



FUTURE TRAJECTORIES OF THE TROPICAL INDIAN OCEAN PELAGIC ECOSYSTEM UNDER FISHERIES MANAGEMENT AND CLIMATE CHANGE SCENARIOS

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Discussions (for information and open discussion):

The paper is to inform meeting participants on the projected impacts of climate change and selected fisheries management measures on the tropical Indian Ocean pelagic ecosystem, based on simulations conducted using an Ecopath with Ecosim modelling framework. Results are presented for alternative climate and management scenarios extending to 2100.

Feedback (to collect input and suggestions)

The paper is to request review and comments on the application of ecosystem modelling approaches for evaluating the long-term ecological consequences of fisheries management measures under changing environmental conditions. The feedback collected will be used to improve the simulation of these and other possible future scenarios of interest for the group.

Conclusion (to record a concluded position or summary)

While fisheries management measures can reduce direct fishing impacts and improve the status of some ecosystem components, climate change remains the dominant driver of long-term ecosystem trajectories. Consequently, under climate change, effective fisheries management will depend not only on regulating fishing mortality, but also on anticipating and adapting to shifting ecological baselines. Integrating climate change into ecosystem-based fisheries management should therefore be considered a central requirement for the future management of tropical tuna fisheries. However, the primary objective must be to reduce greenhouse gas emissions, as this is essential to preserving the ocean's capacity to continue providing important ecosystem services such as food provisioning, cultural identity, and livelihoods.

Abstract

Climate change and fishing are among the main drivers shaping the future of marine ecosystems, yet their cumulative effects remain poorly understood in large oceanic pelagic systems. We used an Ecopath with Ecosim (EwE) model representing the tropical Indian Ocean (TIO) pelagic ecosystem to evaluate the individual and combined effects of climate change and fisheries management on ecosystem dynamics through 2100. Under the high/emission climate change scenario (SSP3-7.0), substantial biomass declines were projected for several target species, particularly tropical tunas and albacore, relative to the baseline scenario. Vulnerable functional groups such as mobulas and sea turtles, and forage communities also exhibited generalized biomass reductions. Fisheries management measures produced contrasting outcomes. Under the yellowfin tuna Total Allowable Catch (TAC) scenario, fishing effort increased for several fleets to attain allocated catch limits, increasing catches for several target species but generally reducing their future biomass and generating mixed responses among vulnerable species. In contrast, improving post-release survival increased the biomass of all vulnerable groups, particularly mobulas, sharks, and sea turtles, with negligible impacts on the rest of the ecosystem. Combined climate and TAC scenarios showed that management measures could partially buffer climate-induced catch losses for some target species but were unable to prevent climate-driven biomass declines across the ecosystem. Overall, the results suggest that fisheries management remains effective for reducing direct fishing impacts but has limited capacity to offset climate-driven ecosystem change. These findings highlight the need to explicitly integrate climate change considerations into ecosystem-based fisheries management within the Indian Ocean Tuna Commission governance framework. They further emphasize the urgent need for countries to limit global warming to 1.5°C or 2°C above pre-industrial levels and, where possible, to significantly reduce their greenhouse gas emissions to achieve carbon neutrality by 2050, as stated in the Paris Agreement, signed in 2015.

Future trajectories of the tropical Indian Ocean pelagic ecosystem under fisheries management and climate change scenarios

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SUMMARY

Climate change and fishing are among the main drivers shaping the future of marine ecosystems, yet their cumulative effects remain poorly understood in large oceanic pelagic systems. We used an Ecopath with Ecosim (EwE) model representing the tropical Indian Ocean (TIO) pelagic ecosystem to evaluate the individual and combined effects of climate change and fisheries management on ecosystem dynamics through 2100. Under the high/emission climate change scenario (SSP3-7.0), substantial biomass declines were projected for several target species, particularly tropical tunas and albacore, relative to the baseline scenario. Vulnerable functional groups such as mobulas and sea turtles, and forage communities also exhibited generalized biomass reductions. Fisheries management measures produced contrasting outcomes. Under the yellowfin tuna Total Allowable Catch (TAC) scenario, fishing effort increased for several fleets to attain allocated catch limits, increasing catches for several target species but generally reducing their future biomass and generating mixed responses among vulnerable species. In contrast, improving post-release survival increased the biomass of all vulnerable groups, particularly mobulas, sharks, and sea turtles, with negligible impacts on the rest of the ecosystem. Combined climate and TAC scenarios showed that management measures could partially buffer climate-induced catch losses for some target species but were unable to prevent climate-driven biomass declines across the ecosystem. Overall, the results suggest that fisheries management remains effective for reducing direct fishing impacts but has limited capacity to offset climate-driven ecosystem change. These findings highlight the need to explicitly integrate climate change considerations into ecosystem-based fisheries management within the Indian Ocean Tuna Commission governance framework. They further emphasize the urgent need for countries to limit global warming to 1.5°C or 2°C above pre-industrial levels and, where possible, to significantly reduce their greenhouse gas emissions to achieve carbon neutrality by 2050, as stated in the Paris Agreement, signed in 2015.

KEYWORDS

EAFM, Ecosim, fisheries, tuna, Indian Ocean, bycatch, climate change, future scenarios

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1. Introduction

Ensuring the long-term sustainability of marine ecosystems and fisheries increasingly requires ecosystem-based management approaches that explicitly account for ecosystem interactions, cumulative pressures, and governance-level trade-offs among fisheries (Kaplan et al., 2010; Borja et al., 2024). This need is becoming increasingly pressing as climate change alters environmental baselines beyond those under which traditional fisheries management has historically operated (Gaines et al., 2018; Holsman et al., 2020; Halpern et al., 2025). Climate-driven responses are already evident across marine ecosystems, with many species shifting their distributions poleward or into deeper waters while exhibiting reductions in body size as ocean temperature increase (Cheung et al., 2012; Erauskin-Extramiana et al., 2019; Pinsky et al., 2020; Thompson et al., 2023).

Among tropical oceans, the Indian Ocean is considered one of the regions most vulnerable to climate change (Dalpadado et al., 2024; Roxy et al., 2024). Specifically, sea surface temperature has increased in the region at a rate of 0.12°C per decade between 1950 and 2020 (Roxy et al., 2024), while climate projections indicate that sea surface temperature will increase by 1.4°C-3.8°C by the end of the century, accompanied by declines in net primary production and surface ocean pH (Doney et al., 2012; Dalpadado et al., 2024; Roxy et al., 2024). Together, these environmental changes are expected to alter species productivity, spatial distributions, trophic interactions (Erauskin-Extramiana et al., 2019; Cossa et al., 2026) and ultimately the stability and functioning of their ecosystem (Barneche et al., 2021). As a result, future access to fishing opportunities is put at risk, with catch potential projected to decline by up to 35% by 2050s under the most pessimistic climate change scenario compared with the 2000s (Erauskin-Extramiana et al., 2023).

The Indian Ocean Tuna Commission (IOTC) has progressively implemented a broad range of conservation and management measures (CMMs) to improve the sustainability of tuna and tuna-like fisheries in the region. Catch limits, prohibition of use of large-scale driftnets, reductions in the use of drifting fish aggregating devices (dFAD), discard bans for purse seiners, and the adoption of best handling and release practices for vulnerable species are among the principal measures adopted by the commission, even that some have not been fully implemented (IOTC, 2026a). However, although IOTC has recently begun incorporating climate change considerations into its management framework, growing evidence suggests that the ecological impacts of climate change may partially offset the benefits expected from current fisheries management measures (Free et al., 2020; Koerner et al., 2026). Therefore, understanding how fishing and climate change interact at ecosystem level represents a major scientific priority, and safeguarding fisheries will ultimately depend on countries seriously implementing their commitments on reducing greenhouse gas emissions under the Paris Agreement (United Nations, 2015).

Dynamic ecosystem models provide one of the few quantitative frameworks capable of evaluating the cumulative effects of climate change and fishing, while simultaneously exploring alternative management strategies and future ecosystem trajectories (Fulton et al., 2011; Rovellini et al., 2025). As such, they are increasingly recognized as essential tools for supporting adaptive ecosystem-based fisheries management (Grüss et al., 2017; Townsend et al., 2019). Within this context, the Ecopath with Ecosim (EwE) modelling framework stands as the most widely used ecosystem modelling framework and it is well-positioned for fisheries management (Howell et al., 2021; Craig & Link, 2023). Several EwE models have also been developed for tropical oceanic ecosystems, particularly in the Pacific Ocean (Olson & Watters, 2003; Allain et al., 2007; Griffiths et al., 2018; Griffiths et al., 2021) providing valuable insights into tuna-dominated pelagic food webs. However, despite these advances, no EwE study has evaluated the combined effects of climate change and distinct fishing strategies in oceanic waters and specifically, at the scale of the tropical Indian Ocean pelagic ecosystem. This limits our ability to anticipate future ecosystem trajectories, assess the resilience of the ecosystem to multiple stressors and evaluate the effectiveness of alternative management strategies under a changing climate.

Here, we applied an EwE model representing the oceanic pelagic ecosystem of the tropical Indian Ocean (TIO) to evaluate the individual and combined effects of climate change and alternative fisheries management strategies on future ecosystem dynamics. The study was structured around three complementary questions: (i) how climate change may alter the organization and functioning of the ecosystem; (ii) whether fisheries management can improve ecosystem outcomes through two complementary dimensions of ecosystem-based fisheries management (EAFM) regulating the exploitation of target species and reducing impacts on vulnerable species; and (iii) whether fisheries management can mitigate the ecological consequences of climate change through synergistic interactions between both drivers.

2. Materials & Methods

2.1. The TIO model

The Tropical Indian Ocean (TIO) model covers an area of over 21.7 million km² between 0 and 500m depth (Figure 1). The model represents the oceanic pelagic ecosystem of the tropical Indian Ocean, excluding continental shelf waters except for small islands and archipelagos located within the study area. It is composed of 35 functional groups (FG), ranging from primary producers to top predators. Includes eight groups of vulnerable species (one seabird group, two cetacean groups, four elasmobranch groups, and one sea turtle group). Main target species were modelled separately such as swordfish (*Xiphias gladius*) or albacore tuna (*Thunnus alalunga*). In addition, the three tropical tuna species (bigeye tuna (BET), yellowfin tuna (YFT), and skipjack tuna (SKJ))

were separated into two ontogenetic functional groups (i.e., matures and immatures) using length-at-first maturity as threshold. This ontogenetic separation was implemented to better represent both ecological differences in trophic ecology and fishery selectivity between mature and immature individuals. The model also includes functional groups representing species or groups of species with the highest incidental catch rates by tuna fleets (e.g., sharks, mobulas, small tunas) (Table 1). For a more detailed description of the Ecopath TIO model, see Amate et al. (2024).



Figure 1. Area of the TIO model (in blue). Continental shelves have been excluded from the model area, except for small islands and archipelagos, as the model represents the pelagic oceanic ecosystem of the tropical Indian Ocean

2.2. Ecosim modeling approach

Ecosim is the time-dynamic module of the EwE approach, built on a set of differential equations that describe biomass dynamics over time (Walters et al., 1997; Christensen & Walters, 2004). These equations are derived from the fundamental Ecopath production equation and are expressed as follows:

$$\frac{dB_i}{dt} = g_i \sum Q_{ji} - \sum Q_{ij} + I_i - (M0_i + F_i + e_i) \times B_i \quad \text{Eq. 1}$$

Where $\frac{dB_i}{dt}$ represents the rate of biomass change, B_i , of the functional group i during the time interval dt . g_i is the net growth efficiency, Q_{ji} is the consumption rate of j by the functional group i , and Q_{ij} is the consumption rate on the functional group i by the predator j . I_i is the immigration rate, while $M0_i$, F_i , e_i represent the natural mortality rate, fishing mortality rate, and emigration rate, respectively. When multiplied by B_i , these yield the net rates of the three factors.

Consumption rates (Q) are estimated using the “foraging arena theory” (Ahrens et al., 2011). This theory is based on the idea that organisms are not constantly exposed to predation risks, as they employ various strategies to reduce it, such as hiding, schooling, or performing vertical migrations. The “foraging arena theory” defines two states: *vulnerable*, when the prey is available to predators, and *non-vulnerable*, when the prey is not accessible to predators. In the model this implies the division of the prey’s biomass between a vulnerable and a non-vulnerable fraction, and the transfer rate or vulnerability (v_{ij}) between the two fractions determines the trophic flow between the predator and the prey (Ahrens et al., 2011). This concept of vulnerability incorporates density-dependent processes and reflects how close a species or functional group is to its carrying capacity. Carrying capacity refers to the maximum population size that a species or group can reach without negatively impacting itself due to the depletion of essential resources required for its own development (Christensen & Walters, 2004; Christensen et al., 2008). The default vulnerability values ($v_{ij} = 2$) represent a mixed trophic flow. A low value ($v_{ij} < 2$) indicates a “bottom-up” flow and a situation closer to the carrying capacity, whereas a high value ($v_{ij} > 2$) suggests a “top-down” flow and a condition further from the carrying capacity (Ahrens et al., 2011). For each predator-prey interaction, the consumption rate is calculated as follows:

$$Q_{ij} = \frac{a_{ij} \times v_{ij} \times B_i \times B_j \times T_i \times T_j \times M_{ij}/D_j}{v_{ij} + v_{ij} \times T_i \times M_{ij} + a_{ij} \times M_{ij} \times B_j \times T_j/D_j} \times f(Env_{function}, t) \quad \text{Eq. 2}$$

Where a_{ij} is the effective search rate of predator j on prey i , v_{ij} is the vulnerability of prey i by predation of j , B_i is the biomass of the prey, B_j is the biomass of the predator, T_i is the relative feeding time of the prey, and T_j is the relative feeding time of the predator. M_{ij} represents mediation effects, and D_j denotes the handling time of the prey by the predator, which limits the consumption rate. $f(Env_{function}, t)$ is a multiplier factor that accounts for the influence of environmental variables (e.g., temperature). This multiplier ranges from 0 to 1 and is derived from the environmental response function, modifying the consumption rate (Q_{ij}) of the functional group. Specifically, the multiplier is calculated based on the intersection between the response function to an environmental factor and the actual conditions of that factor, with a maximum value of 1 and decreasing values as the environmental condition deviates from the optimal range for the functional group.

2.3. TIO Ecopath with Ecosim model updates

To explore the future projections of the ecosystem of the oceanic pelagic tropical Indian ocean under the different scenarios, the TIO model presented in Amate et al. (2024) and in Amate et al. (2025) was updated, refitted and adapted.

2.3.1. Biological updates

First, the model was updated with the outputs of the latest stock assessments for the functional groups (FG) of blue shark (FG. 4) (Rice, 2025), bigeye tuna mature and immature (FG. 13,14) (Phillips et al., 2025), and yellowfin mature and immature (FG. 15,16) (Urtizbarea et al., 2024) (Tables 1 & 2).

A negative biomass accumulation (*BA*) was included for blue shark and bigeye mature and immature to help the model fit the decreasing biomass trend at the beginning of the historical period. A negative *BA* was set also to yellowfin mature and immature to help the model adjust the general decreasing trend of the species instead of the anomalous increase observed between the years 2000 to 2003 due to a *Natosquilla investigatoris* bloom (Potier et al., 2004), which resulted in more prey available for YFT triggering a rapid increase in its biomass (Table 1). For blue shark, the *BA* was tuned iteratively selecting the final value based on its ability to provide the best fit to the observed time series. For the two tuna species, *BA* was calibrated within the multistanza model framework. The values were selected as the ones that produced an estimated immature biomass matching those derived from the stock assessments.

Table 1. Input data and outputs of the Ecopath TIO model. Calculated input parameters are highlighted in bold.. *B* = final biomass (t·km⁻²); *P/B* = production/biomass (year⁻¹); *Q/B* = consumption/ biomass (year⁻¹); *P/Q* = production/consumption ratio; *EE* = ecotrophic efficiency; *TL* = trophic level; *F* = fishing mortality; *F/Z* = exploitation rate; *M2* = predation mortality; *M0* = Other mortality.

Functional group	B	P/B	Q/B	P/Q	EE	TL	F	F/Z	M2	M0
1 Seabirds	0.0005	0.12	77.62	0.00	0.01	4.15	-	-	0.002	0.120
2 Baleen whales	0.0152	0.04	3.98	0.01	0.48	3.77	0.017	0.446	0.001	0.020
3 Toothed whales	0.0460	0.06	8.16	0.01	0.44	4.27	0.004	0.077	0.021	0.032
4 Blue shark	0.0197	0.29	2.92	0.10	0.43	4.52	0.140	0.084	0.057	0.017
5 Silky shark	0.0303	0.32	3.22	0.10	0.30	4.06	0.084	0.261	0.013	0.225
6 Other sharks	0.0255	0.31	3.08	0.10	0.70	4.55	0.199	0.645	0.017	0.092
7 Whale shark	0.0289	0.06	1.82	0.03	0.50	3.32	0.030	0.469	0.002	0.032
8 Pelagic stingray	0.0065	0.85	6.57	0.13	0.50	3.54	0.007	0.008	0.421	0.427
9 Mobulas	0.0022	0.23	3.79	0.06	0.50	3.72	0.078	0.344	0.035	0.113
10 Sea turtles	0.0017	0.19	3.04	0.06	0.53	3.66	0.070	0.377	0.027	0.088
11 Other billfishes	0.0143	0.33	3.48	0.10	0.41	4.47	0.100	0.300	0.037	0.195
12 Swordfish	0.0144	0.37	3.40	0.11	0.38	4.39	0.114	0.312	0.026	0.227
13 Bigeye mature	0.0096	0.73	5.21	0.14	0.87	4.24	0.634	0.444	0.002	0.094
14 Bigeye immature	0.0142	0.82	9.03	0.09	0.43	4.17	0.114	0.061	0.243	0.464
15 Yellowfin mature	0.0386	0.74	5.29	0.14	0.53	4.20	0.318	0.069	0.075	0.347
16 Yellowfin immature	0.0303	0.98	7.93	0.12	0.59	4.01	0.233	0.058	0.349	0.399
17 Skipjack mature	0.0695	1.09	6.81	0.16	0.39	3.99	0.277	0.254	0.150	0.663
18 Skipjack immature	0.0031	1.56	15.05	0.10	0.21	3.92	0.101	0.065	0.224	1.235
19 Albacore	0.0036	0.60	5.05	0.12	0.55	4.14	0.073	0.122	0.255	0.272
20 Small tunas and bonitos	0.1589	0.94	7.21	0.13	0.70	3.73	0.092	0.100	0.564	0.281
21 Jacks, mackerels, runners, trevallies and scads	0.1913	1.01	7.76	0.13	0.80	3.54	0.002	0.002	0.805	0.202
22 Epipelagic fishes – I	0.1470	0.84	6.44	0.13	0.70	3.85	0.002	0.003	0.584	0.251
23 Epipelagic fishes – II	0.2291	1.05	7.51	0.14	0.80	3.48	0.000	0.000	0.840	0.210
24 Small epipelagic fishes	0.5532	2.09	12.24	0.17	0.97	3.17	0.000	0.000	2.02	0.069
25 Large mesopelagic fishes	0.2044	0.49	4.12	0.12	0.70	4.10	0.000	0.000	0.346	0.148
26 Small mesopelagic fishes	2.6816	2.35	13.45	0.18	0.68	2.87	-	-	1.595	0.758
27 Pelagic cephalopods	0.4517	2.67	15.87	0.17	0.90	3.56	-	-	2.403	0.267
28 Pelagic crustaceans	0.8220	3.57	14.27	0.25	0.93	2.50	-	-	3.321	0.246
29 Gelatinous plankton	0.5395	9.47	47.35	0.20	0.43	2.75	-	-	4.065	5.405
30 Macrozooplankton	2.6720	15.39	55.05	0.28	0.29	2.65	-	-	4.518	10.87
31 Mesozooplankton	4.7460	29.59	106.5	0.28	0.58	2.18	-	-	17.26	12.32
32 Microzooplankton	7.0020	53.6	178.7	0.30	0.41	2.02	-	-	21.98	31.62
33 Phytoplankton	11.658	204.8	-	-	0.51	1	-	-	105.0	99.82
34 Discards	0.0110	-	-	-	0.19	1	-	-	-	-
35 Detritus	238.88	-	-	-	0.27	1	-	-	-	-

Table 2. Time series used to drive, adjust and calibrate the TIO Ecosim model. ESP: Spain; FRA: France; SYC: Seychelles; BUM: Blue marlin; BLM: Black marlin; MLS: striped marlin; SFA: Sailfish.

	Data time series	Coverage	References	Drive the model	Adjust the model (compare results)
4. Blue shark	Absolute biomass	2003-2022	Stock assessment (Rice, 2025)	X	X
	Absolute catch; Landings		IOTC - Nominal Catch (accessed. 22-02-2024)		X
	Discard mortality rate; Discard proportion		Calculated		
	Relative harvest rate, Total discards, Discards		Calculated		X
5. Silky shark	Absolut catch	2003-2022	IOTC - Nominal Catch (accessed. 22-02-2024)	X	X
	Discard mortality rate; Discard proportion; Catchability		Calculated		
	Total discards; Discards		Calculated		X
2. Baleen whales; 3. Toothed whales; 6. Other sharks; 7. Whale shark; 8. Pelagic stingray 9. Mobulas; 10. Sea turtles 20. Small tunas and other bonitos 21. Jacks, mackerels, runners, trevallies and scads 22. Epipelagic fishes - I; 23. Epipelagic fishes - II 25. Large mesopelagic fishes	Absolute catch	2003-2022	IOTC - Nominal Catch (accessed. 22-02-2024)		X
	Discard mortality rate; Discard proportion	2003-2022	Calculated	X	
	Total discards; Discards	2003-2022	Calculated		X
11. Other billfishes	Absolute biomass	2003- 2019, 2020 and 2022	BUM - (Parker & Kerwath, 2022); BLM - (Chih-Yu et al., 2024); MLS - (Yun-ju et al., 2024); SFA - (Parker & Espittia, 2022);	X	X
	Absolute catch; Landings	2003-2022	IOTC - Nominal Catch (accessed. 22-02-2024)		X
	Discard mortality rate; Discard proportion; Catchability	2003-2022	Calculated		
	Total discards; Discards	2003-2022	Calculated		X
12. Swordfish	Absolute biomass	2003-2022	Stock assessment (IOTC, 2022b)	X	X
	Absolute catch; Landings		IOTC - Raised catch (accessed. 13-10-2023)		X
	Discard mortality rate; Discard proportion; Catchability		Calculated		
	Total discards; Discards		Calculated		X
13. Bigeye mature 14. Bigeye immature	Absolute biomass	2003-2022	Stock assessment (Phillips et al., 2025)	X	X
	Absolute catch; Landings		IOTC - Raised catch (accessed. 13-10-2023)		X
	Discard mortality rate; Discard proportion		Calculated		
	Total discards; Discards		Calculated		X
15. Yellowfin mature 16. Yellowfin immature	Absolute biomass	2003-2022	Stock assessment (Urtizberea et al., 2024)	X	X
	Absolute catch; Landings		IOTC - Raised catch (accessed. 13-10-2023)		X
	Discard mortality rate; Discard proportion		Calculated		
	Total discards; Discards		Calculated		X
17. Skipjack mature 18. Skipjack immature	Absolute biomass	2003-2022	Stock assessment (IOTC, 2023)	X	X
	Absolute catch; Landings		IOTC - Raised catch (accessed. 13-10-2023)		X
	Discard mortality rate; Discard proportion		Calculated		
	Total discards; Discards		Calculated		X
19. Albacore	Absolute biomass	2003-2022	Stock assessment (IOTC, 2022a)	X	X
	Absolute catch		IOTC - Raised catch (accessed. 13-10-2023)		X
	Discard mortality rate; Discard proportion; Catchability		Calculated		
	Total discards; Discards		Calculated		X
24. Small epipelagic fishes	Absolute biomass	2003-2022	LMTL model (CMEMS - Copernicus) (Lehodey et al., 2015)	X	X
	Discard mortality rate; Discard proportion				
	Total discards; Discards				X
26. Small mesopelagic fishes	Absolute biomass	2003-2022	LMTL model (CMEMS - Copernicus) (Lehodey et al., 2015)		X
30. Macrozooplankton; 31. Mesozooplankton 32. Microzooplankton	Absolute biomass	2003-2022	COPEPOD database and (Wimalasiri et al., 2021)		X
33. Phytoplankton	Absolute biomass	2003-2022	Global Ocean Biogeochemistry Hindcast (CMEMS - Copernicus)		X

Table 2. Continuation.

Data time series	Coverage	References	Drive the model	Adjust the model (compare results)
Relative fishing effort (ESP – Purse seine fleets)	2003-2019	(Báez et al., 2020) & IOTC - Catch & Effort (accessed. 02-04-2025)	X	
Relative fishing effort (FRA – Purse seine fleets)	2003-2022	(Floc'h et al., 2021) & (Laurent Floc'h, <i>pers. comm.</i>)	X	
Relative fishing effort (SYC – Purse seine fleets)	2003-2022	(Assan et al., 2019) & (Cindy Assan, <i>pers. comm.</i>)	X	
Relative fishing effort (Others – Purse seine fleets)	2003-2022	Approximated using the effort of the other purse seine fleets	X	
Relative fishing effort (Longline fleet)	2003-2022	IOTC - Catch & Effort (accessed. 14-10-2024)	X	
Relative fishing effort (Baitboat)	2003-2022	Follows MDV trend; IOTC - Catch & Effort (accessed. 14-10-2024)	X	
Relative fishing effort (Gillnet)	2003-2022	Follows the catch trend of tropical and small tunas of LKA and IRN	X	
Relative fishing effort (Line and Others fleets)	2003-2022	Follow the catch trends - IOTC - Raised catch (accessed. 13-10-2023)	X	
Relative fishing effort (dFAD ghost fishing)	2003-2022	Constant effort	X	
Environmental variable – Primary production (PP)	2003-2022	(Warszawski et al., 2014; Boucher et al., 2020)	X	
Environmental variable – SWT-100m	2003-2022	(Warszawski et al., 2014; Boucher et al., 2020)	X	
Environmental variable – SWT-200m	2003-2022	(Warszawski et al., 2014; Boucher et al., 2020)	X	
Environmental variable – SWT-500m	2003-2022	(Warszawski et al., 2014; Boucher et al., 2020)	X	

2.3.2. Fisheries updates

Discard time series for the purse seine fleets of Spain, France, and Seychelles were updated by assuming the mean value of discards of the corresponding FG presented in Ruiz et al. (2018) and weighted by the total catch of tropical tunas and albacore for each year of the Ecosim period (Table 2; SM – Table 1).

The time series of fishing effort for the baitboat fleet was recalculated to account for the discontinuity in reporting units; the mean CPUE between 2010 to 2012 was multiplied by the fleet's yearly catch of the three tropical tunas between 2013 and 2022 to obtain the corresponding fishing effort for the years 2013 to 2022 (Table 2; SM - Figure 1). Similarly, the effort of the gillnet fleet was updated to follow the combined catch trend of the three tropical tunas and neritic tunas by the Sri Lankan and Iranian gillnet fleets, while for the longline fleet, a previous calculation error was corrected, and the time series updated accordingly (Table 2; SM - Figure 1). In the same way, the effort of the purse seine fleet with unclassified sets was recalculated to follow the catch trend of the three tropical tuna and neritic tuna catches (Table 2; SM - Figure 1).

2.3.3. Environmental forcing

Regarding environmental variables, time series of sea water temperature (SWT) were extracted and averaged at three depths (100, 200, 500m) to account for differences in water column utilization among functional groups (Table 2; SM - Figure 2). Furthermore, chlorophyll-a concentration was integrated over the top 150 m of the water column, the euphotic depth (Sorokin et al., 1985), with its resulting trend used to force the model's primary production (Table 2; SM - Figure 2).

To avoid mismatch of environmental variables between the hindcast and the forecast periods, the Ecosim model was fitted with environmental data extracted from the IPSL-CM6A-LR Earth System Model (Boucher et al., 2020), supplied by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014). It provides environmental data of two differentiated periods: historical (1850-2014) and projections (2015-2100) which projects environmental variables under three Shared Socioeconomic Pathways (SSP1-2.6, SSP3-7.0, and SSP5-8.5). Among these, SSP1-2.6 broadly corresponds to the 2°C global warming limit set out in the Paris Agreement, representing a scenario consistent with sustained decarbonization efforts, whereas SSP3-7.0 and SSP5-8.5 represent scenarios with limited or no additional climate mitigation policy (Meinshausen et al., 2024). As the period of the Ecosim model falls between the two periods, for the years 2000 to 2014 the values were extracted from the historical product while for the following years, from 2015 to 2022, the values under the SSP3-7.0 scenario were selected to fit the model as the difference in value for these seven years was negligible between scenarios. Regarding chlorophyll-a concentration, a constant additive delta adjustment of -4 mg/m² was applied to the future projections. This adjustment was made because a non-biophysical

step-increase of approximately 4 units was identified at the 2014-15 transition probably produced by a mismatch between historical forcing variables and future SSP scenarios rather than by a true climatic response. This adjustment allowed to prevent coupling mismatch between the two periods while preserving the model's original interannual variability.

The environmental response functions ($f(Env_{function}, t)$) in Eq. 2) that link functional group dynamics to the environmental variables were obtained by fitting a double logistic function (Harris, H., 2026) to species-specific temperature preference range compiled from published studies and Aquamaps (SM - Figure 3; SM - Table 3) (Kaschner et al., 2019). Environmental response functions were only applied to the functional groups with stock assessments and to silky shark, for which evaluating climate responses was considered particularly relevant. Responses of the remaining functional groups were assumed to arise indirectly through trophic interactions and changes in primary production.

2.3.4. Structural model developments

Beyond these historical updates and additions, a few structural changes were introduced to expand the model's capacity for future scenario simulation (Table 2).

Estimates of the mortality of silky shark (FG. 5) and sea turtles (FG. 10) resulting from entanglement to drifting FADs (dFAD) were added as discards of new fleet of the model, *dFAD ghost fishing* fleet (SM-Table 2). The total number of FADs was obtained by multiplying the number of purse-seine vessels of each model fleet, obtained from official publications, by the number of dFADs per vessel, obtained from the literature (SM-Table 2). Silky shark, entanglement rates between 2003 to 2013 were adapted from Filmatler et al. (2013) for high entanglement rate dFAD (HERDFAD), between 2014 to 2019 from Grande et al. (2019) for low entanglement rate dFAD (LERDFAD) and from 2020 to 2022 from Grande et al. (2025) for non-entanglement rate dFAD (NERDFAD). Entanglement rates were converted to biomass using a mean individual weight of 0.0066t per individual (Pérez San Juan et al., 2024). The LERDFAD rate for the period 2014–2019 was estimated by assuming that 50% of the dFADs deployed corresponded to non-entangling designs (Ind. 1) and the remaining 50% to low-entanglement-risk designs (Ind. 2 and 3), following the design categories reported in Table 5 of Grande et al. (2019) (SM-Table 2). For sea turtles, entanglement rates were derived from Bourjea et al. (2014). Biomass values were estimated from the total number of reported entanglements relative to the number of dFADs visited, combined with species-specific individual weights, weighted by the relative frequency of each species. The weight assumed for each species are the same presented in Amate et al. (2024). A transition period was assumed between 2014 and 2016, during which the entangling rate was reduced by 33% per year relative to the 2013 value, reaching zero in 2016 and remaining at zero thereafter, reflecting the progressive adoption of non-entangling dFAD

designs in the fishery (SM-Table 2). The fishing effort time series for the dFAD ghost fishing fleet was assumed to follow its catch trend (Table 2; SM - Figure 1).

To facilitate scenarios' simulation, forcing fishing mortality time series were removed, leaving the model to be forced by fishing effort for all functional groups instead. More precisely, time series of fishing effort, discard mortality rate by fleet and group, discard proportion, environmental conditions, and catchability were used to drive the model, while time series of biomass, catch, total discards, relative fishing mortality, discards by fleet and group, and landings were used to calibrate it (Table 2).

2.4. Model fitting

2.4.1. Calibration settings

The fitting procedure estimates various vulnerability parameters to improve model calibration by comparing model predictions with observed data identifying the model that provides the best statistical fit based on the sum-of-squares (SS) and the Akaike Information Criterion (AIC) (Heymans et al., 2016; Bentley et al., 2024).

First, we set the feeding time adjustment for immature stanzas to 0.5 to allow higher immature survival at low stock size (Christensen & Walters, 2004). We kept the power switching parameter at the default value of 0, thereby preventing functional groups changing their feeding strategy. Consequently, functional groups will keep eating the same proportion of each prey even if the abundance between preys' change.

Furthermore, an F_{MSY} analysis was conducted, consisting of subjecting a species to a range of fishing mortality rates to identify the level of exploitation that maximizes sustainable yield (F_{MSY}). This analysis provides a diagnostic to assess if the model can generate expected biomass responses when the species is fished sustainably (Walters et al., 2005).

2.4.2. Time-series weighting

Then, a weight between 0 and 1 was given to each calibration time series depending on their reliability. If each time series was weighted equally, regardless of how reliable it is, the fitting routine would treat noisy, poorly reliable time series, as equally informative as well-validated ones (Bentley et al., 2024). That would bias the model towards trying to fit noisy time series at the expense of more trustfully informative ones. Initially a value of 1 was assigned to all time series of relative fishing mortality, discard mortality rate, discards by fleet and group, landings for species with georeferenced catches, biomass, and for catch time series of species with stock assessment, except for blue shark and other billfishes (FG. 11), for which a value of 0.8 was assigned. A value of 0.5 was assigned to total discards, catch of species without stock assessment, discard rate by fleet and group, and to the landings of species without georeferenced catches. A first run of the model with the time-series was performed to identify the time series that the model

cannot reproduce well due to unreliability with the rest of the dynamics or that forcing the model to fit it would require unrealistic parameters. After the first run, the weight of time series with $SS > 30.3$ was set to 0 to exclude them from the sum of squares calculation. This value, which excludes 10.6% of the time series used to calibrate the model (46 out of 434), was selected because it corresponds to the last large gap in the sum of squares distribution, indicating a natural discontinuity between informing and poorly informing time series (SM -Figure 4).

2.4.3. Vulnerability estimation and model selection

The maximum number of vulnerabilities that can be estimated is $k-1$, where k is the number of observed time series (in this case 41 time series of biomass and catch). To fit the updated Ecosim model, the combined fitting procedure described in Bentley et al. (2024) was used. The model was first fitted by searching for vulnerabilities only by predator and resetting the vulnerabilities to the default value of 2 for each search. Then, the resulting best statistically fitted model was fitted by searching for predator/prey with a maximum number of vulnerabilities to estimate equal to $k-1-v$, where v is the number of vulnerabilities estimated in the first step. A repeated search methodology was performed in this second step of the fitting, repeating the search without resetting the vulnerabilities to the default value until no further improvement on the SS and AIC was obtained.

2.5. Simulation of future scenarios

The updated TIO Ecosim model was used to implement a scenario-based experimental design addressing the three study questions. Seven scenarios were simulated over a 78-year period (2023–2100) to evaluate the effects of climate change, fisheries management, and their interaction (Table 3).

Table 3. Description of the seven scenarios simulated, indicating the scenario reference number, the name, the settings applied to fishing effort, discard mortality rate, and environmental variables relative to the baseline scenario.

Scenario	Name	Fishing Effort	Discard mortality rate	Environmental variables
Scn. 1	Baseline	Kept constant	Kept constant	Kept constant
Scn. 2	SSP1-2.6	Kept constant	Kept constant	Follow SSP1-2.6 trend
Scn. 3	SSP3-7.0	Kept constant	Kept constant	Follow SSP3-7.0 trend
Scn. 4	TAC	Modified to match YFT TAC (as in SM – Table 4)	Kept constant	Kept constant
Scn. 5	BB.PP.	Kept constant	2% annual reduction for 10 years	Kept constant
Scn. 6	TAC+SSP1-2.6	Modified to match YFT TAC (as in SM – Table 4)	Kept constant	Follow SSP1-2.6 trend
Scn. 7	TAC+SSP3-7.0	Modified to match YFT TAC (as in SM – Table 4)	Kept constant	Follow SSP3-7.0 trend

2.5.1 Baseline scenario

The baseline scenario (Scn. 1) represented the continuation of current environmental conditions and fishing dynamics throughout the simulation period. As such, fishing effort, environmental variables, catchability, discard proportion and discard mortality for each functional group and fleet were fixed at their 2022 values and projected throughout the simulated period (2023-2100) (Table 3).

2.5.2 Climate change scenarios

Climate change scenarios were designed to evaluate the ecosystem consequences of two plausible future greenhouse-gas emission pathways defined by the Intergovernmental Panel on Climate Change (IPCC). The model was forced with environmental projections under the low-emission scenario (Global sustainability – SSP1-2.6) (Scn. 2) and the high-emission scenario (Regional rivalry – SSP3-7.0) (Scn. 3) (O'Neill et al., 2016; 2017). The Scenario SSP5-8.5 (Fossil-fueled development) was not considered because it is increasingly regarded as an unlikely future pathway given recent development in climate policy, trends in the costs of renewables, and recent observed emission trajectories (Hausfather & Peters, 2020; Van Vuuren et al., 2026). Together, SSP1-2.6 and SSP3-7.0 span the most plausible range of future climate conditions currently considered by the IPCC and are therefore expected to capture the range of potential ecosystem responses (Table 3).

2.5.3 Fisheries management scenarios

Two fisheries management scenarios were designed to evaluate complementary dimensions of ecosystem-based fisheries management currently being implemented or considered within IOTC (Table 3). The first evaluated whether regulating exploitation of target species can maintain ecosystem structure and functioning, whereas the second assessed whether reducing fishing mortality of vulnerable species through improved fishing practices can reduce ecosystem impacts while maintaining ecosystem functioning.

The first fisheries management scenario (TAC - Scn. 4) evaluated whether regulating the exploitation of target species through implementation of the YFT Total Allowable Catch (TAC) could maintain ecosystem structure and functioning. YFT TAC was selected because it consistently constrains fleet effort before BET or SKJ across CPCs, based on 2022 catch proportions, and because TACs are not assigned for BET or SKJ in most CPCs. From 2023 onwards, fishing effort in all model fleets was adjusted to achieve the YFT TAC established by IOTC for 2020-2026 (EU, 2024; IOTC, 2025a). Recently, a new TAC for YFT has been agreed, however, the differences with the TACs are not very different to the previous TAC used to simulate the scenario (IOTC, 2026c). To estimate the corresponding fishing effort, a catch allocation was first derived for each contracting party and cooperating non-contracting party (CPC) with an assigned or objected YFT TAC based on the average proportion of YFT catches taken by each gear type between 2020 and 2022. This allocation was then adjusted by the proportion of each fleet's YFT catches that originated within the model domain during the same period. The resulting values were multiplied by the national TACs to estimate the expected YFT catch of each country–gear combination under the TAC regime in the model area. These catches were subsequently aggregated according to the tropical Indian Ocean (TIO) model fleets to estimate the YFT catch corresponding to each fleet (SM - Table 4). Finally, the fishing effort

required for each fleet to attain its allocated YFT catch was estimated by proportional scaling using the average effort and YFT catches observed between 2020 and 2022 (SM - Table 5).

Several assumptions were required to account for countries without finalized TAC allocations or complete catch information. As India and Madagascar objected to their 2025 TAC allocations, their mean YFT catch between 2020-2022 were assumed to represent their TAC. The same approach was applied to Taiwan as no YFT TAC has been allocated to this fleet. Similarly, Oman was assigned a YFT TAC of 25,000t, corresponding to the quota agreed for implementation from 2031 onwards (IOTC, 2026c). For Sudan, in the absence of YFT catch prior to 2024, the catch value of 2024 was used as reference. Lastly, as no YFT catch data were available for Philippines, its TAC was assigned to the “Others” fleet within the model.

The second fisheries management scenario (Scn. 5) evaluated whether reducing fishing mortality of vulnerable species through the general adoption of improved fishing practices following the code of good practices by all fleets (Grande et al., 2019) could reduce ecosystem impacts while maintaining ecosystem functioning. The scenario assumed a 2% annual reduction in the discard mortality rate of all vulnerable species across all fleets between 2023-2033, relative to the 2022 value, and maintained until 2100. This scenario is intended to represent improvements in the best handling and release practices, together with the implementation of fauna release devices by all fleets and adapted by fishing gear. These measures have been shown to enhance the post-release survival of vulnerable species in purse seiners (Grande et al., 2022; Stewart et al., 2024; Cronin et al., 2026).

2.5.4 Combined scenarios

Finally, two combined scenarios were simulated to evaluate whether fisheries management can mitigate the ecological consequences of climate change. Specifically, the TAC scenario was combined with each climate pathway (Scn. 6 and Scn. 7; Table 3) to determine whether regulating exploitation of target species can offset, or partially compensate for, future climate-driven ecosystem change. Comparison among climate-only, fisheries-only, and combined scenarios also allowed the interaction between climate change and fisheries management to be evaluated as additive, synergistic, or antagonistic.

2.6. Uncertainty analysis

To assess the uncertainty associated with the input parameters of the Ecopath model, we ran 100 iterations of the Monte Carlo uncertainty routine (Christensen & Walters, 2004; Heymans et al., 2016). The uncertainty was determined by the pedigree values reported in Amate et al., (2024). In each iteration, a new set of input parameters was generated by randomly sampling values within the corresponding confidence intervals. This approach produced 100 different model variations,

allowing us to assess the sensitivity of the base Ecopath model to input values uncertainty and quantify how this uncertainty propagates through subsequent Ecosim simulations.

3. Results

3.1. Historical model performance

The Ecosim model satisfactorily reproduced the observed historical biomass trend for several key functional groups including, other billfishes (FG. 11), yellowfin mature (FG. 15), yellowfin immature (FG. 16), skipjack immature (FG. 18) and albacore (FG. 19) and small epipelagic fishes (FG. 24) (Figure 2). However, model performance was weaker for blue shark (FG. 4), swordfish (FG. 12), bigeye mature (FG. 13), bigeye immature (FG. 14) skipjack mature (FG. 17) and small mesopelagic fishes (FG. 26) (Figure 2).

The calibrated model projected declining historical biomass trends for several fishery-targeted functional groups (Figure 2). Biomass declined for other billfishes, bigeye immature, yellowfin mature, yellowfin immature, skipjack mature, skipjack immature, albacore, small epipelagic fishes, and small mesopelagic fishes during the simulated period. Blue shark and mature bigeye tuna showed an initial decline followed by relatively stable biomass with a slight recovery towards the end of the historical period (Figure 2). Among vulnerable species functional groups, the model predicts reductions in biomass for other sharks (FG. 6), mobulas (FG. 9), and toothed whales (FG. 3) as these are among the main non-target functional groups impacted by fishing in the area. In contrast, it predicts increasing biomass trends for baleen whales (FG. 2), whale shark (FG. 7), silky shark, and sea turtles, the two latest benefited by the change from entangling to non-entangling dFADs. However, the uncertainty surrounding the predictions for these vulnerable species functional groups is considerably higher than for targeted species (SM – Table 6). In general, for intermediate and low trophic level functional groups, the model predicts stable biomass trends (SM – Table 6). Historical biomass trajectories were also generated for the 19 functional groups lacking biomass observations, providing a complete reconstruction of ecosystem dynamics over the simulation period (SM – Table 6).

The model also reproduced satisfactorily the historical catch trajectories for most functional groups (Figure 3). Specifically, the model reproduced the declining trend in the catches of blue shark, swordfish, mature bigeye tuna, mature yellowfin tuna, and albacore. It also shows an increase in the catches of other billfishes, bigeye immature, yellowfin immature and skipjack mature and immature (Figure 3). Time series of observed catch values were available for 12 of the 19 groups without biomass observations (SM – Table 7). Among these, the model was able to predict and fit the catch time series for all the species with observed catch trends. Overall, catch trends of non-targeted species show different trends depending on the fleets that catch them due

to difference in fleets' fishing effort trends throughout the entire period (SM – Figure 1; SM – Table 7).

Model performance was further evaluated by comparing estimated FMSY values with the most recent stock assessments. The model identified similar FMSY estimates for blue shark, swordfish, and albacore but did not reproduce the corresponding estimates for the three tropical tunas (bigeye, yellowfin, and skipjack).

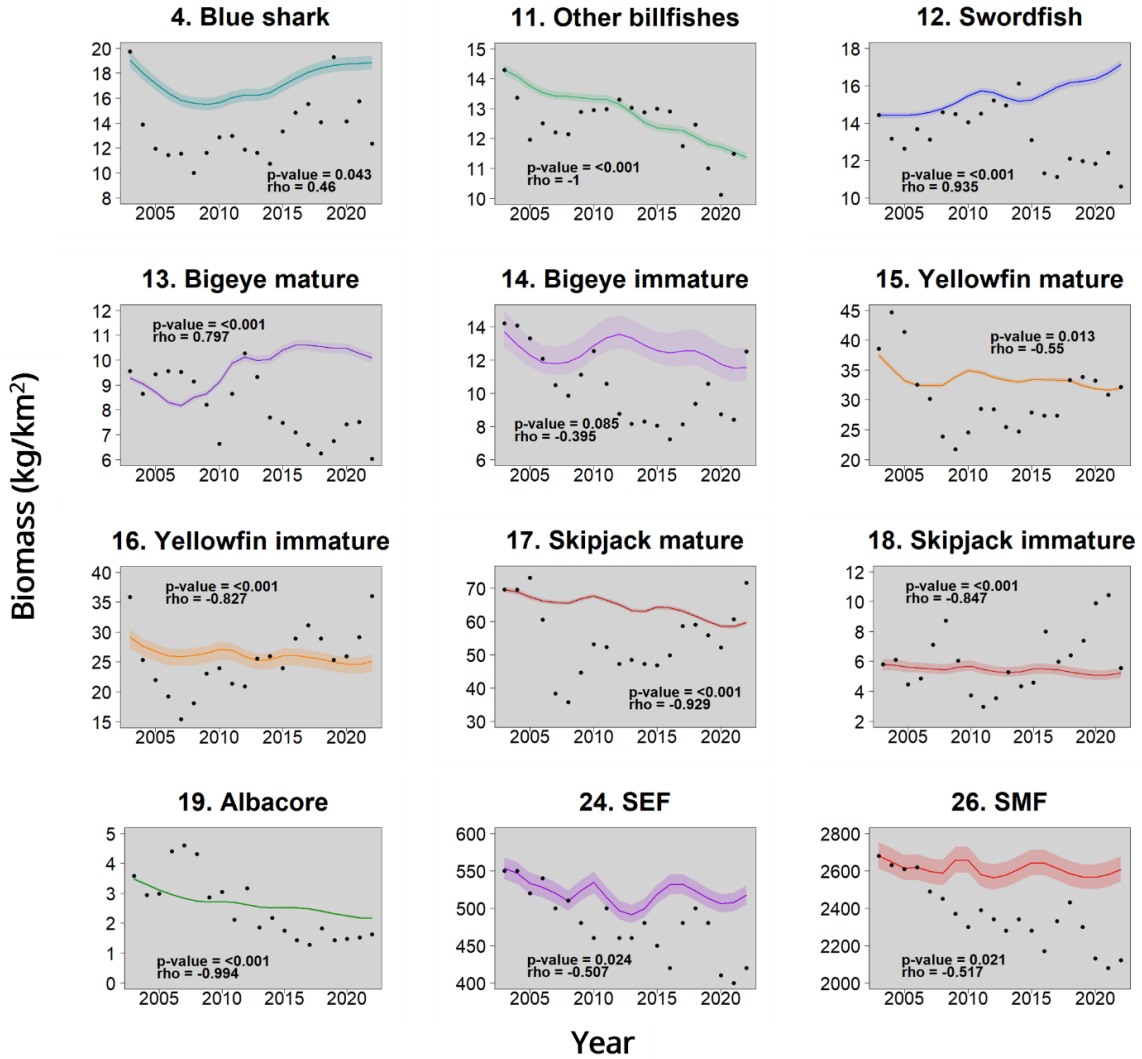


Figure 2. Predicted (solid line) versus observed (black dots) values of biomass (kg·km⁻²) of the functional groups with biomass time series for the period 2003 – 2022 in the TIO model. Coloured areas around the prediction line represent the 5% and 95% percentiles of uncertainty around model predictions obtained by the Monte Carlo routine. The p-value and rho are the results of the spearman correlation test. SEF: small epipelagic fishes. SMF: small mesopelagic fishes.

3.2. Future ecosystem trajectories

3.2.1. Climate change scenarios

Climate change produced a generalized decline in biomass across the tropical Indian Ocean pelagic ecosystem by the end of the 21st century, with stronger impacts under the high emission

scenario SSP3-7.0 (Scn. 3) than under the low emission scenario SSP1-2.6 (Scn. 2). Biomass reductions occurred across fishery-targeted species, vulnerable species, and lower trophic-level functional groups. Differences between the baseline scenario (Scn. 1) and the climate change scenarios became progressively larger after approximately 2070 (Figure 4; Table 4).

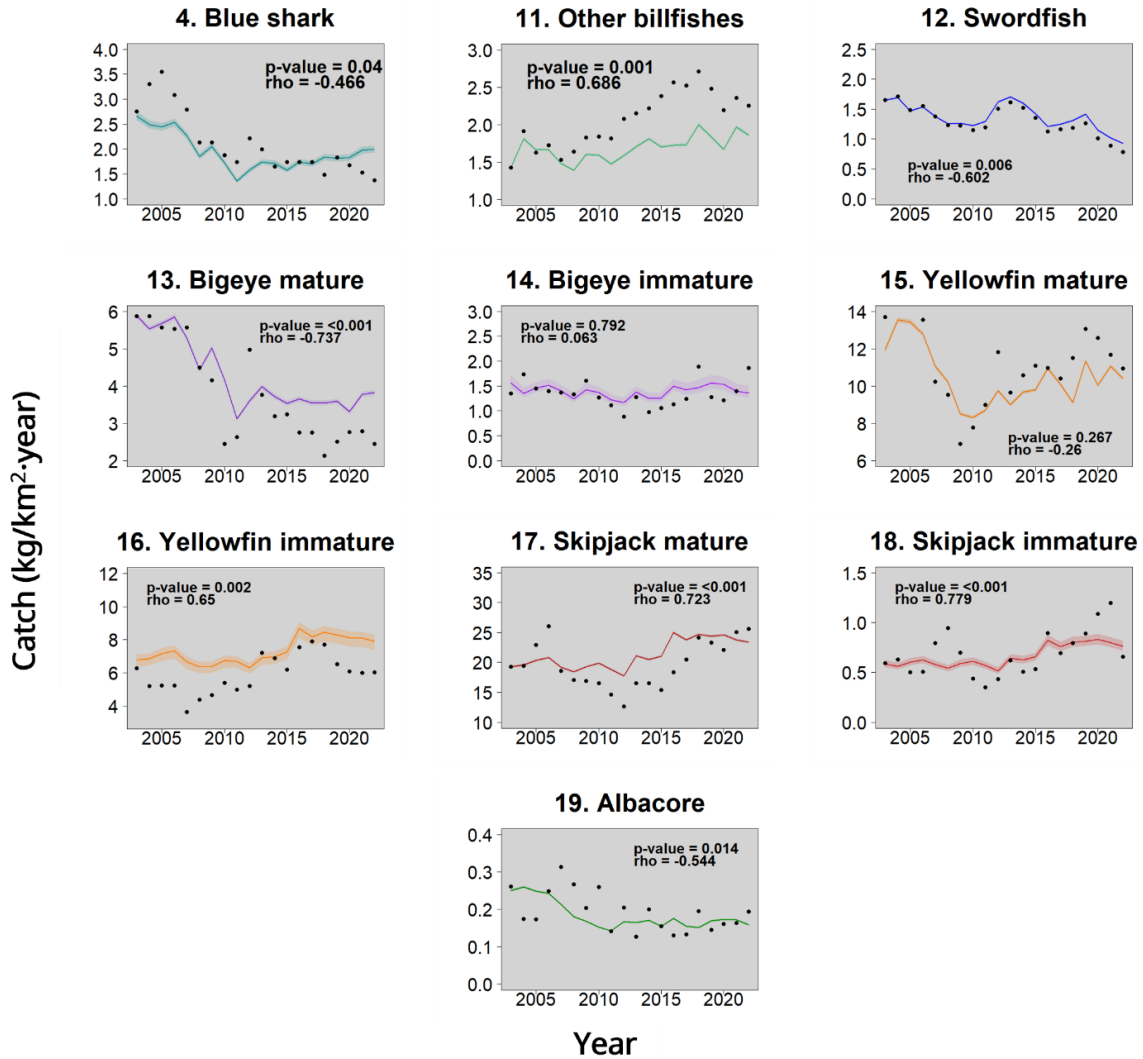


Figure 3. Predicted (solid line) versus observed (black dots) values of catch (kg·km⁻²·year⁻¹) of the functional groups with catch time series for the period 2003–2022 in the TIO model. Coloured areas around the prediction line represent the 5% and 95% percentiles of uncertainty around model predictions obtained by the Monte Carlo routine. The p-value and rho are the results of the spearman correlation test.

Among the principal fishery-target species, all tropical tunas exhibited declining biomass under both climate scenarios, although the magnitude of the response differed among species. Skipjack (FG 17,18) was the most climate-sensitive tropical tuna species. Mature biomass decreased by 10.9% under SSP1-2.6 and by 40.6% under SSP3-7.0 with respect to the baseline scenario, while immature biomass was reduced by 10.6% and 43.6%, respectively (Figure 4e,f; Table 4). Reductions of 9.4% and 29.8% under SSP1-2.6 and SSP3-7.0, respectively, were observed for mature yellowfin tuna, while immature biomass decreased by 10.2% and 34.3% when compared with the baseline scenario (Figure 4c,d; Table 4). A less pronounced negative response was

predicted by bigeye tuna, with mature biomass declining by 8.0% and 15.3% and immature biomass by 8.4% and 19.7% under SSP1-2.6 and SSP3-7.0, respectively (Figure 4a,b; Table 4). Among the remaining target species, albacore exhibited the strongest biomass decline under climate change. Its biomass was reduced by 40.4% under SSP1-2.6 and by 80.4% under SSP3-7.0 relative to the baseline scenario (Figure 2j; Table 4). Swordfish also responded negatively, with biomass reductions of 8.0% and 17.1% under SSP1-2.6 and SSP3-7.0, respectively (Figure 4i; Table 4).

Climate change also showed negative impacts on most vulnerable species included in the model. A biomass decline of 6.6% under SSP1-2.6 and 8.6% under SSP3-7.0 was shown by silky shark (Figure 4h; Table 4), while mobulas also experienced reductions of 7.0% and 11.3%, respectively. A similar pattern was followed by sea turtles, decreasing by 6.0% and 9.3% across the two scenarios. Whale shark biomass was projected to increase by more than 73.4% from 2023 to 2100 under the baseline scenario. Nevertheless, climate change reduced these gains, with biomass under SSP1-2.6 and SSP3-7.0 remaining 4.5% and 6.4% lower, respectively, than in the baseline scenario by 2100. A consistent reduction of around 6.7% regardless of the climate change scenario considered was shown by other sharks. An important decrease under both climate change scenarios was also shown by seabirds (FG. 1), with their biomass being reduced by 16% and 24% under SSP1-2.6 and SSP3-7.0, respectively. Likewise, toothed whales' biomass decreased by 9.8% and 13.8%, while baleen whales' biomass decreased by 8.6% and 12.4% (Table 4).

Climate change also altered the abundance of important forage species and lower trophic-level functional groups. Small epipelagic fishes' biomass was reduced by 12.6% under SSP1-2.6 and by 27.9% under SSP3-7.0 when compared with the baseline scenario, while small mesopelagic fishes' biomass was reduced by 3.6% and 9.5%, respectively (Table 4). By contrast, the biomass of epipelagic fishes - II (FG. 23) increased by 1.2% under the SSP1-2.6 scenario and by 13.5% under the SSP3-7.0 scenario (Table 4). Additionally, climate change effects were observed on other low-trophic-level functional groups. Under scenario SSP3-7.0, phytoplankton (FG. 33), microzooplankton (FG. 32), mesozooplankton (FG. 31), and microzooplankton (FG. 30) decreased by 4.9%, 6.9%, 3.5%, and 6.9%, respectively, when compared with the baseline scenario (Table 4).

Projected catches closely mirrored the biomass responses observed under the climate scenarios. Yellowfin tuna catches declined by 9.4% and 29.8% for mature individuals and by 10.1% and 34.3% for immature individuals under SSP1-2.6 and SSP3-7.0, respectively (Figure 5c,d; Table 5). More moderate reductions were shown by bigeye tuna, ranging from 7.9% to 15.2% in mature individuals and from 8.6% to 19.9% in immature individuals across the two climate scenarios (Figure 5a,b; Table 5). Skipjack tuna, again, emerged as the most climate-sensitive tropical tuna species, with catch reductions of 10.9% and 40.6% in mature individuals and 11.3% and 43.8% in immature individuals under SSP1-2.6 and SSP3-7.0, respectively (Figure 5e,f; Table 5).

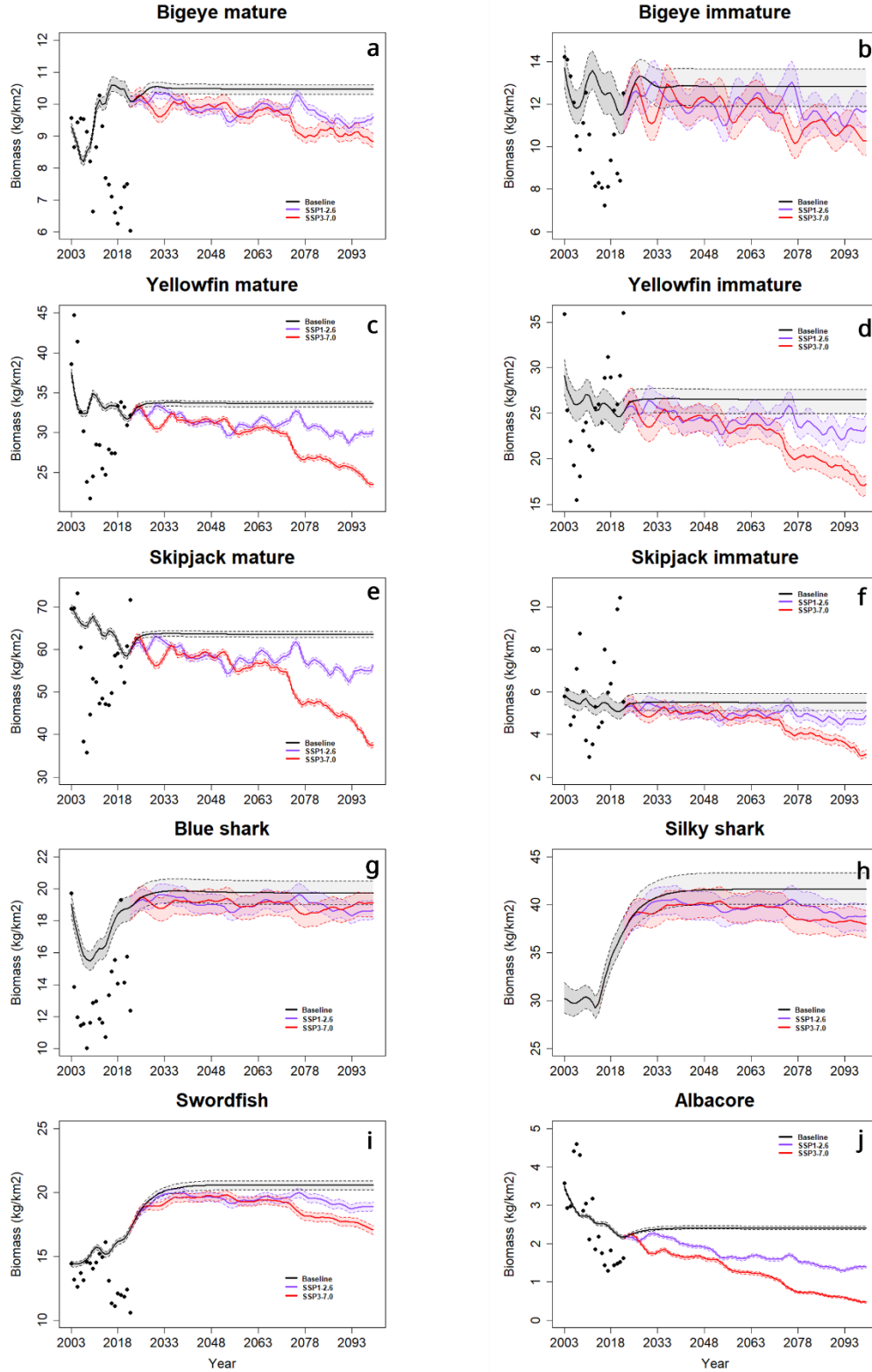


Figure 4. Comparison between predicted (solid lines) and observed (dots) time series of biomass ($\text{kg}\cdot\text{km}^{-2}$), and projections for (a) bigeye mature, (b) bigeye immature, (c) yellowfin mature, (d) yellowfin immature, (e) skipjack mature (f) skipjack immature, (g) blue shark, (h) silky shark, (i) swordfish, and (j) albacore under the two different future scenarios of climate change for the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Black line represents baseline model predictions, and coloured lines represent different scenarios (purple line – SSP1-2.6; red line – SSP3-7.0). Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine.

Table 4. Values of the biomass (kg·km⁻²) at the last year of the hindcasted period (2022) and at the last year of the forecasted period (2100) under each different scenario simulated. Percentages are the change in each scenario compared with baseline. TAC+2.6; TAC+SSP1-2.6; TAC+7.0; TAC+SSP3-7.0.

Functional group	2022	Baseline	SSP1-2.6	%	SSP3-7.0	%	BB.PP.	%	TAC	%	TAC+2.6	%	TAC+7.0	%
1 Seabirds	0.48	0.50	0.42	-16.00	0.38	-24.00	0.49	-2.00	0.50	0.00	0.42	-16.00	0.38	-24.00
2 Baleen whales	17.36	22.16	20.25	-8.62	19.41	-12.41	22.17	0.05	22.20	0.18	20.29	-8.44	19.45	-12.23
3 Toothed whales	43.75	44.86	40.47	-9.79	38.65	-13.84	45.55	1.54	45.40	1.20	40.95	-8.72	39.09	-12.86
4 Blue shark	18.85	19.73	18.65	-5.47	19.09	-3.24	20.07	1.72	19.13	-3.04	18.11	-8.21	18.50	-6.23
5 Silky shark	37.20	41.59	38.84	-6.61	38.01	-8.61	42.40	1.95	42.07	1.15	39.33	-5.43	38.48	-7.48
6 Other sharks	20.19	20.22	18.87	-6.68	18.92	-6.43	21.87	8.16	17.37	-14.09	16.27	-19.54	16.40	-18.89
7 Whale shark	31.32	54.32	51.87	-4.51	50.87	-6.35	56.67	4.33	55.89	2.89	53.40	-1.69	52.38	-3.57
8 Pelagic stingray	6.81	7.04	6.87	-2.41	6.86	-2.56	6.92	-1.70	7.16	1.70	7.00	-0.57	6.97	-0.99
9 Mobulas	1.83	1.86	1.73	-6.99	1.65	-11.29	2.03	9.14	1.98	6.45	1.84	-1.08	1.75	-5.91
10 Sea turtles	2.26	2.68	2.52	-5.97	2.43	-9.33	2.81	4.85	2.33	-13.06	2.17	-19.03	2.09	-22.01
11 Other billfishes	11.37	11.37	10.56	-7.12	10.28	-9.59	11.32	-0.44	11.41	0.35	10.60	-6.77	10.31	-9.32
12 Swordfish	17.13	20.57	18.93	-7.97	17.05	-17.11	20.46	-0.53	20.01	-2.72	18.40	-10.55	16.51	-19.74
13 Bigeye mature	10.10	10.42	9.59	-7.97	8.83	-15.26	10.35	-0.67	8.99	-13.72	8.29	-20.44	7.63	-26.78
14 Bigeye immature	11.57	12.77	11.70	-8.38	10.26	-19.66	12.67	-0.78	12.57	-1.57	11.34	-11.20	9.87	-22.71
15 Yellowfin mature	31.91	33.39	30.26	-9.37	23.43	-29.83	33.25	-0.42	32.43	-2.88	29.39	-11.98	22.84	-31.60
16 Yellowfin immature	25.09	26.20	23.54	-10.15	17.22	-34.27	26.06	-0.53	25.21	-3.78	22.63	-13.63	16.66	-36.41
17 Skipjack mature	59.67	63.11	56.23	-10.90	37.52	-40.55	62.61	-0.79	55.79	-11.60	49.44	-21.66	33.04	-47.65
18 Skipjack immature	5.21	5.46	4.88	-10.62	3.08	-43.59	5.43	-0.55	5.04	-7.69	4.48	-17.95	2.79	-48.90
19 Albacore	2.17	2.35	1.40	-40.43	0.46	-80.43	2.28	-2.98	2.36	0.43	1.40	-40.43	0.46	-80.43
20 Small tunas and bonitos	147.09	148.63	143.44	-3.49	146.97	-1.12	148.31	-0.22	146.31	-1.56	141.25	-4.97	144.14	-3.02
21 Jacks, mackerels, runners, trevallies and scads	195.71	197.08	191.76	-2.70	198.06	0.50	197.09	0.01	201.17	2.08	196.00	-0.55	201.99	2.49
22 Epipelagic fishes – I	147.44	149.81	142.11	-5.14	141.41	-5.61	149.52	-0.19	152.16	1.57	144.68	-3.42	143.94	-3.92
23 Epipelagic fishes – II	244.22	242.34	245.18	1.17	275.13	13.53	242.71	0.15	250.20	3.24	253.30	4.52	282.37	16.52
24 Small epipelagic fishes	517.35	544.04	475.31	-12.63	392.31	-27.89	541.08	-0.54	536.79	-1.33	468.49	-13.89	387.12	-28.84
25 Large mesopelagic fishes	214.08	218.16	208.06	-4.63	220.08	0.88	217.96	-0.09	222.17	1.84	212.26	-2.70	224.00	2.68
26 Small mesopelagic fishes	2607.57	2642.35	2547.69	-3.58	2390.46	-9.53	2643.45	0.04	2625.48	-0.64	2531.67	-4.19	2381.04	-9.89
27 Pelagic cephalopods	467.01	469.10	463.31	-1.23	455.43	-2.91	468.23	-0.19	475.08	1.27	468.92	-0.04	458.55	-2.25
28 Pelagic crustaceans	822.73	821.49	817.62	-0.47	789.78	-3.86	822.06	0.07	820.06	-0.17	816.03	-0.66	788.90	-3.97
29 Gelatinous plankton	537.80	539.95	528.06	-2.20	503.24	-6.80	539.93	0.00	540.39	0.08	528.50	-2.12	503.52	-6.75
30 Macrozooplankton	2674.97	2675.51	2622.68	-1.97	2479.55	-7.32	2676.80	0.05	2679.28	0.14	2626.17	-1.84	2481.83	-7.24
31 Mesozooplankton	4740.23	4747.54	4696.49	-1.08	4579.99	-3.53	4747.14	-0.01	4746.55	-0.02	4695.64	-1.09	4579.51	-3.54
32 Microzooplankton	6976.71	7005.44	6849.94	-2.22	6523.05	-6.89	7005.45	0.00	7006.17	0.01	6850.65	-2.21	6523.48	-6.88
33 Phytoplankton	11651.07	11659.68	11501.42	-1.36	11093.99	-4.85	11659.68	0.00	11659.30	0.00	11501.03	-1.36	11093.72	-4.85
34 Discards	8.08	8.81	8.29	-5.90	8.19	-7.04	7.90	-10.33	9.29	5.45	8.74	-0.79	8.61	-2.27
35 Detritus	238300.50	238926.50	235213.20	-1.55	227174.90	-4.92	238927.10	0.00	238926.10	0.00	235212.70	-1.55	227174.50	-4.92

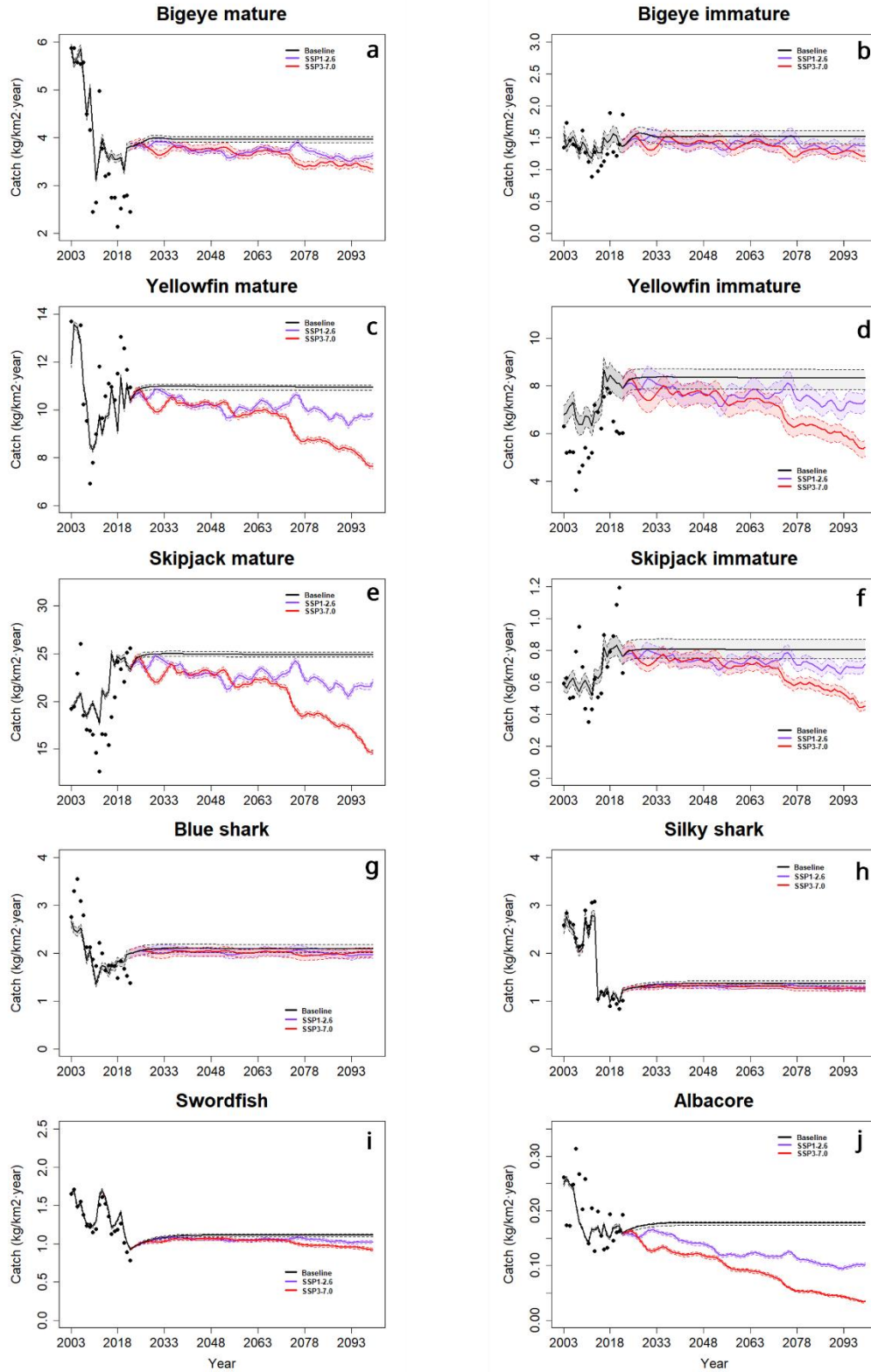


Figure 5. Comparison between predicted (solid lines) and observed (dots) time series of catch ($\text{kg}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$), and projections for (a) bigeye mature, (b) bigeye immature, (c) yellowfin mature, (d) yellowfin immature, (e) skipjack mature, (f) skipjack immature, (g) blue shark, (h) silky shark, (i) swordfish, and (j) albacore under the two different future scenarios of climate change for the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Black line represents baseline model predictions, and coloured lines represent different scenarios (purple line – SSP1-2.6; red line – SSP3-7.0). Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine.

Table 5. Values of the catch ($\text{kg}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$) at the last year of the hindcasted period (2022) and at the last year of the forecasted period (2100) under each different scenario simulated. Percentages are the change in each scenario compared with baseline. TAC+2.6: TAC+SSP1-2.6; TAC+7.0: TAC+SSP3-7.0

Functional group	2022	Baseline	SSP1-2.6	%	SSP3-7.0	%	BB.PP.	%	TAC	%	TAC+2.6	%	TAC+7.0	%
1 Seabirds	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Baleen whales	0.01	0.01	0.01	0	0.01	0	0.01	0	0.01	0	0.01	0	0.01	0
3 Toothed whales	0.28	0.28	0.26	-7.14	0.24	-14.29	0.29	3.57	0.26	-7.14	0.23	-17.86	0.22	-21.43
4 Blue shark	2.00	2.09	1.97	-5.74	2.02	-3.35	2.13	1.91	2.52	20.57	2.39	14.35	2.44	16.75
5 Silky shark	1.22	1.37	1.28	-6.57	1.25	-8.76	1.40	2.19	1.39	1.46	1.30	-5.11	1.27	-7.30
6 Other sharks	5.32	5.33	4.97	-6.75	4.99	-6.38	5.77	8.26	5.42	1.69	5.08	-4.69	5.12	-3.94
7 Whale shark	1.33	2.31	2.21	-4.33	2.17	-6.06	2.41	4.33	2.12	-8.23	2.03	-12.12	1.99	-13.85
8 Pelagic stingray	0.03	0.03	0.03	0.00	0.03	0.00	0.03	0.00	0.04	33.33	0.04	33.33	0.04	33.33
9 Mobulas	0.21	0.21	0.19	-9.52	0.18	-14.29	0.23	9.52	0.20	-4.76	0.18	-14.29	0.18	-14.29
10 Sea turtles	0.16	0.19	0.18	-5.26	0.17	-10.53	0.20	5.26	0.20	5.26	0.19	0.00	0.18	-5.26
11 Other billfishes	1.86	1.86	1.72	-7.53	1.68	-9.68	1.85	-0.54	1.82	-2.15	1.69	-9.14	1.65	-11.29
12 Swordfish	0.93	1.11	1.02	-8.11	0.92	-17.12	1.11	0.00	1.24	11.71	1.14	2.70	1.02	-8.11
13 Bigeye mature	3.82	3.94	3.63	-7.87	3.34	-15.23	3.92	-0.51	4.90	24.37	4.51	14.47	4.15	5.33
14 Bigeye immature	1.36	1.51	1.38	-8.61	1.21	-19.87	1.49	-1.32	2.08	37.75	1.88	24.50	1.63	7.95
15 Yellowfin mature	10.40	10.88	9.86	-9.38	7.64	-29.78	10.83	-0.46	11.00	1.10	9.97	-8.36	7.75	-28.77
16 Yellowfin immature	7.90	8.25	7.42	-10.06	5.42	-34.30	8.21	-0.48	9.38	13.70	8.42	2.06	6.19	-24.97
17 Skipjack mature	23.39	24.73	22.04	-10.88	14.70	-40.56	24.54	-0.77	30.07	21.59	26.64	7.72	17.80	-28.02
18 Skipjack immature	0.76	0.80	0.71	-11.25	0.45	-43.75	0.79	-1.25	1.00	25.00	0.89	11.25	0.56	-30.00
19 Albacore	0.16	0.17	0.10	-41.18	0.03	-82.35	0.17	0.00	0.19	11.76	0.11	-35.29	0.04	-76.47
20 Small tunas and bonitos	22.82	23.06	22.26	-3.47	22.80	-1.13	23.01	-0.22	25.89	12.27	25.00	8.41	25.51	10.62
21 Jacks, mackerels, runners, trevallies and scads	0.48	0.49	0.47	-4.08	0.49	0.00	0.49	0.00	0.49	0.00	0.48	-2.04	0.49	0.00
22 Epipelagic fishes – I	0.44	0.45	0.42	-6.67	0.42	-6.67	0.45	0.00	0.45	0.00	0.43	-4.44	0.42	-6.67
23 Epipelagic fishes – II	0.06	0.06	0.06	0	0.07	16.67	0.06	0.00	0.08	33.33	0.08	33.33	0.09	50.00
24 Small epipelagic fishes	0.00	0.00	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
25 Large mesopelagic fishes	0.00	0.00	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
26 Small mesopelagic fishes	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27 Pelagic cephalopods	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28 Pelagic crustaceans	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29 Gelatinous plankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30 Macrozooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31 Mesozooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32 Microzooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33 Phytoplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34 Discards	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35 Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3.2.2. Fisheries management scenarios.

– *Target species management (TAC)*

The TAC scenario (Scn. 4) resulted in a trade-off between biomass conservation and fishery production, with reduced biomass but increased catches of the principal target species. The biomass of mature bigeye, yellowfin, and skipjack tuna decreased by 13.7%, 2.9%, and 11.6%, respectively, compared with the baseline scenario (Figure 6; Table 4). In contrast, catches of all targeted tuna species increased under the TAC scenario. Mature skipjack catches rose by 21.6%, while bigeye catches increased by 24.4% and 37.7% for mature and immature individuals, respectively. Yellowfin catches followed a similar trend, growing by 1.1% and 13.7% for mature and immature individuals (Figure 7; Table 5). Catches of targeted species increased because of the increase in fishing effort of multiple fleets to achieve the catch rate that equals the assigned TAC (SM - Table 5).

The TAC scenario also produced contrasting responses among vulnerable species. While silky shark, mobulas, and whale shark increased their biomass by, 1.2%, 6.5%, and 2.9%, respectively, other sharks and sea turtles decreased their biomass by 14.1% and 13.1%, respectively (Figure 6h; Table 4). Overall, these results indicate that the increase in catches permitted under the TAC scenario is accompanied by moderate reductions in the future biomass of several exploited and vulnerable species.

– *Vulnerable species management (BB.PP.)*

Improving the post-release survival of discarded vulnerable species under the BB.PP. scenario (Scn. 5) increased the biomass of all vulnerable functional groups (Figure 8; Table 4). The largest increase was observed in mobulas (9.1%), followed by other sharks (8.2%), sea turtles (4.9%), whale shark (4.3%), and silky shark (1.9%) (Figure 8a-d; Table 4). Predicted catches of these vulnerable groups also increased. Mobula catches increased by 9.5%, sea turtles by 5.3%, whale shark by 4.3%, and other sharks by 8.3%. Catch in Ecosim are the sum of landings and discards, returned dead or alive. Therefore, as their biomass increased, their catch would increase, however, their fishing mortality would decrease (Figure 9a-d; Table 5).

The positive effects of the BB.PP. scenario were largely restricted to the functional groups directly benefiting from the reduction in discard mortality. In contrast, the effects of this measure on the rest of the functional groups were minimal, with only minor differences observed relative to the baseline scenario (Table 4).

3.2.3 Combined climate and fisheries scenarios

The combined scenarios of TAC and climate change highlighted that climate change was the main driver of future ecosystem dynamics. TAC+SSP1-2.6 (Scn. 6) presented intermediate values between the TAC scenario (Scn.5) and the TAC+SSP3-7.0 scenario (Scn. 7) (Figure 6; Table 4).

The TAC+SSP3-7.0 scenario produced the lowest biomass values among all the scenarios simulated for multiple exploited species (Table 4). For example, biomass decreased by 26.8% and 22.7% for mature and immature bigeye, by 31.6% and 36.4% for mature and immature yellowfin, and by 47.7% and 48.9% for mature and immature skipjack, compared with the baseline scenario (Figure 6a-f; Table 4). Albacore showed the greatest biomass reduction, decreasing by 80.4% (Figure 6j; Table 4). Among vulnerable species, the TAC+SSP-7.0 resulted in biomass declines of 7.5% for silky shark, 18.9% for other sharks, 5.9% for mobulas, 22.0% for sea turtles, 3.6% for whale shark, and 24.0% for seabirds (Figure 6h; Table 4). In general, biomass reductions under the combined scenarios were slightly lower than the sum of the individual climate change and TAC effects, suggesting a weak antagonistic interaction between both drivers. However, the negative effects observed on the lower trophic levels under the climate change scenarios were not mitigated by TAC management scenario, and the magnitude of the biomass decrease remained similar.

Catches followed similar trends to those observed for biomass under the combined scenarios although absolute catches remained higher than the baseline for some target species because of the increased fishing effort under the TAC scenarios. Under the TAC+SSP1-2.6 scenario, bigeye mature and immature catches increased by 14.5% and 24.5%, respectively, compared with the baseline scenario (Figure 7a,b; Table 5). In contrast, yellowfin mature catches decreased by 8.4%, while yellowfin immature catches increased by 2.1%, compared with the baseline scenario (Figure 7c,d; Table 5). Under the TAC+SSP3-7.0 scenario, important reductions were observed in most targeted species. While bigeye catches still increased by 5.3% and 7.9% for mature and immature individuals, respectively, yellowfin and skipjack mature and immature catches decreased by 28.8%, 25%, 28%, and 30%, respectively (Figure 7a-f; Table 5). Albacore catches showed the most severe decline of all species, decreasing by 35.3% under TAC+SSP1-2.6 and by 76.5% under TAC+SSP3-7.0 compared with the baseline scenario (Figure 7j; Table 5), consistent with the pronounced biomass losses observed for this species. Swordfish catches increased slightly by 2.7% under TAC+SSP1-2.6 but decreased by 8.1% under TAC+SSP3-7.0, compared with the baseline scenario (Figure 7i; Table 5). Although the initial increase in catches was driven by higher fishing effort under the TAC scenarios, the overall catch trend seems to be shaped by the underlying decline in biomass linked to climate change, especially under the most severe sea water warming scenario (TAC+SSP3-7.0). Important catch reductions were also observed for vulnerable species. Under the TAC+SSP3-7.0 scenario, catches of silky shark, other sharks, mobulas, sea turtles, and whale shark were reduced by 7.3%, 3.9%, 14.3%, 5.3%, and 13.9%, respectively, compared with the baseline scenario.

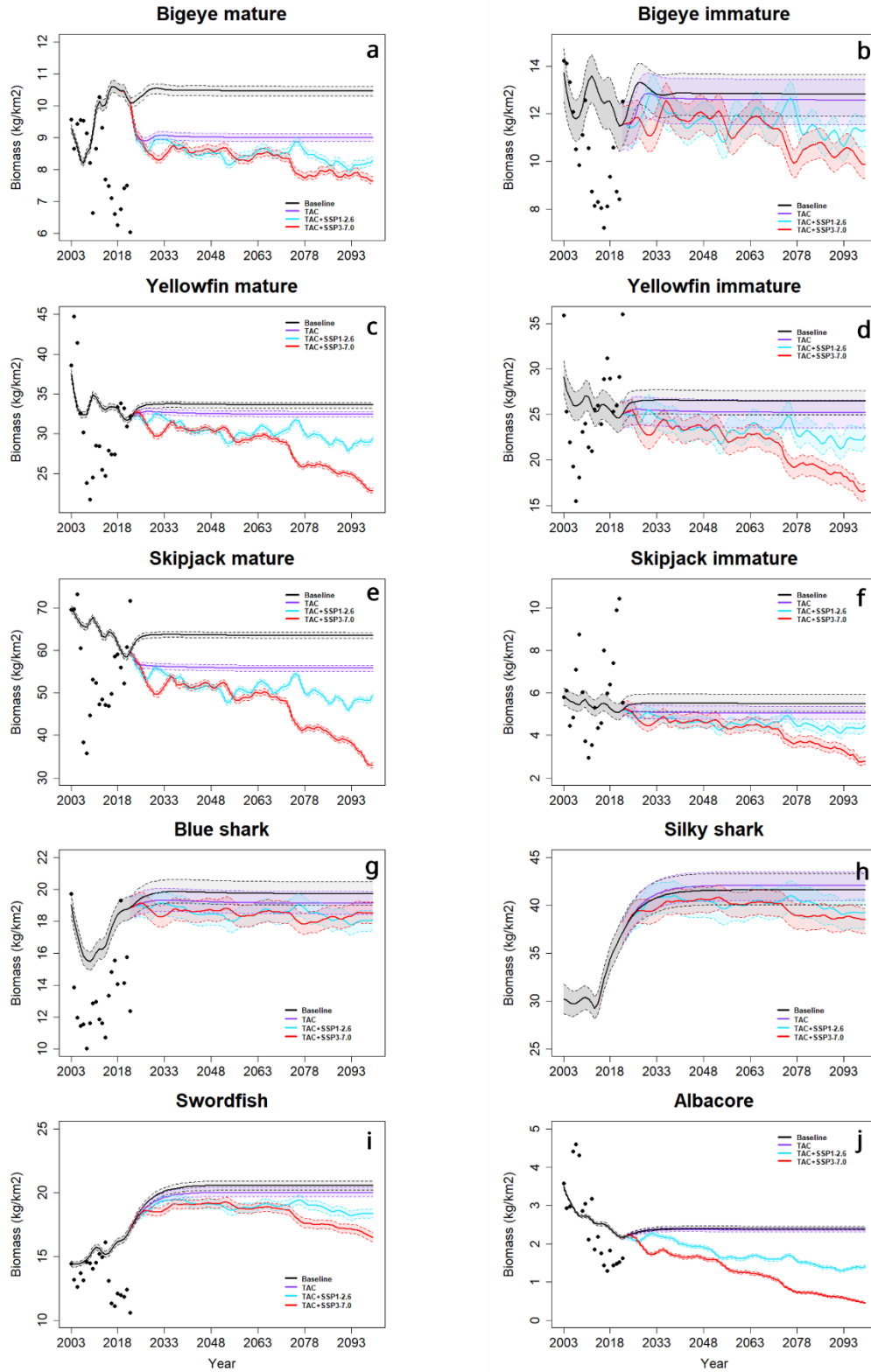


Figure 6. Comparison between predicted (solid lines) and observed (dots) time series of biomass ($\text{kg}\cdot\text{km}^{-2}$), and projections for (a) bigeye mature, (b) bigeye immature, (c) yellowfin mature, (d) yellowfin immature, (e) skipjack mature (f) skipjack immature, (g) blue shark, (h) silky shark, (i) swordfish, and (j) albacore under the baseline (black line), the TAC (purple line), and the two scenarios of TAC combined with climate change projections for the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Black line represents baseline model predictions, and coloured lines represent different scenarios. Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine. TAC+2.6: TAC+SSP1-2.6 (blue line); TAC+7.0: TAC+SSP3-7.0 (red line).

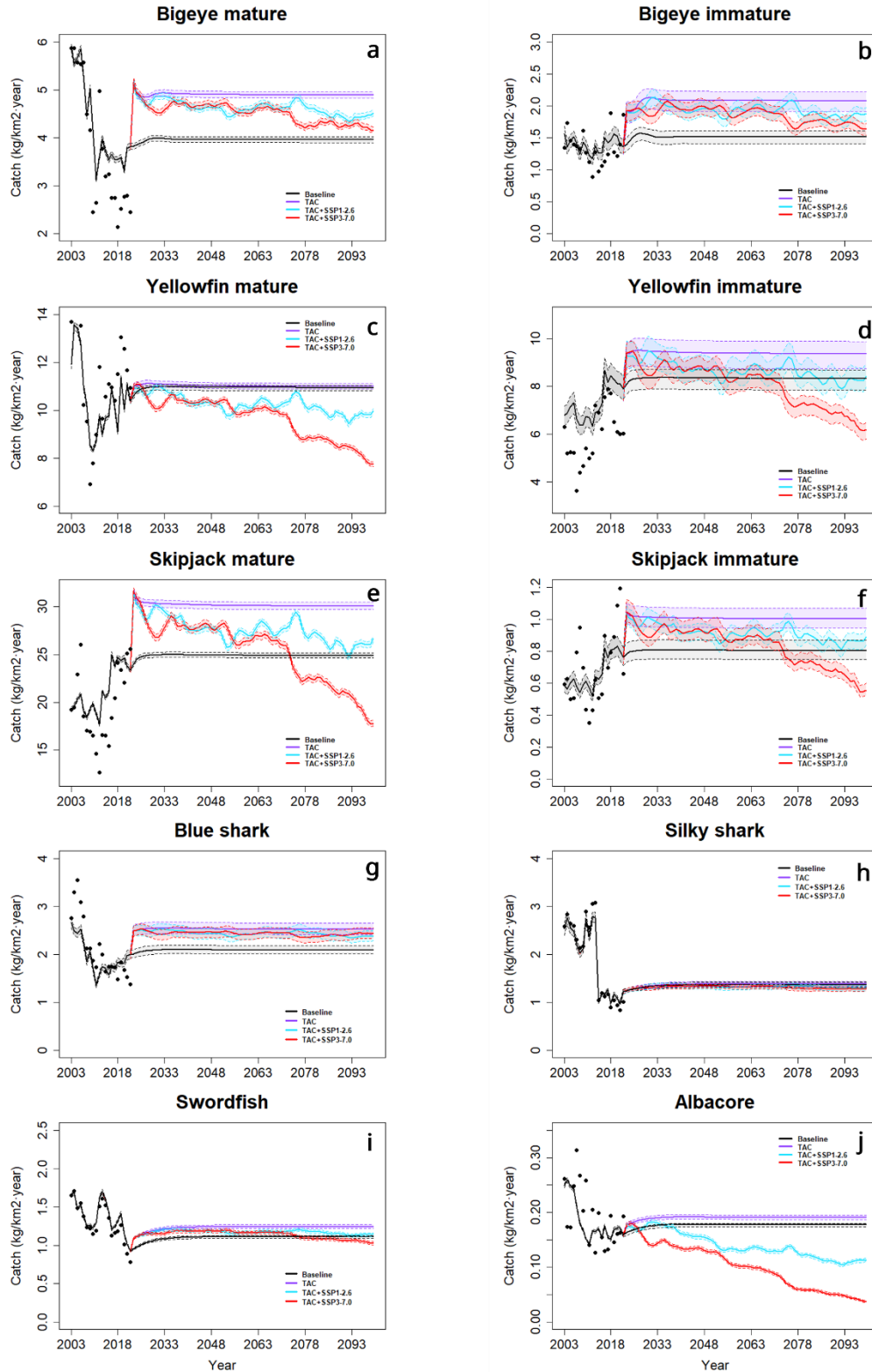


Figure 7. Comparison between predicted (solid lines) and observed (dots) time series of catch ($\text{kg}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$), and projections for (a) bigeye mature, (b) bigeye immature, (c) yellowfin mature, (d) yellowfin immature, (e) skipjack mature (f) skipjack immature, (g) blue shark, (h) silky shark, (i) swordfish, and (j) albacore under the baseline (black line), the TAC (purple line), and the two scenarios of TAC combined with climate change projections for the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Black line represents baseline model predictions, and coloured lines represent different scenarios. Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine. TAC+2.6: TAC+SSP1-2.6 (blue line); TAC+7.0: TAC+SSP3-7.0 (red line).

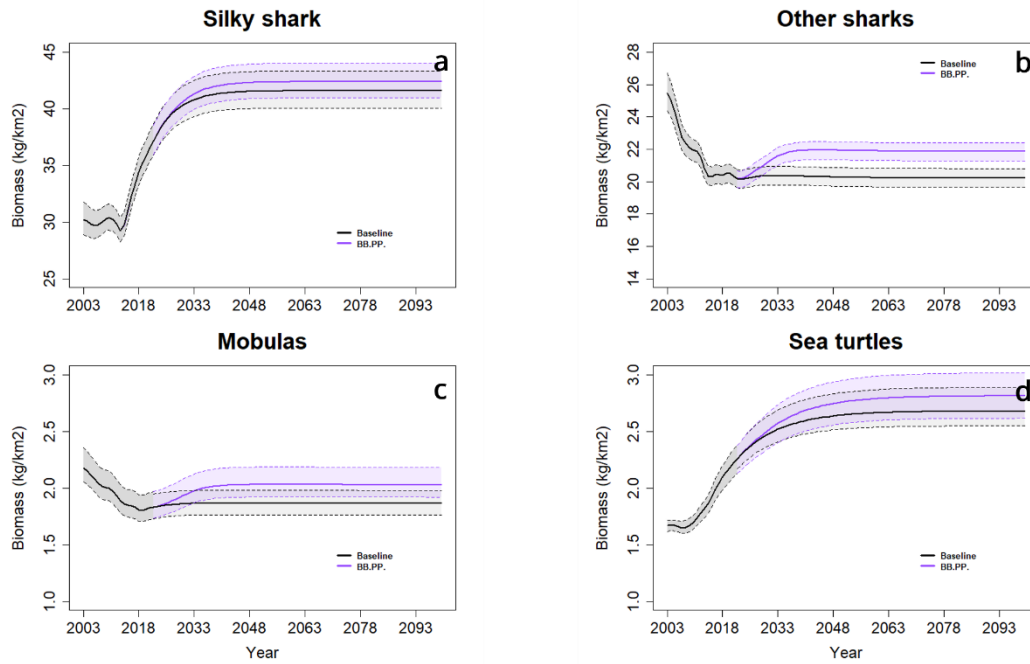


Figure 8. Predicted biomass ($\text{kg}\cdot\text{km}^{-2}$) trajectories under the baseline (black line) and the BB.PP. (purple line) scenarios for (a) silky shark, (b) other sharks, (c) mobulas, and (d) sea turtles in the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine.

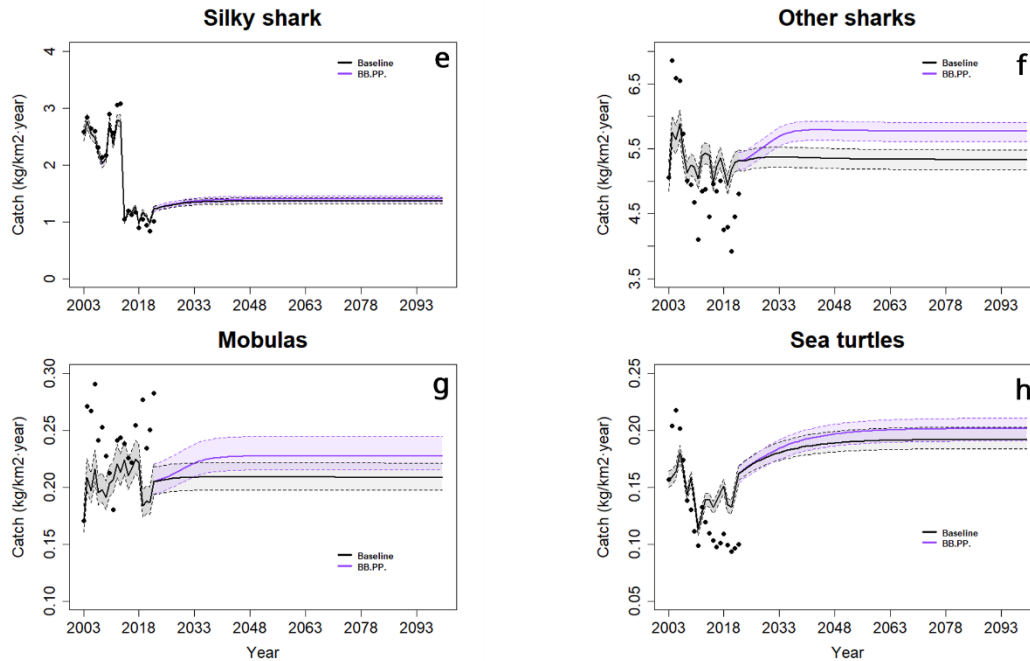


Figure 9. Predicted catch ($\text{kg}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$) trajectories under the baseline (black line) and the BB.PP. (purple line) scenarios for (a) silky shark, (b) other sharks, (c) mobulas, and (d) sea turtles in the oceanic pelagic tropical Indian Ocean ecosystem model for the period 2003–2100. Shadows represent the 5% and 95% percentiles of uncertainty around model predictions obtained using the Monte Carlo routine.

4. Discussion

Our results indicate that climate change is projected to be the dominant driver shaping the future of the oceanic pelagic ecosystem of the tropical Indian Ocean. Fisheries management remains effective for reducing the direct impacts of fishing, but its capacity to offset climate-driven ecosystem change remains limited. This underscores the pressing need for nations to adhere to the Paris Agreement, cutting greenhouse gas emissions to keep global warming below 1.5°C or 2°C and achieve carbon neutrality by mid-century. Under current fisheries management and fishing pressure, the ecosystem is projected to remain close to its present state, suggesting that the current management measures adopted by the IOTC are effective at stabilizing exploited populations and support the recovery of some target vulnerable species, consistent with recent observations of increasing biomass in several tropical tuna stocks after 2022, beyond the time frame covered by our time series. However, it should be noted that our projections are based on a baseline that may already reflect the effects of historical climate change on stock productivity, given that warming trends have been underway for decades. As such, the impacts reported here likely represent a conservative estimate of the full extent to which climate change has influenced, and will continue to influence, stock abundance. Our simulations further indicate that fisheries management actions aiming at improving post-release survival of vulnerable species can improve the state of the functional groups to which the measure are directly applied. However, when climate change is introduced, alone or in combination with fisheries management measures, future biomass trajectories across the food web are reshaped by sea water warming and declining productivity irrespective of the fisheries management measure tested. Overall, our results indicate that fisheries management is necessary and effective for controlling and regulating fisheries impacts on the ecosystem, whereas climate change, a process equally driven by human activity, increasingly governs ecosystem-wide dynamics and constrains the long-term effectiveness of current management measures. Upholding commitments such as those made under the Paris Agreement would therefore be key to mitigating these impacts, supporting more efficient fisheries management and potentially more productive stocks in the future.

Ecosystem-wide biomass declines projected under climate change scenarios are primarily driven by the reduction in primary production and ocean warming, with impacts becoming progressively stronger as the magnitude of climate change intensifies. The reduction in primary production propagates through the food web as a bottom-up signal, quickly affecting low-trophic-level species and forage species supporting upper trophic levels. Our results suggest that this bottom-up signal does not propagate uniformly across the food web. Instead, it appears to stabilize at intermediate trophic positions rather than continuing to amplify towards top predators. This dampening suggests that mid-trophic-level groups may be exerting a buffering effect on the

propagation of the bottom-up signal, consistent with a wasp-waist control dynamic, in which a relatively narrow set of mid-trophic species regulates energy flow between lower and upper trophic levels and thereby moderates the transmission of perturbations to the top of the food web, a control type previously observed in large oceanic ecosystems (Griffiths et al., 2013; Riccialdelli et al., 2020).

Superimposed on these food-web processes, species-specific responses to climate change appear to be determined by differences in thermal tolerance, habitat use, and vertical behavior. Species with lower thermal tolerance or less diving capacity are more impacted to ocean warming than species with higher thermal tolerance or a higher capacity to dive into deeper colder waters, which provides thermal refugia as surface waters warm (Pinsky et al., 2013). This vertical habitat buffering could explain why species with very similar thermal limits can show very different vulnerabilities to ocean warming. Bigeye tuna, for example, is projected to be less affected than yellowfin and skipjack tuna despite sharing similar thermal range, because its greater diving capacity provides access to deeper thermal refugia unavailable for the other two species (Dueri, 2017; Erauskin-Extramiana et al., 2019). Yellowfin and skipjack tuna have similar diving capacity, both performing bounce-diving behavior to depths between 50 and 300m (Dueri, 2017). However, under climate change scenarios a stronger decline in skipjack abundance compared to yellowfin is projected probably due to the fact that it feeds on a lower variety of prey and with more intensity on species of lower trophic level, whose abundance will be reduced by the decrease in primary production (Olson et al., 2016; Sardenne et al., 2016). A comparable mechanism appears to operate among temperate predatory species. Albacore is projected to experience the largest biomass decline due to its lower tolerance to warmer water and a greater impact from the decline in its prey availability (Erauskin-Extramiana et al., 2023), whereas swordfish is expected to show a smaller decrease in abundance due to its higher thermal tolerance to warm waters and potentially greater prey availability resulting from the reduced competition with large tunas, which exploit similar prey resources (Potier et al., 2007; Young et al., 2010). Overall, these results suggest that climate impacts in the tropical Indian Ocean pelagic ecosystem are not transmitted linearly through the food web. Instead, climate-driven reductions in productivity appear to interact with mid-trophic-level energy pathways and species-specific habitat use, producing contrasting responses among tuna, billfish and other pelagic predators.

Two fisheries management measures addressing different pathways through which fishing affects the ecosystem were evaluated. Together they show how ecosystem-based fisheries management can be used to evaluate how management actions affect target species, vulnerable species, and broader food-web components simultaneously (Fulton et al., 2014; Griffiths et al., 2018). The TAC scenario shows that if all CPCs increased their fishing effort to reach their allocated

yellowfin TAC, catches would generally increase while biomass would decline for the main species caught by the fisheries as a consequence of higher fishing mortality. At the same time, biomass would increase for species that compete with or that are preyed upon by these main species. This scenario acts on the direct exploitation of target species, and its scope is bound by the IOTC's current management framework, as on May of 2026, the IOTC became the first tuna RFMO to adopt individual catch quotas for all three tropical tuna species under its mandate (IOTC, 2026b). As a result, the fishing effort of each CPC is constrained not only by its yellowfin quota, but also by the quota of whichever of the three species is most limiting for its fleet, effectively acting as an implicit multispecies constraint.

The BB.PP. scenario, by contrast, targets an impact that catch limits do not reach, the post-release mortality of vulnerable species that interact with tropical tuna fisheries. All vulnerable functional groups benefited from this management action, especially mobulas and other sharks. For other sharks the beneficial effect of this measure could even mitigate the detrimental effect that climate change would have on them. Because vulnerable species are characterized by low productivity, slow growth and limited capacity to compensate for additional mortality (Pardo et al., 2016; Juan-Jordá et al., 2022), improving survival after release is particularly effective for promoting population recoveries (Grande et al., 2022; Stewart et al., 2024). The benefits of this measure were restricted to the functional groups directly affected, with neither significant positive nor negative effects emerging on other functional groups. This suggests that reducing post-release mortality can provide conservation benefits while avoiding the trade-offs in fishery productivity that are often associated with more restrictive management measures (Acevedo-Iglesias et al., 2025). Best handling and release practices have been increasingly promoted by the IOTC, but their implementation remains limited and has so far been voluntarily adopted only by the European purse seine fleets (Acevedo-Iglesias et al., 2025; Murua et al., 2025). Achieving these levels of benefit would require stronger commitments from all CPCs and a large, coordinated effort across all major fishing fleets operating in the Indian Ocean.

Because fisheries are inherently multispecies, an increase in fishing effort directed at one species also affects the catch and abundance of the other species interacting with that fishery, and this same interconnectedness shapes how fishing and climate change combine. Understanding these combined effects is central to the ecosystem-based fisheries management because marine ecosystems are increasingly exposed to interacting fishing and climate-related pressures, whose cumulative effects remain difficult to predict despite growing research attention (Crain et al., 2008; Halpern et al., 2015; Côté et al., 2016). Under the cumulative scenarios analyzed, climate change remained the main driver of future species abundance. Species generally followed similar trajectories to those under climate change alone, with only minor changes associated with the

TAC scenario. Although the implementation of a TAC partially buffered climate-related catch losses for some target species, its ability to offset the impacts of severe climate scenarios was very limited. This is consistent with previous studies indicating that climate change can offset the expected benefits of fisheries management measures (Free et al., 2020; Erauskin-Extramiana et al., 2023), and with other ecosystem modelling studies in which climate change altered biomass, productivity and trophic interactions without triggering a shift to an alternative ecosystem state (Fulton et al., 2014; Serpetti et al., 2017). The practical implication is that fisheries management, however well designed, cannot be expected to compensate for the ecosystem-wide consequences of climate change under the scenarios evaluated here. This highlights the pressing need for countries to reduce their greenhouse gas emissions in line with the objectives of the Paris Agreement, to minimize current and future climate impacts.

This study provides a dynamic ecosystem modelling framework to support climate-ready ecosystem-based fisheries management advice in the tropical Indian Ocean. By combining fishing-effort forcing, climate projections, and management scenario testing, the model offers a tool for evaluating future ecosystem trajectories. For the IOTC, this tool could complement single species stock assessment by evaluating how target, bycaught and vulnerable species respond to fishing, management measures and climate change, both individually and at ecosystem level. This information can contribute to advisory products such as Ecocards (Andonegi et al., 2019; Juan-Jordá et al., 2019) helping IOTC fisheries management progressively advance towards the implementation of the ecosystem-based fisheries management while supporting recent efforts to better understand and incorporate climate change impacts into the IOTC management framework (IOTC, 2025b).

Several caveats and limitations should be considered when using and interpreting these results. Biomass estimates emerge from the internal structure of the model (predator-prey interactions, vulnerabilities, other mortality, and response to environmental variables). Therefore, its fit depends entirely on how well the model trophic structure and parameters correctly represent the ecological processes determining the abundance of each functional group. This makes biomass considerably more sensitive to structural errors, uncertainty in the diet matrix, or processes not captured by the model, factors that could explain the poorer fit observed for several functional groups. The strong projected increase in whale shark biomass under all scenarios is likely unrealistic, as the model is not able to adequately simulate this species due to the scarcity of reliable biological and fishery information. Similarly, while the model estimates plausible FMSY values for mono-specific functional groups, it fails to do so for multi-stanza groups, which limits its capacity to generate realistic biomass predictions for these groups when they are sustainably exploited (Walters et al., 2005). Regarding the impact of ocean temperature rise due to climate

change, the model only includes explicit response functions to temperature for seven species (10 functional groups). Therefore, temperature has no direct effect on most of the remaining functional groups, so probably, the impact of ocean warming on the ecosystem as a whole is likely underestimated. The model also does not account for other climate-related stressors such as acidification and deoxygenation, which has been previously shown to negatively affect the productivity and the distribution of species (Cheung et al., 2012; Dueri, 2017; Dalpadado et al., 2024). Additionally, the model does not account for the potential of species to acclimate or adapt physiologically to rising temperatures over time (Senina et al., 2018), meaning that impacts projected under slower warming trajectories, such as SSP1-2.6, may be overestimated relative to those under more rapid warming scenarios like SSP3-7.0, where adaptive capacity is likely more constrained. Finally, the base model shows limited parameter flexibility, as reflected in the notably narrow Monte Carlo uncertainty ranges, likely a consequence of the large number of time series used to inform and constrain the model fit. These uncertainty ranges are the propagation of the uncertainty around the base model parameters, not the uncertainty around model predictions. Therefore, they do not represent the real full range of uncertainty around model fitting and predictions. This is particularly relevant when projecting the model beyond the range of conditions used to fit it, where the true uncertainty in biomass projections is likely larger than that indicated by the Monte Carlo ranges.

Addressing these limitations should be a priority for future development of the model, especially if the framework is extended to Ecospace, the spatially explicit module of the EwE approach. An Ecospace implementation would allow future work to evaluate climate-driven species redistribution rather than assuming a fixed spatial domain with spatially homogeneous environmental responses, allowing the identification of climate refugia and helping to determine whether changes in abundance are driven by species redistribution to more suitable areas outside the model domain or by a genuine variation in stock biomass. To obtain a more complete understanding of the uncertainty of model predictions, a sensitivity analysis on the vulnerabilities and other Ecosim tuning parameters should be performed. The extension of temperature-dependent functional responses to a broader set of functional groups and the inclusion of additional environmental drivers such as oxygen availability or ocean acidification would allow for a better characterization at species and ecosystem-wide level of climate change impacts. The tropical Indian Ocean is a major fishing ground for tuna, and the suggested decrease in biomass of the main targeted species, or their redistribution towards more suitable habitats, threatens the food security, livelihoods, and economic development of many coastal and island nations (Lam et al., 2020; Sumaila & Tai, 2020). Therefore, the integration of socioeconomic dimensions would allow to characterize trade-offs between conservation outcomes and fleet-level economic performance to be evaluated explicitly.

5. Conclusions

This study shows that in the tropical Indian Ocean climate change emerges as the dominant driver shaping the future of the oceanic pelagic ecosystem. While fisheries management remains effective in regulating direct fishing impacts by stabilizing exploited populations and improving the state of vulnerable species, its capacity to offset climate driven ecosystem change remains limited. This underscores the importance of countries to adhere to the Paris Agreement and reducing their greenhouse gas emissions, particularly as many nations may already be experiencing the consequences of a climate change to which fisheries have contributed only marginally, with impacts that extend far beyond fisheries and affect other sectors and the general economy. The TIO model represents the first time-dynamic ecosystem model for the tropical Indian Ocean pelagic ecosystem explicitly designed to support climate-ready ecosystem-based fisheries management within the IOTC framework. However, results should be interpreted as exploratory scenario projections given the current limitations of the model. The limited number of thermal response functions, the absence of other climate stressors, and incomplete characterization of projection uncertainty should be addressed. Despite these limitations which many are part of the challenges of modelling data-poor ecosystems, this study demonstrates that ocean warming and reductions in primary production can significantly affect large oceanic pelagic ecosystems. These findings suggest that, under climate change, effective fisheries management will depend not only on regulating fishing mortality, but also on anticipating and adapting to shifting ecological baselines. Integrating climate change into ecosystem-based fisheries management should therefore be considered a central requirement for the future management of tropical tuna fisheries. However, the primary objective must be to reduce greenhouse gas emissions, as this is essential to preserving the ocean's capacity to continue providing important ecosystem services such as food provisioning, cultural identity, and livelihoods.

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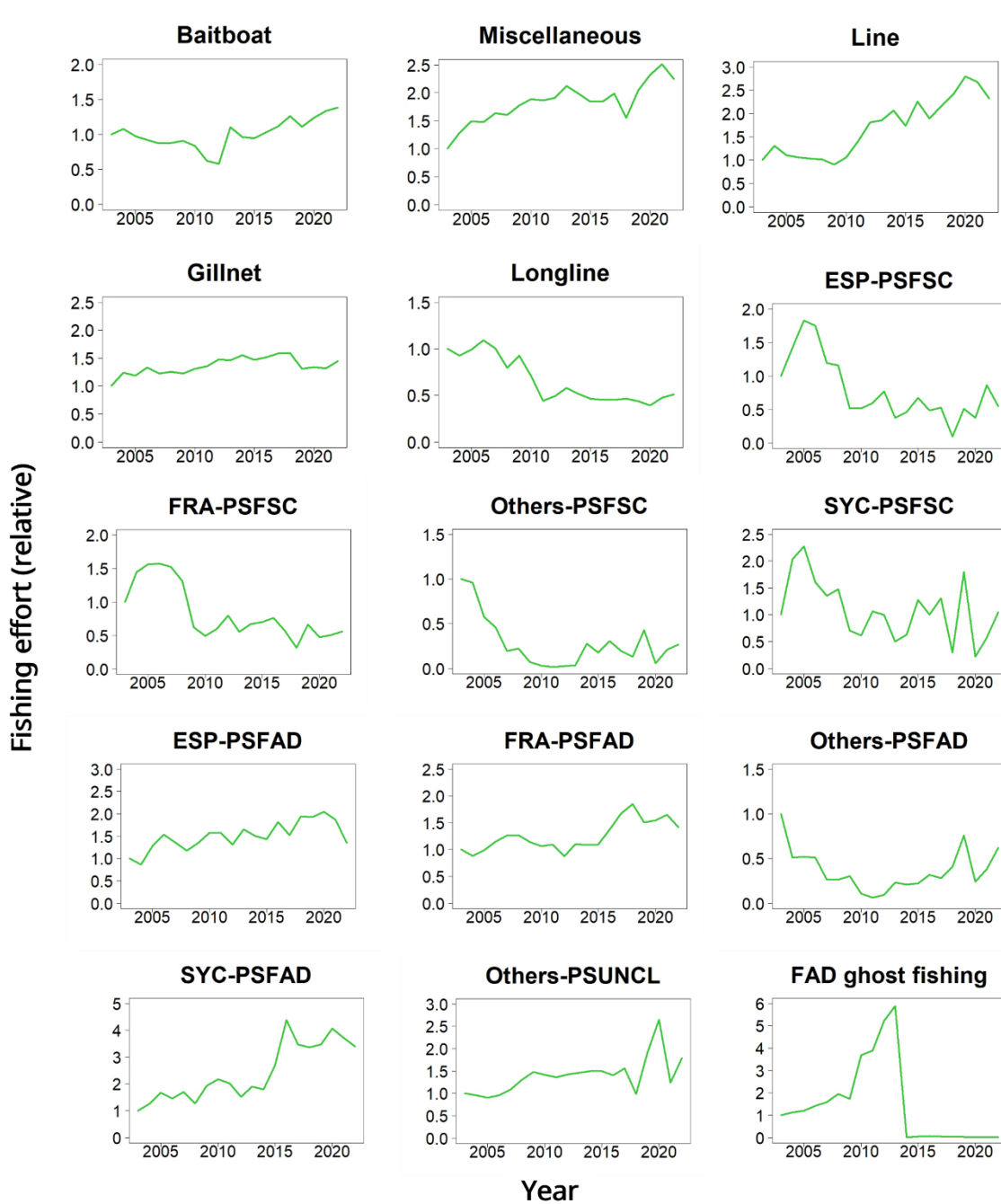
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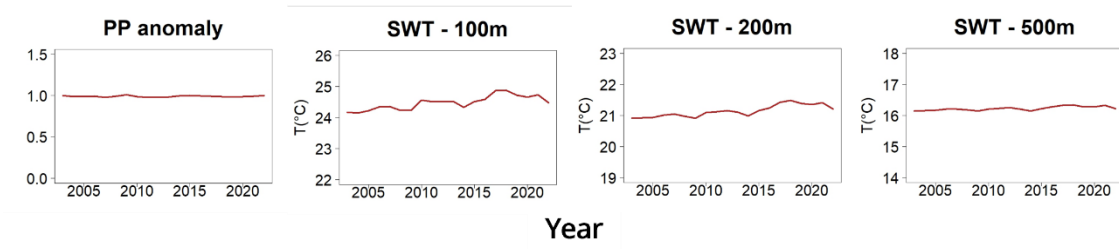
Supplementary material

SM -Table 1. References used to calculate the discard rate by fleet and functional group.

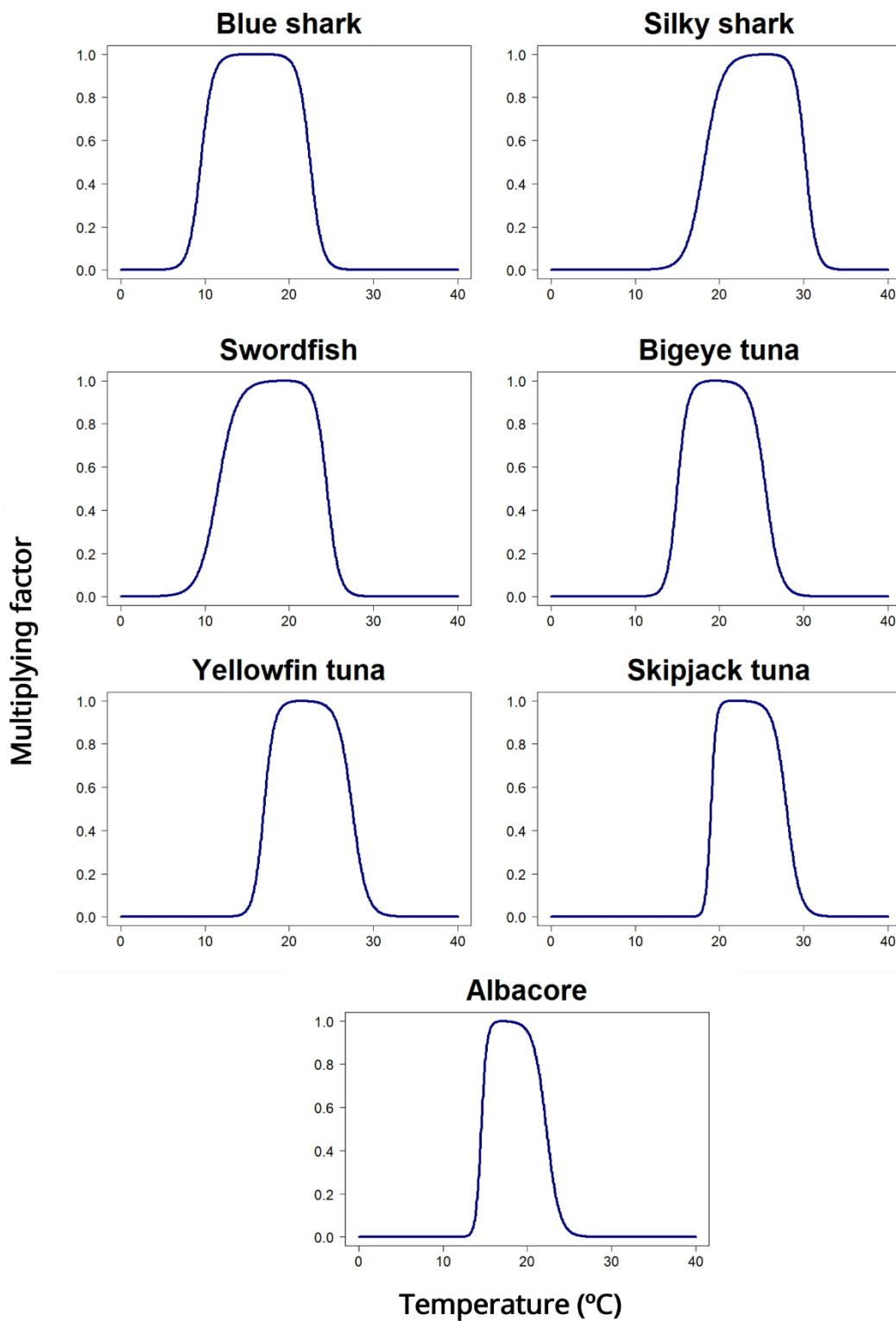
Functional group/Fleet	Gillnet	Longline	Purse seine – FSC & FAD (ESP, FRA, SYC)	Purse seine – FSC & FAD (Others)
2. Baleen whales	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)		
3. Toothed whales	(Anderson et al., 2020)	(Garcia & Herrera, 2018)		
4. Blue Shark	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
5. Silky shark	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
6. Other sharks	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
7. Whale shark	(Garcia & Herrera, 2018)			(Garcia & Herrera, 2018)
8. Pelagic stingray	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)		
9. Mobulas	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)		
10. Sea turtles	(Garcia & Herrera, 2018)	(Garcia & Herrera, 2018)		
11. Other billfishes		(Huang & Liu, 2010)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
12. Swordfish		(Huang & Liu, 2010)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
13. Bigeye mature		(Huang & Liu, 2010)		
14. Bigeye immature		(Huang & Liu, 2010)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
15. Yellowfin mature				
16. Yellowfin immature		(Huang & Liu, 2010)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
17. Skipjack mature				
18. Skipjack immature			(Ruiz et al., 2018)	(Ruiz et al., 2018)
19. Albacore		(Huang & Liu, 2010)	(Ruiz et al., 2018)	(Ruiz et al., 2018)
20. Small tunas and other bonitos			(Ruiz et al., 2018)	(Ruiz et al., 2018)
21. Jacks, mackerels, runners, trevallies and scads	(Shahifar, 2018)		(Ruiz et al., 2018)	(Ruiz et al., 2018)
22. Epipelagic fishes – I	(Shahifar, 2018)		(Ruiz et al., 2018)	(Ruiz et al., 2018)
23. Epipelagic fishes - II			(Ruiz et al., 2018)	(Ruiz et al., 2018)
24. Small epipelagic fishes			(Ruiz et al., 2018)	(Ruiz et al., 2018)
25. Large mesopelagic fishes			(Ruiz et al., 2018)	



SM - Figure 1. Time series of relative fishing effort used to drive the model.



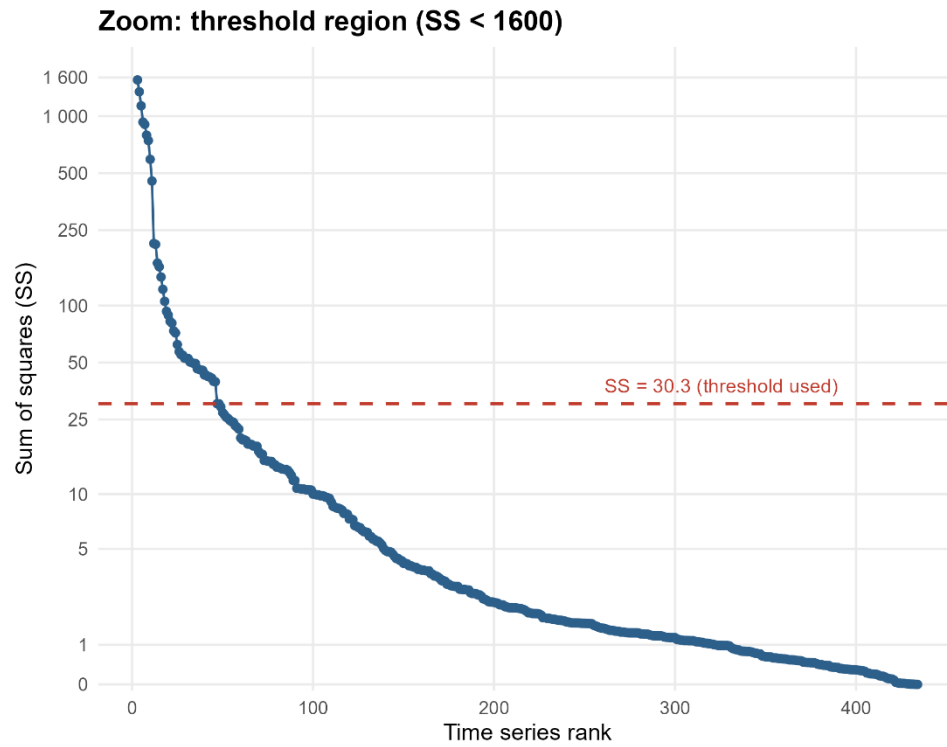
SM - Figure 2. Time series of relative primary production (PP anomaly) and sea water temperature integrated at 100, 200, and 500m, used to drive the model.



SM -Figure 3. Response function of the species to sea water temperature. The vertical axis represents the value between 0 and 1 of the factor that multiplies the consumption of the functional. The consumption will be maximum when the species is at its optimum temperature and will decrease when the species stays outside of the optimum value. The same function is applied for mature and immature individuals of the three tropical tuna species

SM - Table 2. Estimated annual entanglement of silky sharks (*Carcharhinus falciformis*) and sea turtles in dFADs deployed by the Indian Ocean tropical tuna purse seine fishery (2003–2022) for the dFAD ghost fishing fleet of the model. For each year, the number of active purse seine vessels is shown by flag (Spain - ESP, France - FRA, Seychelles – SYC, and Others), together with the estimated number of dFADs deployed per vessel or the total number of dFADs set in the Indian Ocean (IO). The total number of FADs was multiplied by the species- and design-specific entanglement rates ($t \cdot dFAD^{-1} \cdot y^{-1}$) and divided by the model area (21,755,112.32 km²) to estimate annual entanglement in $t \cdot km^{-2} \cdot y^{-1}$: high-entanglement-risk design (HERDFAD), low-entanglement-risk design (LERDFAD), and non-entangling design (NERDFAD)

										Silky shark ($t \cdot km^{-2} \cdot y^{-1}$)			Sea turtles ($t \cdot km^{-2} \cdot y^{-1}$)		
										HERDFAD	LERDFAD	NERDFAD	HERDFAD	LERDFAD	NERDFAD
Number of active PS vessels					N° of dFADs					(Filmlalter et al., 2013)	(Grande et al., 2019)	(Grande et al., 2025)	(Bourjea et al., 2014)		
Year	ESP	FRA	SYC	Others	Reference	By vessel	Total in the IO	Reference	Total n° of dFADs	$0.845t \cdot dFAD^{-1} \cdot y^{-1}$	$0.009t \cdot dFAD^{-1} \cdot y^{-1}$	$0.002t \cdot dFAD^{-1} \cdot y^{-1}$	$0.0005134t \cdot dFAD^{-1} \cdot y^{-1}$		
2003	19	17	11	9	(SFA, 2005; IOTC, 2025b)	105			5880	0.0002284			0.0000001		
2004	20	16	14	5	(SFA, 2005; IOTC, 2025b)	120		(Maufroy et al., 2017)	6600	0.0002564			0.0000002		
2005	21	18	11	2	(SFA, 2006; IOTC, 2025b)	135			7020	0.0002727			0.0000002		
2006	22	18	10	6		150			8400	0.0003263			0.0000002		
2007	23	18	10	2			9325		9325	0.0003622			0.0000002		
2008	17	20	10	3			11479		11479	0.0004459			0.0000003		
2009	15	14	0	6			10222		10222	0.0003970			0.0000002		
2010	13	8	9	5			21658		21658	0.0008411			0.0000005		
2011	15	0	8	1			22858	(Schiller et al., 2025)	22858	0.0008877			0.0000005		
2012	14	8	0	3			30753		30753	0.0011943			0.0000007		
2013	14	13	7	15			34659		34659	0.0013460			0.0000008		
2014	15	13	8	24	(IOTC, 2025b)		11182		11182		0.0000046			0.0000002	
2015	15	13	13	20			28740		28740	0.0000119			0.0000002		
2016	15	13	13	18		550		(IOTC, 2015)	32450	0.0000134			0		
2017	14	13	13	13		550			29150	0.0000121			0		
2018	14	12	13	5		350		(IOTC, 2017)	15400	0.0000064			0		
2019	15	13	13	4		350			15750	0.0000065			0		
2020	15	18	13	14		300			18000			0.0000017			0
2021	16	11	13	5		300		(IOTC, 2019)	13500			0.0000012			0
2022	15	9	13	12		300			14700			0.0000014			0



SM - Figure 4. Ranked sum of squares (SS) values for all fitted time series (zoomed to SS < 1600). The dashed line marks the SS = 30.3 threshold, set at the last large gap in the distribution, above which time series were excluded (weight = 0) from the second model run. The two highest SS values (17173.4 and 16000.0) are not shown.

SM - Table 3. Minimum (*TempMin*), preferred minimum (*TempPrefMin*), preferred maximum (*TempPrefMax*), and maximum (*TempMax*) temperature thresholds (°C) used to parameterize the temperature response functions for the Ecosim functional groups listed in the table. Temperature limits were compiled from species-specific literature sources and used to define the thermal suitability curves driving environmental response in Ecosim. The depth range indicates which time series of temperature (100, 200, 500m) will be applied to the forcing function to obtain the factor that will multiply the consumption.

FG	Species	Depth range (m)	Ref. depth range	TempMin	TempPrefMin	TempPrefMax	TempMax	Ref. Pref Temps	Ref. MinMax Temps
4	Blue shark	0-500	(Rochman et al., 2021)	7	12	20	21	(Shark Research Institute, 2026)	(Compagno, 1984)
5	Silky Shark	0-100	(Curnick et al., 2020)	12.73	23.66	28.16	32.36	(Kaschner et al., 2019)	(Kaschner et al., 2019)
12	Swordfish	0-200	(Romanov et al., 2026)	5	18	22	27	(Collette et al., 2022)	(Nakamura, 1985)
13	Bigeye mat.	0-200	(Sabarros et al., 2015)	13	17	22	29	(Collette et al., 2021d)	(Collette et al., 2021d)
14	Bigeye imm.	0-200	(Sabarros et al., 2015)	13	17	22	29	(Collette et al., 2021d)	(Collette et al., 2021d)
15	Yellowfin mat.	0-100	(Sabarros et al., 2015)	15	19	24	31	(Collette et al., 2021c)	Assumed similar range as BET
16	Yellowfin imm.	0-100	(Sabarros et al., 2015)	15	19	24	31	(Collette et al., 2021c)	Assumed similar range as BET
17	Skipjack mat.	0-100	(Arrizabalaga et al., 2015)	18	20	25	31	(Collette et al., 2021a)	(Collette et al., 2021a)
18	Skipjack imm.	0-100	(Arrizabalaga et al., 2015)	18	20	25	31	(Collette et al., 2021a)	(Collette et al., 2021a)
19	Albacore	0-200	(Arrizabalaga et al., 2015)	13.5	15.6	19.4	25.2	(Collette et al., 2021b)	(Collette et al., 2021b)

SM - Table 4. Distribution of the 2026 Yellowfin Tuna (YFT) Total Allowable Catch (TAC) among CPCs, countries, gear categories, set type and model fleets. For each fleet segment, the table provides the average proportion of YFT catches by flag and gear during 2020–2022, the proportion of catches occurring within the model area (MA), and the corresponding amount of TAC estimated to be taken by the combination of flag and gear within the MA. *: TAC assumed to be the mean YFT catch during 2020-2022; **: TAC agreed by the Omani fleet to be applied from 2031 onwards; +: values from 2024 YFT catch; ^: No data available. Assumed that catches are be done entirely inside the MA and by other gears in the case of Philippines. TACs values extracted from IOTC (2025a) and redistributed TAC for European Union countries extracted from EU (2024).

CPC code	CPC name	Country code	Country name	Gear	Set type	YFT TAC 2026	YFT gear's proportion by flag (20-22)	Prop. YFT caught in MA (20-22)	TAC prop. that will be done in MA	Model fleet
AUS	Australia	AUS	Australia	GN		2000	0.039	0	0	
AUS	Australia	AUS	Australia	LI		2000	0.039	0	0	
AUS	Australia	AUS	Australia	LL		2000	0.922	0	0	
BGD	Bangladesh	BGD	Bangladesh	OT		2000	1	1	2000.000	OT
CHN	China	CHN	China	LL		3083	1	0.873	2692.880	LL
COM	Comoros	COM	Comoros	GN		5279	0.017	1	90.630	GN
COM	Comoros	COM	Comoros	LI		5279	0.983	1	5188.370	LI
EUR	European Union	ESP	Spain	PS	FS	42903	0.354	1	15188.869	ESP-PS-FSC
EUR	European Union	ESP	Spain	PS	LS	42903	0.646	1	27714.131	ESP-PS-FAD
EUR	European Union	FRA	France	PS	FS	27710	0.436	1	12095.191	FRA-PS-FSC
EUR	European Union	FRA	France	PS	LS	27710	0.564	1	15614.809	FRA-PS-FAD
EUR	European Union	ITA	Italy	PS	FS	2365	0.436	1	1032.303	FRA-PS-FSC
EUR	European Union	ITA	Italy	PS	LS	2365	0.564	1	1332.697	FRA-PS-FAD
EUR	European Union	PRT	Portugal	LL		100	1	0	0	LL
GBR	Great Britain	GBR	Great Britain	LI		500	1	1	500.000	LI
FRAT	France OT	REU & MYT	Réunion & Mayotte	LI		500	0.344	0.325	55.759	LI
FRAT	France OT	REU & MYT	Réunion & Mayotte	LL		500	0.656	0.018	5.947	LL
IDN	Indonesia	IDN	Indonesia	BB		45426	0.059	1.000	2701.372	BB
IDN	Indonesia	IDN	Indonesia	GN		45426	0.190	0.420	3635.299	GN
IDN	Indonesia	IDN	Indonesia	LI		45426	0.332	0.316	4776.727	LI
IDN	Indonesia	IDN	Indonesia	LL		45426	0.129	0.233	1365.820	LL
IDN	Indonesia	IDN	Indonesia	OT		45426	0.022	0.704	711.268	OT
IDN	Indonesia	IDN	Indonesia	PS	UNCL	45426	0.267	0.353	4276.948	PS-UNCL
IND	India	IND	India	BB		22000*	0.155	1	3408.387	BB
IND	India	IND	India	GN		22000*	0.321	1	7058.843	GN
IND	India	IND	India	LI		22000*	0.465	1	10232.693	LI
IND	India	IND	India	LL		22000*	0.000	1	5.352	LL
IND	India	IND	India	OT		22000*	0.053	1	1163.276	OT
IND	India	IND	India	PS	UNCL	22000*	0.006	1	131.449	PS-UNCL
IRN	Iran	IRN	Iran	GN		32623	0.715	1	23320.222	GN
IRN	Iran	IRN	Iran	LI		32623	0.272	1	8880.051	LI
IRN	Iran	IRN	Iran	PS	LS	32623	0.013	1	422.727	Ot-PS-FAD
JPN	Japan	JPN	Japan	LL		4003	0.987	0.479	1891.900	LL
JPN	Japan	JPN	Japan	PS	LS	4003	0.013	1	51.784	Ot-PS-FAD
KEN	Kenya	KEN	Kenya	GN		3654	0.445	1	1626.540	GN
KEN	Kenya	KEN	Kenya	LI		3654	0.281	1	1027.994	LI
KEN	Kenya	KEN	Kenya	LL		3654	0.228	1	834.740	LL
KEN	Kenya	KEN	Kenya	OT		3654	0.000	1	0.937	OT
KEN	Kenya	KEN	Kenya	PS	UNCL	3654	0.045	1	163.789	PS-UNCL
KOR	Korea	KOR	Korea	LL		9056	0.068	0.613	376.069	LL

SM - Table 4. Continuation.

CPC code	CPC name	Country code	Country name	Gear	Set type	YFT TAC 2026	YFT gear's proportion by flag (20-22)	Prop. YFT caught in MA (20-22)	TAC prop. that will be done in MA	Model fleet
KOR	Korea	KOR	Korea	PS	FS	9056	0.171	1	1549.228	Ot-PS-FSC
KOR	Korea	KOR	Korea	PS	LS	9056	0.761	1	6893.308	Ot-PS-FAD
LKA	Sri Lanka	LKA	Sri Lanka	GN		33123	0.035	1	1143.390	GN
LKA	Sri Lanka	LKA	Sri Lanka	LI		33123	0.674	1	22335.143	LI
LKA	Sri Lanka	LKA	Sri Lanka	LL		33123	0.275	1	9103.904	LL
LKA	Sri Lanka	LKA	Sri Lanka	OT		33123	0.001	1	48.175	OT
LKA	Sri Lanka	LKA	Sri Lanka	PS	UNCL	33123	0.015	1	492.387	PS-UNCL
MDG	Madagascar	MDG	Madagascar	LI		700*	0.952	0.400	266.653	LI
MDG	Madagascar	MDG	Madagascar	LL		700*	0.048	0.997	33.254	LL
MDV	Maldives	MDV	Maldives	BB		47195	0.464	1	21910.175	BB
MDV	Maldives	MDV	Maldives	LI		47195	0.536	1	25284.825	LI
MUS	Mauritius	MUS	Mauritius	LL		10490	0.005	0.962	51.335	LL
MUS	Mauritius	MUS	Mauritius	PS	FS	10490	0.028	1	296.244	FRA-PS-FSC
MUS	Mauritius	MUS	Mauritius	PS	LS	10490	0.967	1	10140.388	FRA-PS-FAD
MOZ	Mozambique	MOZ	Mozambique	LI		2000	0.249	0.920	457.199	LI
MOZ	Mozambique	MOZ	Mozambique	LL		2000	0.745	0.303	451.903	LL
MOZ	Mozambique	MOZ	Mozambique	PS	UNCL	2000	0.007	0.250	3.329	PS-UNCL
MYS	Malaysia	MYS	Malaysia	LL		2000	1	0.579	1158.002	LL
OMN	Oman	OMN	Oman	GN		25000**	0.098	1	2457.995	GN
OMN	Oman	OMN	Oman	LI		25000**	0.881	1	22018.956	LI
OMN	Oman	OMN	Oman	LL		25000**	0.003	0.955	77.813	LL
OMN	Oman	OMN	Oman	OT		25000**	0.003	1	67.392	OT
OMN	Oman	OMN	Oman	PS		25000**	0.015	1	374.175	PS
PAK	Pakistan	PAK	Pakistan	GN		14468	0.997	1	14429.851	GN
PAK	Pakistan	PAK	Pakistan	LI		14468	0.003	1	38.149	LI
PHL	Philippines	PHL	Philippines	OT		700	1 [^]	1 [^]	0	OT
SDN	Sudan	SDN	Sudan	GN		2000	0.719 ⁺	1 [^]	1438.000	GN
SDN	Sudan	SDN	Sudan	LI		2000	0.182 ⁺	1 [^]	364.000	LI
SDN	Sudan	SDN	Sudan	OT		2000	0.072 ⁺	1 [^]	144.000	OT
SDN	Sudan	SDN	Sudan	PS	UNCL	2000	0.027 ⁺	1 [^]	54.000	PS-UNCL
SYC	Seychelles	SYC	Seychelles	LI		39577	0.014	1	557.999	LI
SYC	Seychelles	SYC	Seychelles	LL		39577	0.073	0.826	2381.824	LL
SYC	Seychelles	SYC	Seychelles	PS	FS	39577	0.204	1	8074.221	SYC-PS-FSC
SYC	Seychelles	SYC	Seychelles	PS	LS	39577	0.709	1	28061.767	SYC-PS-FAD
THA	Thailand	THA	Thailand	PS	UNCL	2000	1	1	2000.000	PS-UNCL
TWN	Taiwan	TWN	Taiwan	LL		29000*	1	0.822	23838.000	LL
TZA	Tanzania	TZA	Tanzania	GN		3872	0.816	1	3158.327	GN
TZA	Tanzania	TZA	Tanzania	LI		3872	0.022	1	84.546	LI
TZA	Tanzania	TZA	Tanzania	LL		3872	0.010	1	39.015	LL
TZA	Tanzania	TZA	Tanzania	PS	FS	3872	0.036	1	138.231	Ot-PS-FSC
TZA	Tanzania	TZA	Tanzania	PS	LS	3872	0.117	1	451.882	Ot-PS-FAD
YEM	Yemen	YEM	Yemen	GN		16474	0.015	1	252.763	GN
YEM	Yemen	YEM	Yemen	LI		16474	0.985	1	16221.237	LI
ZAF	South Africa	ZAF	South Africa	LL		2000	1	0	0	

SM - Table 5. Calculation of the relative effort needed by each fleet to achieve the TAC of yellowfin tuna (YFT) based on the mean effort and catch between 2020 and 2022. Catch in kg-km⁻² and effort in relative value with respect to 2003.

TIO model fleet	Mean YFT landings in MA (2020-2022)	Mean effort (2020-2022)	Mean YFT landings in MA at TAC	Effort at TAC	Effort change (%)
Baitboat	12608.19	1.3174	28019.93	2.9277	222.2
Miscellaneous	2371.40	2.3604	4835.05	4.8127	203.9
Line	160829.61	2.5990	118290.30	1.9116	-26.4
Gillnet	62190.21	1.3673	58611.86	1.2886	-5.8
Longline	25503.22	0.4596	44307.76	0.7985	173.7
ESP-PSFSC	12763.99	0.5983	15188.87	0.7120	119.0
FRA-PSFSC	16719.45	0.5120	13423.74	0.4111	-19.7
Others-PSFSC	2960.58	0.1780	1687.46	0.1015	-43.0
SYC-PSFSC	4484.56	0.6172	8074.22	1.1112	180.0
ESP-PSFAD	30824.65	1.7562	27714.13	1.5790	-10.1
FRA-PSFAD	21161.13	1.5356	27087.89	1.9657	128.0
Others-PSFAD	4493.74	0.4148	7819.70	0.7217	174.0
SYC-PSFAD	25794.09	3.7231	28061.77	4.0505	108.8
Others -PSUNCL	4136.35	1.8912	7121.90	3.2563	172.2

SM - Table 6. Biomass (kg·km⁻²) predicted by the model for each functional group for the historical period (2003-2022).

year\FG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2003	0.50	15.21	45.99	19.04	30.24	25.48	28.86	6.47	2.18	1.67	14.30	14.44	9.28	13.71	37.53	29.12	69.62	5.80
2004	0.50	15.21	45.96	18.03	30.07	25.07	28.74	6.47	2.16	1.67	14.08	14.40	9.04	12.94	35.26	27.67	68.99	5.75
2005	0.50	15.20	45.85	17.18	29.82	24.33	28.53	6.42	2.12	1.67	13.77	14.41	8.72	12.30	33.25	26.81	67.42	5.61
2006	0.50	15.17	45.68	16.39	29.70	23.45	28.29	6.42	2.08	1.66	13.53	14.45	8.30	11.88	32.45	26.06	66.24	5.56
2007	0.50	15.14	45.53	15.82	29.78	22.74	28.05	6.43	2.04	1.65	13.43	14.57	8.17	11.77	32.38	25.90	65.72	5.50
2008	0.49	15.14	45.32	15.60	29.97	22.36	27.83	6.40	2.02	1.66	13.42	14.78	8.50	11.88	32.46	26.12	65.48	5.44
2009	0.49	15.17	45.15	15.49	30.29	22.09	27.66	6.48	2.01	1.67	13.36	15.06	8.66	12.26	33.83	26.46	66.83	5.62
2010	0.49	15.22	45.11	15.64	30.37	21.95	27.49	6.62	2.00	1.70	13.32	15.45	9.12	12.87	34.94	27.07	67.74	5.69
2011	0.49	15.30	45.03	16.03	30.20	21.87	27.22	6.56	1.97	1.74	13.30	15.72	9.86	13.35	34.59	26.96	66.39	5.46
2012	0.49	15.39	44.78	16.27	29.79	21.50	26.87	6.44	1.93	1.78	13.16	15.64	10.14	13.55	33.81	25.94	65.08	5.33
2013	0.48	15.46	44.48	16.24	29.22	20.88	26.51	6.40	1.89	1.81	12.87	15.35	9.99	13.35	33.29	25.22	63.35	5.26
2014	0.48	15.61	44.23	16.45	29.73	20.37	26.68	6.46	1.86	1.86	12.55	15.16	10.04	12.92	33.02	25.39	63.07	5.33
2015	0.48	15.85	44.13	17.02	31.05	20.32	27.29	6.64	1.85	1.93	12.36	15.23	10.41	12.59	33.36	26.05	64.34	5.49
2016	0.48	16.09	44.13	17.59	32.30	20.45	27.91	6.79	1.85	1.99	12.31	15.56	10.61	12.45	33.43	26.08	64.10	5.51
2017	0.48	16.32	44.13	18.08	33.37	20.42	28.49	6.86	1.83	2.05	12.27	15.92	10.60	12.54	33.33	25.79	63.20	5.42
2018	0.48	16.54	44.08	18.43	34.36	20.38	29.04	6.84	1.81	2.10	12.05	16.15	10.55	12.55	33.25	25.48	61.65	5.28
2019	0.48	16.75	44.00	18.63	35.20	20.49	29.60	6.78	1.81	2.14	11.81	16.23	10.47	12.22	32.40	24.98	60.01	5.16
2020	0.48	16.95	43.90	18.73	35.85	20.50	30.17	6.73	1.81	2.18	11.72	16.37	10.47	11.75	31.89	24.67	58.64	5.07
2021	0.48	17.15	43.81	18.77	36.55	20.34	30.74	6.74	1.83	2.23	11.54	16.69	10.28	11.50	31.65	24.60	58.47	5.09
2022	0.48	17.36	43.75	18.85	37.20	20.19	31.32	6.81	1.83	2.26	11.37	17.13	10.10	11.57	31.91	25.09	59.67	5.21

SM - Table 6. Continuation.

year\FG	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
2003	3.47	160.52	192.98	147.50	231.46	553.41	205.06	2680.02	456.07	822.36	539.52	2671.78	4746.08	7002.03	11658.28	10.96	238883.00
2004	3.29	159.33	192.85	147.69	231.85	547.04	206.38	2649.20	455.43	813.67	529.68	2602.35	4696.76	6873.72	11473.46	11.04	235660.60
2005	3.11	157.27	191.57	146.96	231.65	533.21	207.20	2613.47	448.70	808.47	526.59	2595.06	4697.25	6845.78	11477.02	11.23	235101.70
2006	2.95	156.43	192.02	146.83	232.88	527.97	208.27	2618.46	450.17	814.80	530.75	2625.32	4712.94	6894.65	11542.63	11.75	236302.60
2007	2.83	156.08	192.39	146.96	234.12	520.16	209.78	2597.43	449.70	806.98	520.80	2552.05	4656.02	6759.81	11332.75	11.65	232860.70
2008	2.73	154.76	191.12	145.97	233.78	509.50	209.60	2586.68	443.15	808.20	526.28	2607.75	4703.23	6846.46	11508.66	10.83	235210.30
2009	2.71	155.75	193.84	146.97	236.14	523.60	210.27	2656.72	456.49	831.75	546.22	2735.11	4781.89	7087.56	11809.01	10.44	241092.10
2010	2.73	156.98	196.45	148.93	238.42	534.49	212.60	2656.44	464.77	820.68	532.01	2612.25	4688.15	6885.72	11450.66	9.88	235809.80
2011	2.70	153.57	192.40	147.18	235.47	514.49	211.57	2579.28	444.56	796.81	516.74	2532.20	4649.71	6719.75	11302.71	8.99	231954.90
2012	2.62	148.87	188.56	144.34	232.44	496.91	208.32	2563.15	433.49	799.39	516.89	2547.20	4656.27	6725.79	11340.48	8.71	232199.70
2013	2.54	146.14	187.98	142.93	232.10	491.29	206.22	2577.93	438.20	809.79	520.71	2573.36	4667.57	6768.79	11391.11	8.95	233237.90
2014	2.51	145.89	190.46	143.49	234.49	499.33	206.27	2609.71	451.71	824.27	533.26	2656.51	4725.43	6926.17	11605.69	8.70	237144.00
2015	2.52	148.44	194.87	145.97	238.62	518.45	208.72	2643.30	467.46	831.75	540.28	2686.66	4742.24	7001.28	11662.62	8.00	238850.90
2016	2.52	150.28	197.44	148.21	241.47	531.54	211.70	2641.49	472.33	825.89	538.92	2669.81	4735.70	6983.98	11627.55	7.70	238384.30
2017	2.47	150.17	197.50	149.12	242.49	532.22	213.82	2612.93	468.34	814.41	531.08	2615.73	4701.65	6886.63	11496.43	7.88	235969.50
2018	2.40	149.06	195.52	148.44	241.75	523.22	214.10	2583.62	459.21	806.78	526.18	2591.65	4688.44	6832.40	11448.91	8.57	234707.80
2019	2.32	147.76	193.60	147.28	240.81	513.14	213.41	2567.58	453.70	803.96	521.94	2567.08	4668.34	6778.26	11380.11	8.31	233376.40
2020	2.24	145.78	192.62	146.30	240.61	506.08	212.70	2564.56	452.85	807.17	523.97	2587.77	4683.19	6808.10	11438.86	7.69	234178.60
2021	2.18	145.69	193.58	146.40	241.96	507.83	212.89	2580.18	458.79	814.29	528.77	2617.34	4699.81	6863.81	11503.46	7.78	235519.80
2022	2.17	147.09	195.71	147.44	244.22	517.35	214.08	2607.57	467.01	822.73	537.80	2674.97	4740.23	6976.71	11651.07	8.08	238300.50

SM - Table 7. Catch trends ($\text{kg}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$) predicted by the model for each functional group for the historical period (2003-2022). 0.00: indicates value lower than 0.005.

year\FG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2003	0	0.26	0.20	2.66	2.54	5.06	0.85	0.04	0.17	0.16	1.43	1.65	5.88	1.56	11.93	6.78	19.26	0.58
2004	0	0.24	0.25	2.49	2.77	5.75	1.05	0.04	0.21	0.16	1.81	1.69	5.54	1.36	13.56	6.87	19.57	0.56
2005	0	0.26	0.24	2.44	2.55	5.64	1.00	0.04	0.20	0.16	1.66	1.47	5.68	1.46	13.43	7.16	20.34	0.60
2006	0	0.28	0.27	2.53	2.49	5.89	1.11	0.05	0.22	0.18	1.67	1.54	5.85	1.51	12.79	7.32	20.83	0.63
2007	0	0.26	0.24	2.26	2.21	5.45	1.02	0.04	0.20	0.17	1.48	1.38	5.29	1.41	11.06	6.66	19.19	0.58
2008	0	0.21	0.25	1.85	2.03	5.13	1.03	0.04	0.20	0.14	1.39	1.25	4.44	1.24	10.20	6.37	18.41	0.54
2009	0	0.24	0.24	2.05	2.11	5.25	1.00	0.04	0.19	0.16	1.60	1.26	5.02	1.43	8.51	6.40	19.27	0.59
2010	0	0.19	0.26	1.72	2.75	5.22	1.07	0.03	0.20	0.14	1.59	1.23	4.16	1.37	8.32	6.74	19.87	0.61
2011	0	0.12	0.27	1.35	2.37	5.03	1.09	0.02	0.21	0.11	1.47	1.29	3.12	1.22	8.70	6.70	18.84	0.57
2012	0	0.14	0.29	1.58	2.79	5.40	1.17	0.02	0.22	0.13	1.59	1.62	3.60	1.16	9.75	6.32	17.74	0.52
2013	0	0.16	0.28	1.74	2.77	5.43	1.14	0.03	0.21	0.14	1.70	1.70	3.98	1.38	8.99	6.90	21.12	0.64
2014	0	0.01	0.30	1.71	1.01	5.40	1.22	0.02	0.22	0.14	1.81	1.60	3.72	1.25	9.67	6.98	20.49	0.63
2015	0	0.01	0.28	1.58	1.17	4.99	1.18	0.02	0.21	0.13	1.70	1.43	3.54	1.26	9.79	7.27	21.05	0.66
2016	0	0.01	0.29	1.74	1.16	5.21	1.24	0.02	0.22	0.14	1.72	1.21	3.65	1.50	10.94	8.68	25.00	0.82
2017	0	0.01	0.31	1.70	1.26	5.36	1.33	0.02	0.22	0.15	1.73	1.24	3.55	1.42	10.08	8.18	23.79	0.76
2018	0	0.01	0.31	1.84	0.98	5.19	1.36	0.02	0.22	0.15	2.00	1.31	3.55	1.47	9.10	8.45	24.69	0.81
2019	0	0.01	0.25	1.81	1.17	4.94	1.14	0.02	0.18	0.14	1.83	1.42	3.59	1.56	11.35	8.28	24.36	0.81
2020	0	0.01	0.26	1.83	1.09	5.18	1.19	0.02	0.19	0.13	1.67	1.15	3.31	1.53	10.04	8.12	24.64	0.83
2021	0	0.01	0.25	1.97	0.98	5.29	1.20	0.02	0.19	0.15	1.97	1.02	3.78	1.40	11.06	8.09	23.79	0.80
2022	0	0.01	0.28	2.00	1.22	5.32	1.33	0.03	0.21	0.16	1.86	0.93	3.82	1.36	10.40	7.90	23.39	0.76

SM – Table 7. Continuation.

year\FG	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
2003	0.25	14.76	0.34	0.31	0.04	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2004	0.26	17.68	0.37	0.35	0.04	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2005	0.25	16.91	0.38	0.36	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2006	0.24	17.91	0.43	0.39	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2007	0.21	17.31	0.39	0.36	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2008	0.18	17.60	0.39	0.36	0.04	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2009	0.17	17.77	0.40	0.36	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2010	0.15	18.98	0.42	0.39	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2011	0.14	19.51	0.42	0.39	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2012	0.17	20.85	0.42	0.39	0.04	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2013	0.16	20.98	0.44	0.41	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2014	0.17	21.95	0.46	0.42	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2015	0.15	20.72	0.46	0.42	0.05	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2016	0.18	22.48	0.52	0.48	0.07	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2017	0.15	22.67	0.52	0.48	0.07	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2018	0.15	21.75	0.54	0.50	0.08	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2019	0.17	21.93	0.48	0.44	0.08	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2020	0.17	23.94	0.48	0.44	0.08	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2021	0.17	22.09	0.47	0.43	0.07	0.00	0.00	0	0	0	0	0	0	0	0	0	0
2022	0.16	22.82	0.48	0.44	0.06	0.00	0.00	0	0	0	0	0	0	0	0	0	0

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