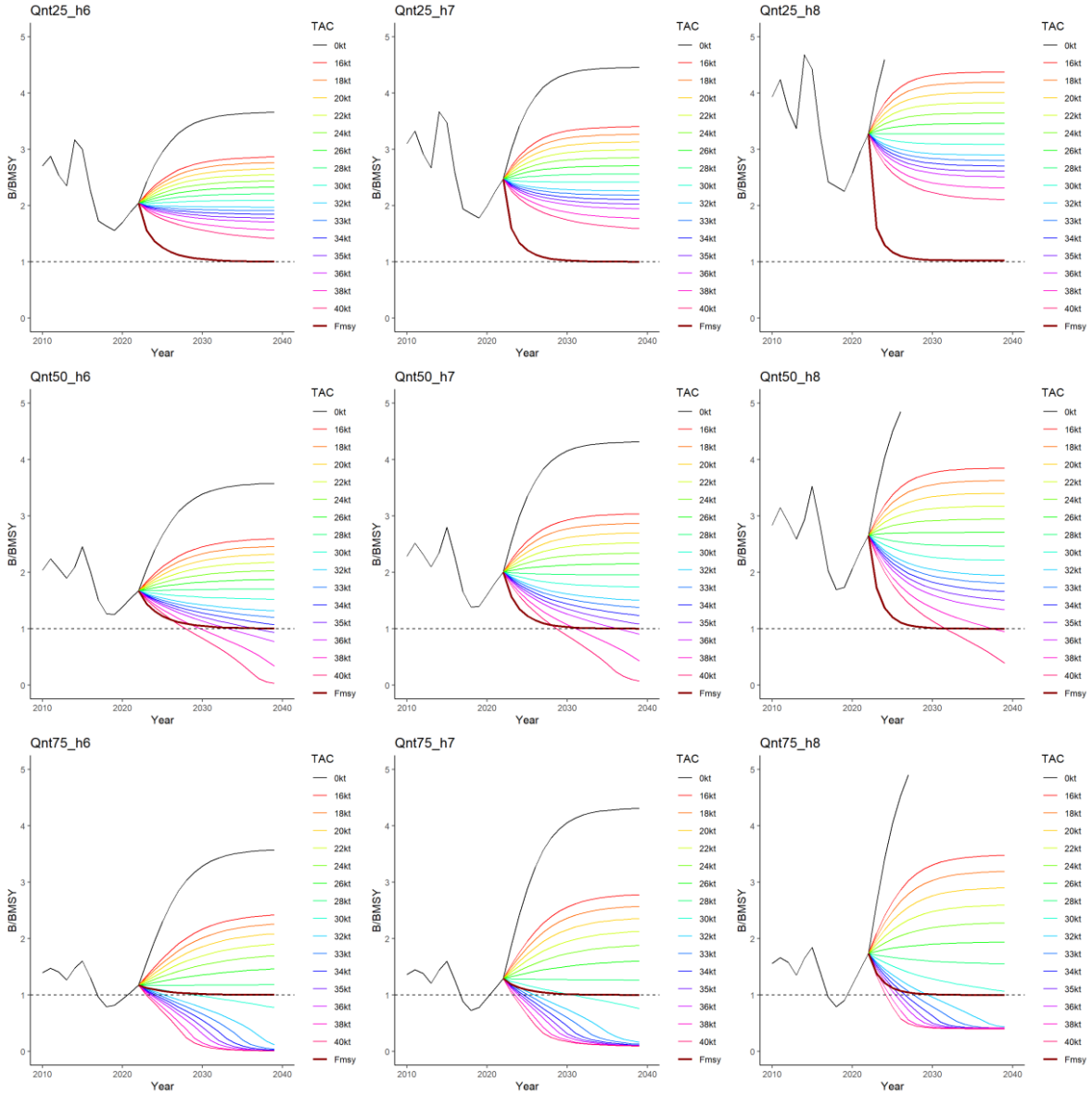

Figure 7. Deterministic projections of SSB/SSB_{MSY} for the individual 9 Stock Synthesis uncertainty grid runs at 0, 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock.

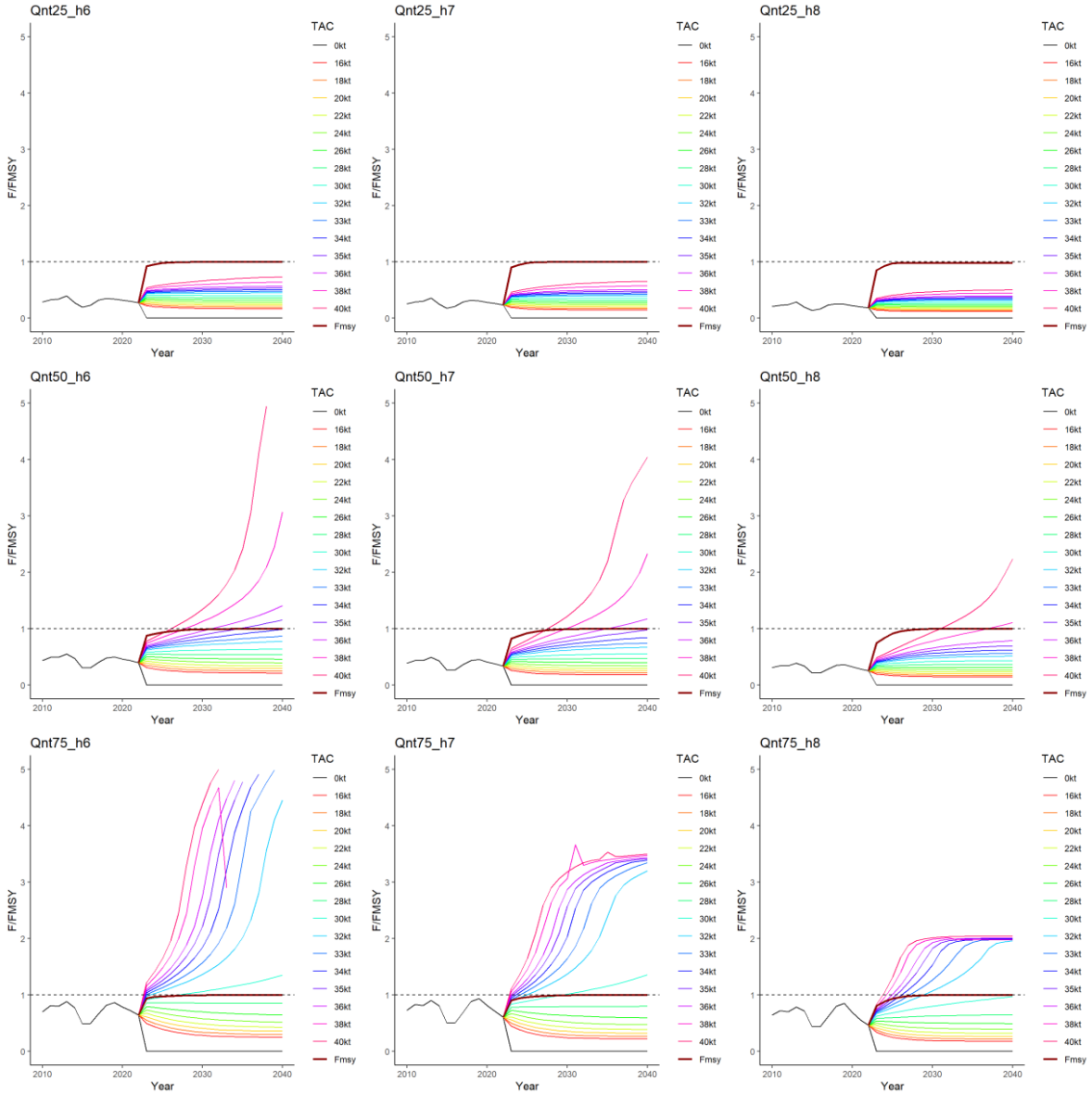

Figure 8. Deterministic projections of F/F_{MSY} for the individual 9 Stock Synthesis uncertainty grid runs at 0, 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock.

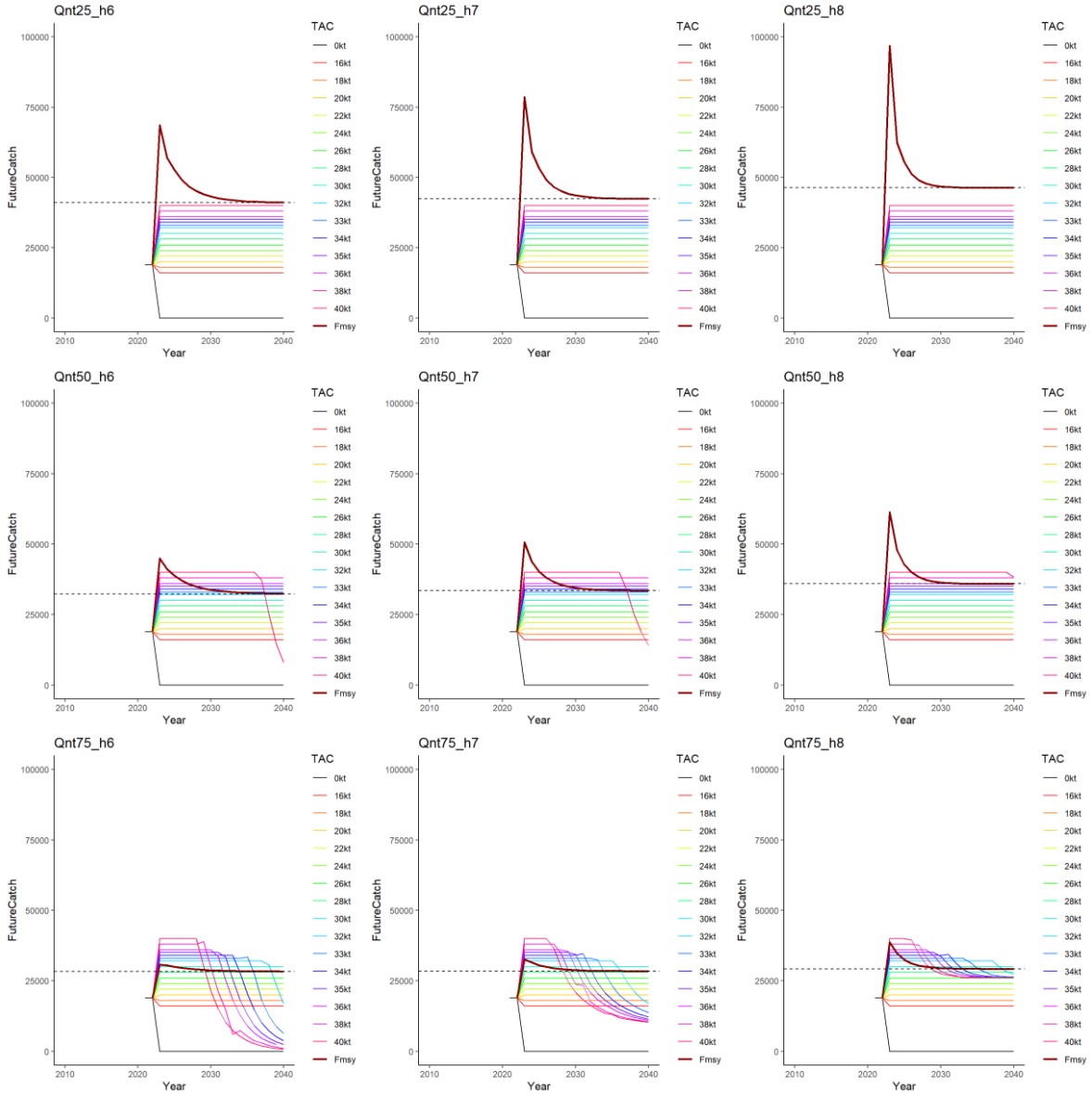

Figure 9. Deterministic projections of future catches for the individual 9 Stock Synthesis uncertainty grid runs at 0, 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock.

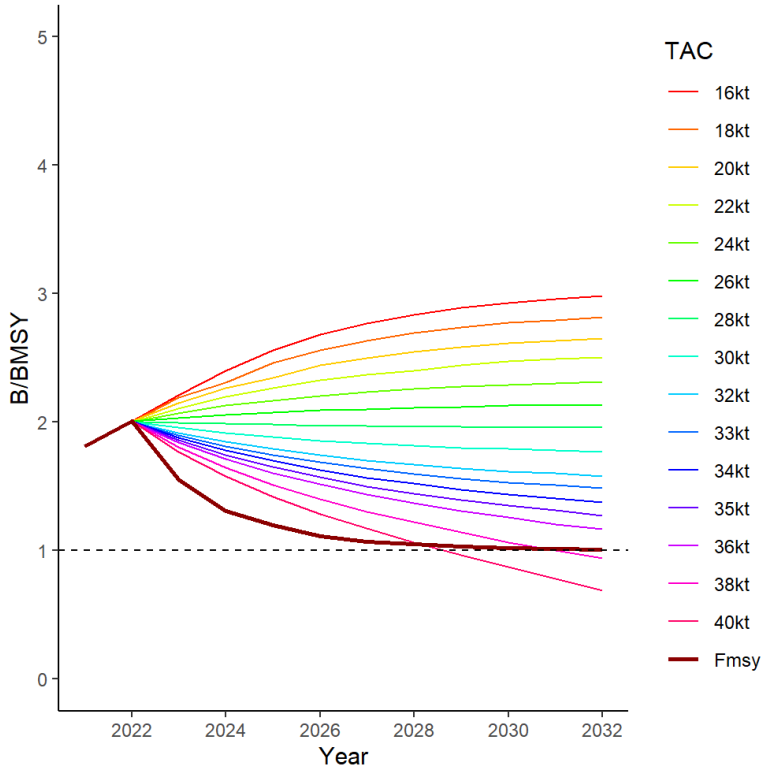

Figure 10. Stochastic MVLN projections of SSB/SSB_{MSY} for the 9 Stock Synthesis uncertainty grid runs at 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock. The lines are the median of 200000 iterations.

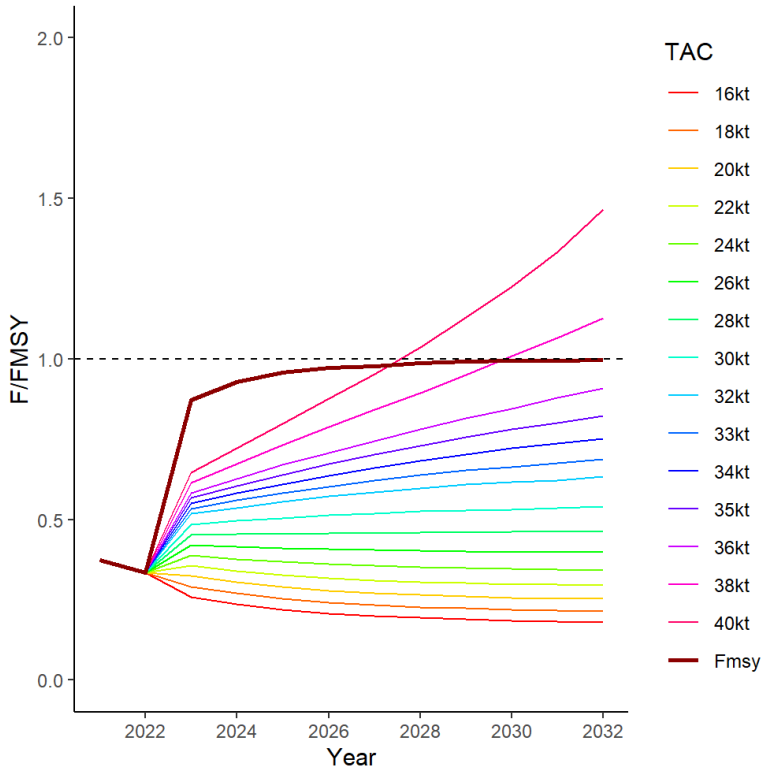

Figure 11. Stochastic MVLN projections of F/F_{MSY} for the 9 Stock Synthesis uncertainty grid runs at 16-40 thousand mt constant TACs and constant F_{MSY} for the western Atlantic skipjack stock. The lines are the median of 200000 iterations.

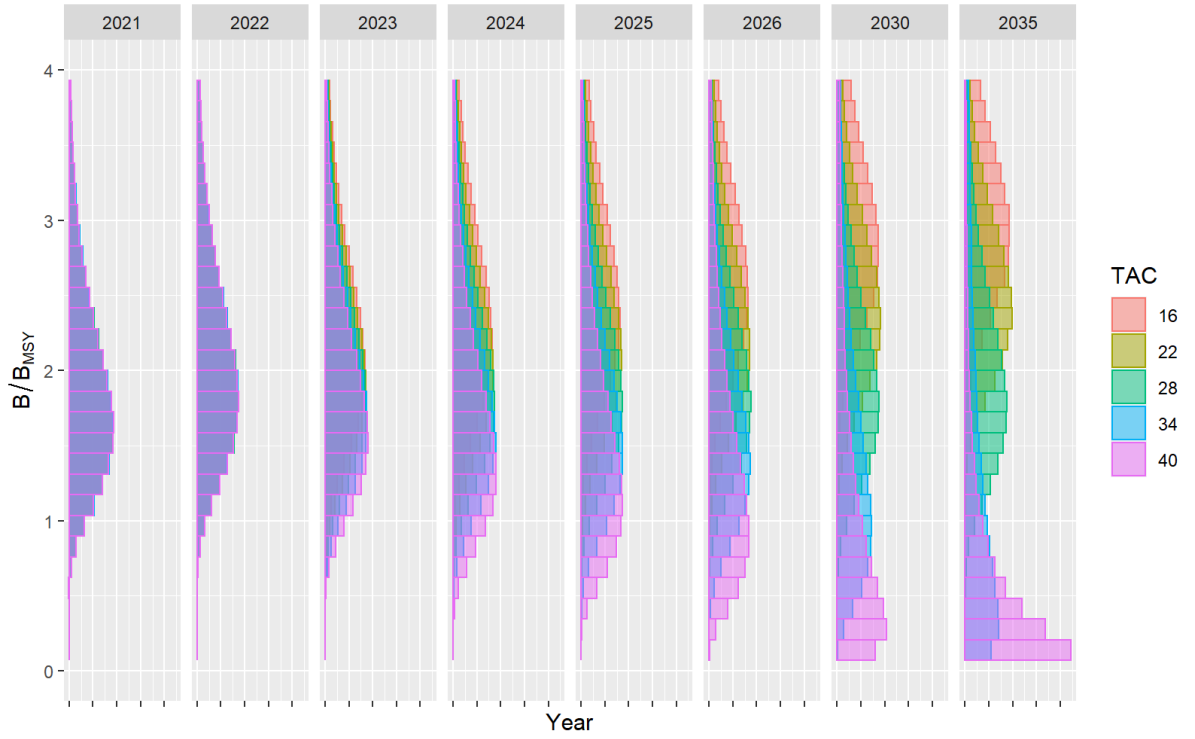

Figure 12. Histogram of SSB/SSB_{MSY} by year (2021-2026, 2030, 2035), constant catch scenario (16, 22, 28, 34 and 40 thousand t) based on the MVLN approximation.

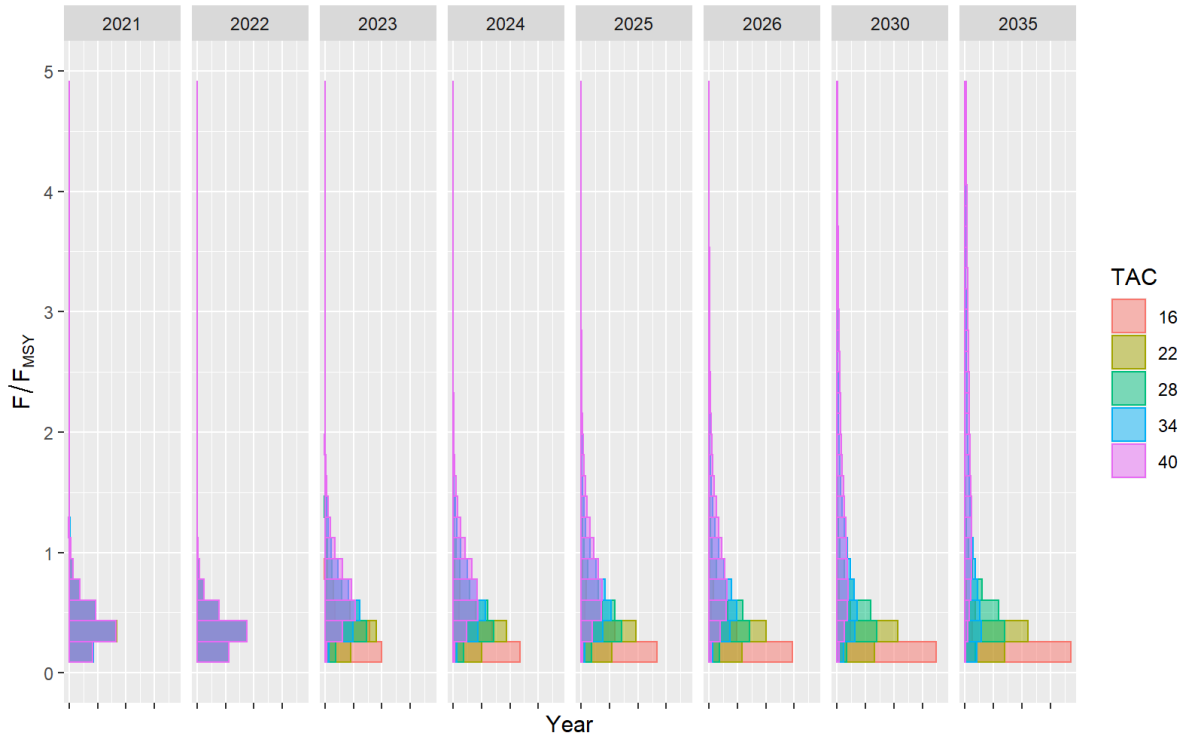

Figure 13. Histogram of F/F_{MSY} by year (2021-2026, 2030, 2035), constant catch scenario (16, 22, 28, 34 and 40 thousand t) based on the MVLN approximation.