Responses of tuna stocks to temporal closures in the Indian Ocean

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Abstract

Implementing temporal closures is a potential management tool to control the fishing pressure and for stock rebuilding plans. In the Indian Ocean, the yellowfin and bigeye stocks are estimated to be overfished and subject to overfishing, and the Commission has requested to investigate diverse management measures to improve the status of these stocks. In this study, we used the assessment models implemented in Stock Synthesis 3 (SS3) to evaluate the impacts on the future stock status of different closure strategies for yellowfin, bigeye, and skipjack. We found that closing any quarter to all the fisheries would result in stocks not being overfished and not being subject to overfishing by the last year of the projection period. Analyzing fleet-specific closures, we found that closing only the purse seine fishery that uses fish aggregating devices (PS-FAD) would produce the largest positive effect on the stock status compared to the other fisheries. We also compare the status of the stock in the last year of the projection period under the current recommendations for catch reduction.

1. Introduction

Tunas are widely distributed throughout temperate and tropical oceans and support several industrial and artisanal fishing communities worldwide. In the Indian Ocean, the tropical tuna species (skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*Thunnus obesus*)) support valuable fisheries. The Indian Ocean tropical tuna fishery comprises several coastal countries and distant water fishing nations, and several types of fishing fleets (e.g., longline, bait boat, purse seines, handline, gillnet and small-scale artisanal fisheries) operate in this area. Skipjack is the main species in tuna catches, with an average catch of 546,095 metric tons (mt, 2016-2020), followed by yellowfin, with an average catch of 434,569 mt (2016-2020), and bigeye, with an average catch of 87,488 mt (2017-2021). The western Indian Ocean is the main fishing ground, contributing 78.2% of the total tuna catch in this ocean (Gopalakrishna Pillai and Satheeshkumar, 2012).

The purse seine fishery is the main fishery operating in the Indian Ocean, taking about 45% of the total tropical tuna catch. The purse seine fishing fleet divides its activity into two modalities: on free schools ('free school') and fish aggregating devices ('FAD sets'). Gillnet is the second most important fishing gear in terms of catch contribution (~20%), represented by fleets from Iran, Sri Lanka, and Indonesia primarily. Longline is another important fishing gear categorized into two types: 'distant water', which uses freezing methods and operates in offshore areas, and 'fresh tuna'. Handline and bait boat are also important fishing gears but contribute less to the total catch than previous fleets. The relative importance of each fishing gear might vary depending on the tuna stock. For example, in recent years, the catches of yellowfin by the handline fleets have been the largest compared to other fleets. The catch level is an indicator to evaluate the impact of each fishery on a tuna stock; however, we should also consider other factors such as selectivity. For example, for yellowfin, the longline fishery mainly catches adults while the bait boat and purse seine mainly catch juveniles, which could cause different impacts on the tuna population dynamics.

In order to provide management advice on total allowable catch, the Scientific Committee of the Indian Ocean Tuna Commission (IOTC) performs (i) projections based on hypotheses on the future stock dynamics and catch by fleet and (ii) applies adopted a harvest control rule (HCR for skipjack) and a management procedure (MP, for bigeye) Recently, the Scientific Committee and the Working Group on FADs have discussed the potential impacts of the implementation of non-fishing quarters (i.e., closed quarters) on the recovery of the stock, with a specific focus on the PS-FAD fishery. Also, in 2023, the IOTC adopted a voluntary closure to all gears in the Indian Ocean for the conservation of tropical tunas (Resolution 23/03). This Resolution requests advice from the Scientific Committee on appropriate fishing closures applicable to all fishing gears. The requested information needs to consider area, closure period and any other detail to reduce the mortality of juvenile tropical tunas, particularly bigeye and yellowfin.

This study aims to compare the consequences of different temporal closure strategies on the stock status and catches of the skipjack, yellowfin, and bigeye stocks in the Indian Ocean. We evaluated the effects of the following factors: 1) fleet-specific closed quarters in the whole Indian Ocean, 2) fleet and area-specific closed quarters, 3) closure duration, , and 4) levels of reallocation of catch from a period of closure to the rest of the fishing year. We also added in our comparison the effects of the implementation of current recommended catch levels on the stock status. We show predicted levels of exploitation (spawning biomass and fishing mortality) under different closure modalities and factors to help Commission improve the state of exploitation of tropical tunas.

2. Methods

The yellowfin, bigeye, and skipjack stocks were assessed using the Stock Synthesis 3 platform (SS3, Methot and Wetzel, 2013) between 2020 and 2022 (Fu, 2020; Fu et al., 2022, 2021). SS3 is a flexible and widely used statistical age-structured population modeling framework that uses the integrated analysis paradigm (Maunder and Punt, 2013). For the yellowfin and bigeye cases, the models were spatially explicit, assuming four areas and a quarterly time resolution. The model fleet definitions were area-specific (Tables 1 and 2), as well as the data included: catches, CPUEs, marginal length compositions, and tagging data. For the skipjack case, the SS3 model temporal resolution was annual with four seasons (i.e., quarters) within a year and assumed a single area. Catch data from seven fisheries were considered (Table 3), as well as four CPUE time series, marginal length compositions, and tagging data. For the three tuna stocks, we used the models assuming steepness of 0.8, base natural mortality and growth, and lambda of 1 (no data reweighting). The model period included data from 1950 to 2019, 2020, and 2021 for skipjack, yellowfin, and bigeye, respectively.

First, we evaluated the impact of activity reductions of the main fleets targeting tropical tunas in the Indian Ocean by producing fishery impact plots. In these plots, the estimated spawning biomass in the absence of each one of the fleets is estimated. These plots help understand the differential impact attributed to each fishery. We show these plots for the three tuna stocks (Figures 1-3).

Then, we ran 10-year projections in SS3 for the three tuna stocks assuming distinct closure scenarios (see below). The 'base scenario' did not implement closures (i.e., all quarters open) during the projection period and had projected catch allocations per fleet and quarter as the average quarterly catch per fleet observed during the last three years of the model period (Figure 4-6). For projections, the recruitment was deterministic and calculated from the stock-recruitment relationship, and the biology and fishery parameters were kept constant.

When specifying catch allocations in stock projections, we sometimes might allocate catch larger than the vulnerable biomass for some fleet, representing an unfeasible scenario. In order to avoid this and before testing different closure strategies, we made sure that the base scenario was feasible by comparing the vulnerable biomass and allocated catch during the projection period. The vulnerable biomass (vSB) to the fishery f in the area where that fishery operates was calculated as:

$$vSB_{f,q} = \sum_{a} N_{a,q} * S_{a,f} * W_{a,f}$$

Where the subindices a and q represent age and quarter, respectively. N, S, and W represent the population abundance in the area where the fishery f operates, selectivity, and body weight, respectively. If the allocated catch for the fishery f was greater than the vulnerable biomass (i.e., $C_{f,q} > vSB_{f,q}$) for any q during the projection period, we reduced the projected catch for all fisheries operating in the area where the fishery f operates in order to obtain a feasible base scenario (i.e., $C_{f,q} < vSB_{f,q}$ for all q).

We tested several closure scenarios. The first group of scenarios applied quarter and fleet-specific closures to the entire stock area (i.e., Indian Ocean) during the projection period. The second group of closures applied quarter, area (based on the areas defined in the assessment model), and fleet-specific closures. Area-specific closures were not tested for skipjack since the base SS model used for this analysis is not spatially explicit.

We evaluated the effects on the stock status and projected catches of the following fleet-specific closure strategies:

1) Closure duration: a quarter could be closed 3 months (i.e., whole quarter), 2 months, or 1 month.
2) Catch allocation strategy: 100%, 50%, or 0% of the catch corresponding to a closed quarter could be reallocated proportionally among the open quarters in a year.

We used Kobe plots to examine the changes in the stock status in the terminal year (Y) of the projection period produced by closure strategies. The stock status indicators were $F_Y/Fmsy$ and SB_Y/SB_{msy}, where msy is the maximum sustainable yield, F is the fishing mortality, and SB is the spawning biomass. A Kobe plot classifies the stock status in four states:

- Red quadrant: subject to overfishing ($F/F_{msy} > 1$) and overfished ($SB/SBmsy_{msy} < 1$).
- Orange quadrant: subject to overfishing ($F/F_{msy} > 1$) and not overfished ($SB/SB_{msy} > 1$).
- Yellow quadrant: not subject to overfishing ($F/F_{msy} < 1$) and overfished ($SB/SB_{msy} < 1$).
- Green quadrant: not subject to overfishing ($F/F_{msy} < 1$) and not overfished ($SB/SB_{msy} > 1$).

The management goal is to be in the green quadrant. A closure strategy could have a positive impact on the stock if it moves the stock status by the terminal year in the direction to the green quadrant with respect to the base scenario.

We also show the estimated stock status in the last year of the stock assessment period, and the stock status in the last year of the projection period when the recommended TAC is implemented (‘TAC scenario’, no closures):

- Yellowfin: Total annual catch of 379,673 tons, reached by reducing the projected catch by 24% for PS-FAD, 18% for gillnet and longline, 13% for baitboat, and 8% for handline, PS (free school), others, troll, and longline (fresh tuna) with respect to the average catch of the last three years of the model period.

- Bigeye: Total annual catch of 80,583 tons, reached by reducing the projected catch by 9.25% for all the fisheries with respect to the average catch of the last three years of the model period. This is directly taken from Resolution 23/04.
- Skipjack: Total annual catch of 513,00 tons, reached by reducing the projected catch by 7.4% for all the fisheries with respect to the average catch of the last three years of the model period. As recommended by applying the HCR adopted in Resolution 16/02.

For the closure scenarios, we also examined the reductions in catches (%) for the projection period with respect to the observed catches in the last year of the model period produced by the closure strategies.

3. Results

Yellowfin

The impact plot showed that removing the PS-FAD and gillnet fisheries would produce the largest increase in spawning biomass (Figure 1). In terms of catches reported in the last year of the model period, the purse seine, the handline, longline (fresh tuna), and gillnet fisheries were the most important fisheries for this stock, with quarterly catches usually larger than 9,000 tons (Figure 4). We observed large variations in the catches by quarter for most fisheries. For our base scenario, we noticed that the projected catches of the longline (fresh tuna) in area 4 and handline in area 1 fisheries produced unfeasible projections (i.e., catches larger than vulnerable biomass), and also led to unfeasible projections for all the closure scenarios. For this reason, for the base and all the closure scenarios, we reduced the projected catches of all the fisheries operating in area 1 and 4 in 5% and 30%, respectively, in order to produce feasible projections.

The base scenario produced a stock status in the red quadrant by the terminal year of the projection period, while the TAC scenario moved it to the yellow quadrant, very close to the MSY benchmark. Therefore, a catch reduction to 379,673 tons would stop the strong from being subject to overfishing but would be short to recover the stock above SB_{msy} by 2030.

Closing all the fisheries simultaneously for any quarter with a catch reallocation of 0% always led to the largest positive impact on the stock (Figure 7), resulting in a stock status in the green quadrant by the terminal year. This positive effect was larger when closing quarter 1, 3 or 4 compared to quarter 2. Increasing the catch reallocation and decreasing the number of closed months in a quarter diminished the positive effect on the stock status. A catch reallocation of 100% produced equivalent results to the base scenario (i.e., when no closure was applied). This suggest that, if fishing fleets proportionally increase catch during the open seasons, the closure will not have any effect on the recovery of the stocks.

For fishery-specific closures in the entire Indian Ocean, the PS-FAD fishery was the only one that, when closed in quarter 1 and without any catch reallocation to the open season, allowed the stock to reach the green quadrant by the terminal year of the projection period. Closing the PS-FAD in quarter 2, 3, or 4 was also beneficial for the stock status, moving it to the yellow quadrant by the terminal year. Depending on the quarter, the closure of the gillnet and handline fisheries would also allow bordering the yellow area ($F<F_{MSY}$)

by 2030 if the closure was applied in seasons 1 and 2 (for handline) and 1-4 (for gillnet). Catch reductions in the projection period with respect to the average values of the last three years of the model period were always present for all the fisheries (Figure 8). These reductions were not larger than 55% per fleet for any closure scenario. The largest reductions were observed when closing any entire quarter (i.e., 3 months) and catch reallocation of 0%. For the PS FAD, gillnet and handline fisheries, the catch reductions could be reduced by 40% from current catch, under the assumption that there would not be catch re-allocation to the open season.

For fishery and area-specific closures, the positive impact on the stock status was always smaller than closure strategies applied to the entire Indian Ocean. As expected, the closure of the area 1 (area with the highest reported catches) generally produced the largest positive impact on the stock status, especially for the PS-FAD, gillnet, and handline fisheries (Table 4).

Bigeye

The impact plot showed that removing the PS-FAD and longline fisheries would produce the largest increase in spawning biomass (Figure 2). Regarding catches reported in the last year of the model period, the longline (fresh tuna), baitboat, and PS-FAD fisheries were the most important fisheries for this stock, with quarterly catches usually larger than 2,000 tons (Figure 5). The base scenario was feasible; therefore, we did not reduce the projected catch for any fishery.

The base scenario produced a stock status in the red quadrant by the terminal year, while the TAC scenario moved it to the yellow quadrant. As with yellowfin, the stock would be close to the MSY benchmark but the catch reduction to 80,583 tons would be short to recover the stock above SB_{msy} by 2030, although the stock would not be subject to overfishing.

Closing all the fisheries simultaneously for any quarter with a catch reallocation of 0% always led to the largest positive impact on the stock (Figure 9), resulting in a stock status in the green quadrant by the terminal year. This positive effect was larger when closing quarter 1, 3, or 4 compared to quarter 2. Increasing the percentage of catch reallocation and decreasing the number of closed months in a quarter reduced the positive effect on the stock status. A catch reallocation of 100% resulted in a stock status similar to the base scenario.

For fishery-specific closures in the entire Indian Ocean, the positive impact of closing only the PS FAD fishery was larger compared to the other fisheries. Closing the PS FAD fishery in quarter 1 or 3 resulted in the stock status in the green quadrant by the terminal year, and closing it in quarter 2, or 4 moved the stock status to the yellow quadrant, even considering a 50% reallocation in most cases. No other fleet-specific closure moved the stock status out of the red quadrant by the terminal year of the projection period. Projected annual catch reductions were always present, except when the catch reallocation was 100% (Figure 10). These reductions were not larger than 45% per fleet for any closure scenario. The largest reductions were observed when closing any entire quarter (i.e., 3 months) and catch reallocation of 0%. For the PS FAD fishery, the catch reductions were not larger than 30%.

For fishery and area-specific closures, the positive impact on the stock status was always smaller than closure strategies applied to the entire Indian Ocean. Unlike the yellowfin case, the importance of the closure of a specific area was less evident for bigeye. The closure of the PS-FAD fishery in area 4 (1N) resulted in the largest positive impacts on the stock status (Table 5).

Skipjack

The impact plot showed that removing the PS-FAD fishery would produce the largest increase in spawning biomass (Figure 3). Regarding the average catches reported in the last three years of the model period, the gillnet, line, PS-FAD, and 'others' fisheries were the most important fisheries for this stock, with annual catches larger than 70,000 tons (Figure 6). The base scenario was feasible, therefore, we did not reduce the projected catch for any fishery.

The base scenario produced a stock status in the red quadrant by the terminal year, while the TAC scenario moved it to the green quadrant. Therefore, the correct implementation of Resolution 16/02 would allow maintaining the stock as not overfished and not subject to overfishing by 2030.

Closing all the fisheries simultaneously for any quarter with a catch reallocation of 0% always led to the largest positive impact on the stock (Figure 11), resulting in a stock status in the green quadrant by the terminal year. This positive effect was larger when closing quarter 4 or 3 compared to quarter 1 or 2. Increasing the percentage of catch reallocation and decreasing the number of closed months in a quarter reduced the positive effect on the stock status. Closing quarter 1 and reallocating 100% of the catch worsened the projected stock status by the terminal year with respect to the base scenario.

For fishery-specific closures in the entire Indian Ocean, closing the PS FAD fishery in any quarter moved the stock status to the green quadrant by the terminal year. Depending on the quarter, the closure of the 'others' (Q4), line (Q3), and gillnet (Q3 and 4) fisheries also had a positive impact on the stock status, moving it to the green quadrant by the terminal year or by the MSY benchmark in all quarters. Projected annual catch reductions were always present, except when the catch reallocation was 100% (Figure 12). These reductions were not larger than 45% for any closure scenario. The largest reductions were observed when closing any entire quarter (i.e., 3 months) and catch reallocation of 0%. For the PS FAD, gillnet and handline fisheries, the catch reductions were not larger than 30%. For Others would reach 40%.

4. Discussion

In this study, we used the stock assessment platform (SS3) to illustrate the impacts of the different gears over tropical tuna stocks and to evaluate alternative closure strategies on the stock status by the terminal year of a 10-years projection period for yellowfin, bigeye, and skipjack tunas in the Indian Ocean. We found that the projections assuming a constant catch as the average from the last three years of the model period would lead to a stock status subject to overfishing and overfished (red quadrant of the Kobe plot) by the terminal year for the three tuna stocks if no closure or other measures to reduce catch are implemented (i.e., base scenario). Reducing the projected catch to the TAC recommendation moved the stock status of the three stocks out of the red quadrant, which means that they would be not subject to overfishing. However, bigeye and yellowfin would still be overfished, very close to SB_{msy}. Note that we have used projections using one scenario of the model ensembles used in the most recent stock assessments and therefore, these results should be interpreted with caution.

Closing any entire quarter to all fleets with catch reallocation of 0% always produced a stock status not subject to overfishing and not overfished (i.e., green quadrant) for the three stocks, producing the largest positive effects of all scenarios. When looking at fleet-specific closures in the entire Indian Ocean, closing only the PS-FAD fishery would produce the largest positive impact on the stocks, moving the stock status to the green quadrant (not being subject to overfishing and not overfished) by the terminal year in most cases. Closing other fisheries has also significant effects, particularly gillnet (YFT, SKJ), baitboat (BET), line (SKJ) and others (SKJ).

When projecting the stock and catches, we might have catches larger than the portion of the stock vulnerable to the fishery (i.e., vulnerable biomass, which considers the selectivity effect) as observed for the yellowfin and bigeye projections. This situation might be caused by 1) the assumed biology of the stock (e.g., recruitment variability, recruitment apportionment, movement rates) during the projection period is not realistic, 2) the projected catches are not feasible, or 3) both. In this study, we did not change the assumed biology during the projection period, but we recommend exploring this option in the future. Moreover, we assumed that the projected catches were not feasible for some fleets and areas, so we reduced them. We also noticed that this situation appeared in spatially explicit stock assessment models (e.g., yellowfin), where the total biomass is disaggregated by area and finding a low vulnerable biomass/high catch case is more likely. Another assumption we made is that the projected catch per fleet was an average from the last three years of the model period. The catch observed from a short period might be influenced by many factors (e.g., atypical biomass produced by unusual recruitments in previous years, uncommon fishing effort, socioeconomic circumstances), and we recommend also testing other catch projection assumptions.

Besides the fact that a complete closure for all fisheries produces the most positive impact on the stock status for the three tuna species, we found that, fleet specifically, one-quarter closures for the PS-FAD had the largest positive impact, assuming no catch reallocation. The stocks would also benefit from closures on handline, baitboat, gillnet and other gears. Restricting the catch of juveniles during a quarter produces a faster increase in the stock biomass during this period, potentially also increasing the spawning biomass, and therefore also increasing the recruitment in the subsequent quarters. The selection of which quarter to close is also relevant and the answer might not be the same for the three stocks. We recommend that the decision to select which quarter to close also considers socioeconomic factors ignored in this study.

We also analyzed different reallocation strategies for our closure scenarios. In summary, we found that a 100% reallocation did not differ from the base scenario (when no closure was implemented) for yellowfin and bigeye and worsened the stock status by 2030 for skipjack. This difference among stocks is partially caused by the model configurations. The SS3 model for yellowfin and bigeye has a quarterly time resolution, which calculates the spawning biomass and generates recruits every quarter using the stock-recruitment relationship. Conversely, the skipjack model has an annual time resolution with four seasons (i.e., quarters), which calculates the spawning biomass and generates recruits at the start of season 1 and then distributes those recruits among quarters with fixed proportions (25%, 30%, 24%, and 21% in season 1, 2, 3, and 4, respectively). We observed that closing quarter 1 with 100% reallocation produced lower spawning biomass, and therefore recruitment, at the start of the subsequent year, reducing the projected biomass in the long term with respect to the base scenario. While both configurations attempt to represent the same biological aspect (continuous spawning throughout the year), they can produce different responses to closure strategies as observed in this study.

For bigeye and yellowfin, we also analyzed area and fleet-specific closures since the SS3 model was spatially explicit. Our results suggest that, in some cases, implementing closures to specific areas and fleets might improve the status of the stock by the terminal year of the projection period. However, closing an area during any quarter might produce an increase in the effort and therefore catches in surrounding areas by a specific fleet, aspect that was not studied here and may need further exploration.

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Tables

Table 1. Fleet description for the Yellowfin SS3 model.

Fishery name	SS3 Fishery code	Fishery description	Area
Gillnet	GI1a	Gillnet	1
	GI4		4
Handline	HD1a	Handline	1
LL-DWater	LL1a	Longline (distant water)	1
	LL1b		1
	LL2		2
	LL3		3
	LL4		4
Others	OT1a	Other	1
	OT4		4
Baitboat	BB	Bait boat	1
PS-FSchool	FS1b	Purse seine, school sets	1
	FS2		2
	FS4		4
PS-FADs	LS1b	Purse seine, log/FAD sets	1
	LS2		2
	LS4		4
Troll	TR1b	Troll	1
	TR2		2
	TR4		4
LL-FrTuna	LF4	Longline (fresh tuna)	4

Table 2. Fleet description for the Bluefin SS3 model.

Fishery name	**SS3 Fishery code**	**Fishery description**	**Area**
LL-FrTuna	FL2	Longline (fresh tuna)	2
LL-DWater	LL1s	Longline (distant water)	1
	LL2		2
	LL3		3
	LL1n		4
PS-FSchool	PSFS1S	Purse seine, school sets	1
	PSFS2		2
	PSFS1N		4
Others	OT1	Others	4
	OT2		2
PS-FADs	PSLS1S	Purse seine, log/FAD sets	1
	PSLS2		2
	PSLS1N		4
Baitboat	BB1	Bait boat	1
Line	LINE2	Mixed gears (handline, gillnet/longline)	2

Table 3. Fleet description for the Skipjack SS3 model.

Fishery name	**SS3 Fishery code**	**Fishery description**	**Area**
Baitboat	PL	Bait boat	1
PS-FADs	PSLS	Purse seine, log/FAD sets	1
PS-FSchool	PSFS	Purse seine, school sets	1
Gillnet	GL	Gillnet	1
Handline	LI	Handline primarily	1
LL-DWater	LL	Longline (distant water)	1
Others	Other	Others	1

Table 4. Yellowfin tuna. Changes in SB_Y/SB_{msy} and F_Y/F_{msy} (with respect to the base scenario) produced by quarter, area, and fleet-specific closures. We only report the closure strategies with the three largest positive impacts per fleet.

Fishery closed	Area closed	Quarter closed	No. months closed	Catch reallocation	Change in SB_Y/SB_{msy}	Change in F_Y/F_{msy}
Gillnet	1	3	3	0%	0.2	-0.28
	1	4	3	0%	0.2	-0.28
	1	1	2	0%	0.18	-0.24
Handline	1	1	3	0%	0.22	-0.28
	1	2	3	0%	0.19	-0.25
	1	1	2	0%	0.15	-0.22
LL-DWater	1	1	3	0%	0.04	-0.07
	1	2	3	0%	0.03	-0.05
	1	1	2	0%	0.03	-0.05
Others	4	2	3	0%	0.07	-0.12
	4	1	3	0%	0.06	-0.12
	4	3	3	0%	0.05	-0.1
Baitboat	1	1	3	0%	0.12	-0.2
	1	4	3	0%	0.11	-0.2
	1	3	3	0%	0.08	-0.16
PS-FSchool	1	2	3	0%	0.08	-0.14
	1	2	2	0%	0.06	-0.1
	1	1	3	0%	0.05	-0.1
PS-FADs	1	1	3	0%	0.35	-0.46
	1	3	3	0%	0.34	-0.45
	1	4	3	0%	0.31	-0.42
Troll	1	3	3	0%	0.05	-0.1
	1	1	3	0%	0.04	-0.09
	1	4	2	0%	0.04	-0.08
LL-FrTuna	4	1	3	0%	0.07	-0.1

	4	3	3	0%	0.06	-0.08
	4	4	3	0%	0.05	-0.07

Table 5. Bigeye tuna. Changes in SB_Y/SB_{msy} and F_Y/F_{msy} (with respect to the base scenario) produced by quarter, area, and fleet-specific closures. We only report the closure strategies with the three largest positive impacts per fleet.

Fishery closed	Area closed	Quarter closed	No. months closed	Catch reallocation	Change in SB_Y/SB_{msy}	Change in F_Y/F_{msy}
LL-FrTuna	2	4	3	0%	0.03	-0.07
	2	1	3	0%	0.02	-0.06
	2	2	3	0%	0.02	-0.05
LL-DWater	1	4	3	0%	0.08	-0.16
	1	4	2	0%	0.05	-0.12
	1	1	3	0%	0.03	-0.09
PS-FSchool	4	1	3	0%	0.04	-0.18
	1	2	3	0%	0.03	-0.1
	4	1	2	0%	0.02	-0.14
Others	2	1	3	0%	0.04	-0.1
	2	1	2	0%	0.03	-0.07
	2	1	3	50%	0.02	-0.06
PS-FADs	4	1	3	0%	0.2	-0.57
	4	3	3	0%	0.18	-0.55
	4	4	3	0%	0.17	-0.55
Baitboat	1	4	3	0%	0.13	-0.41
	1	2	3	0%	0.09	-0.32
	1	4	2	0%	0.08	-0.31
Line	2	3	3	0%	0.04	-0.08
	2	1	3	0%	0.03	-0.07
	2	2	3	0%	0.03	-0.06

Figures

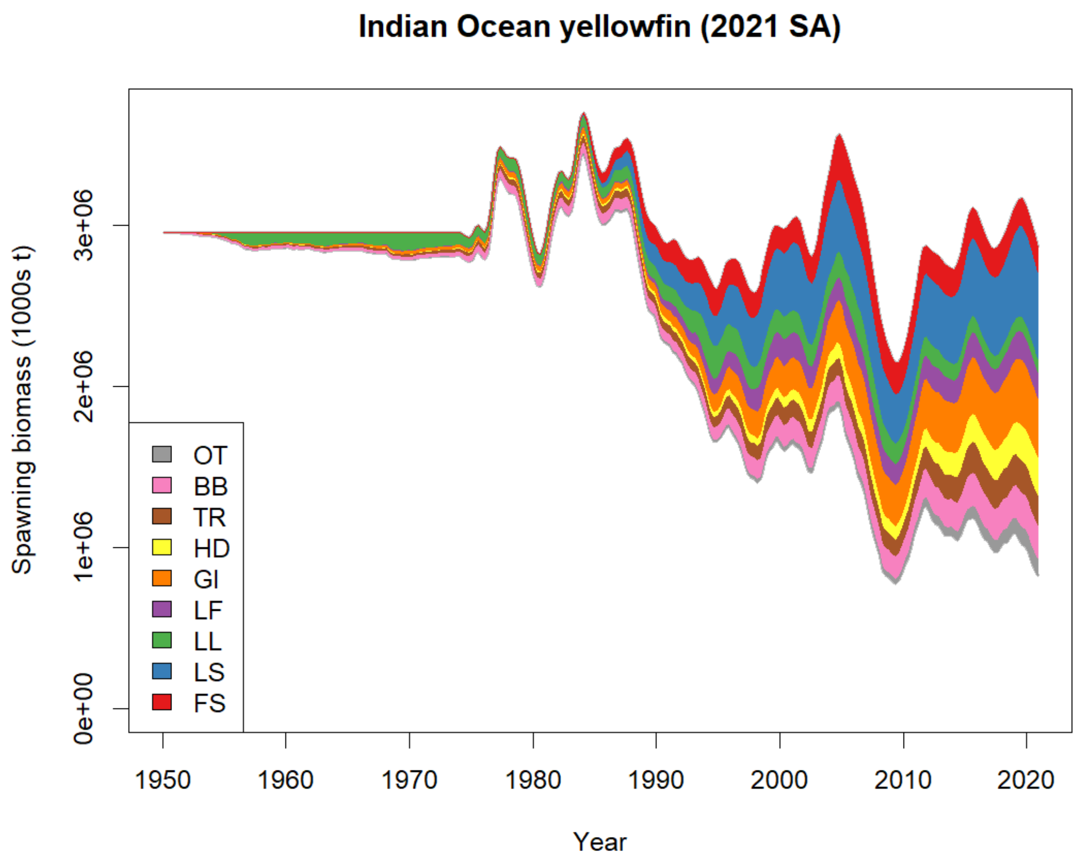

Figure 1. Impact plot for yellowfin. This plot shows the change in spawning biomass if a specific fleet is removed from the stock assessment model.

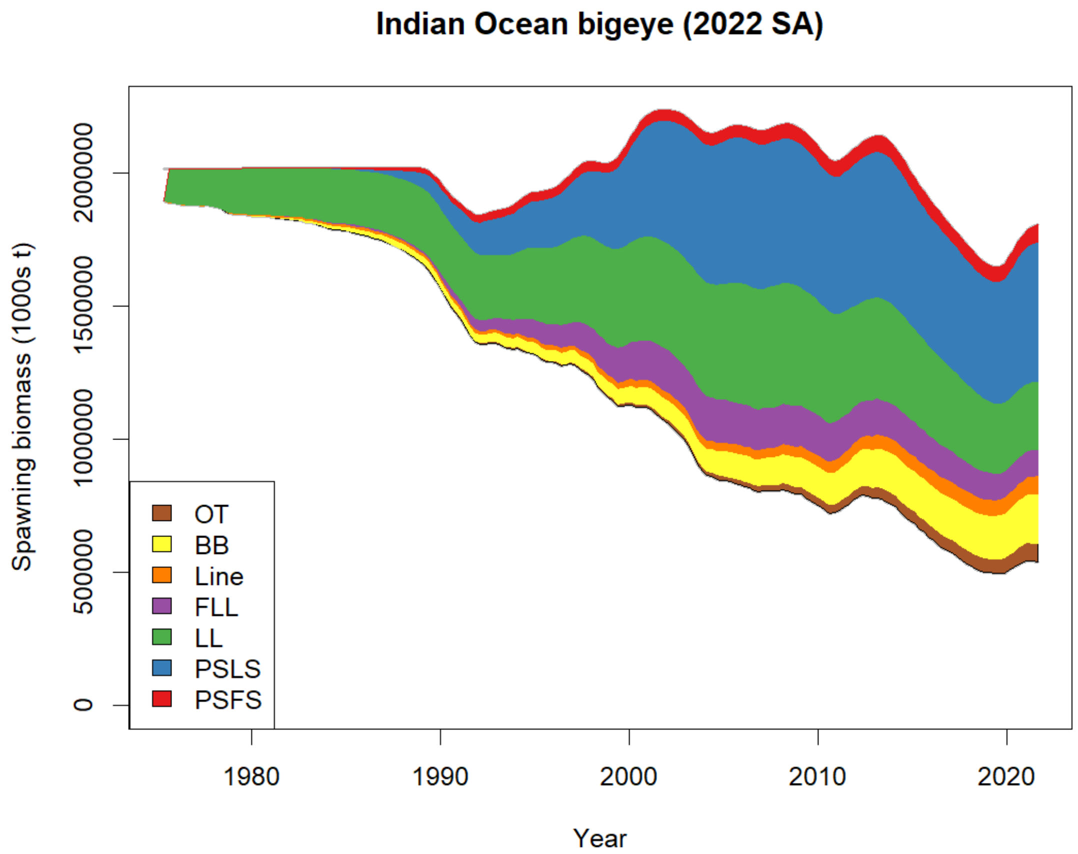

Figure 2. Impact plot for bigeye. This plot shows the change in spawning biomass if a specific fleet is removed from the stock assessment model.

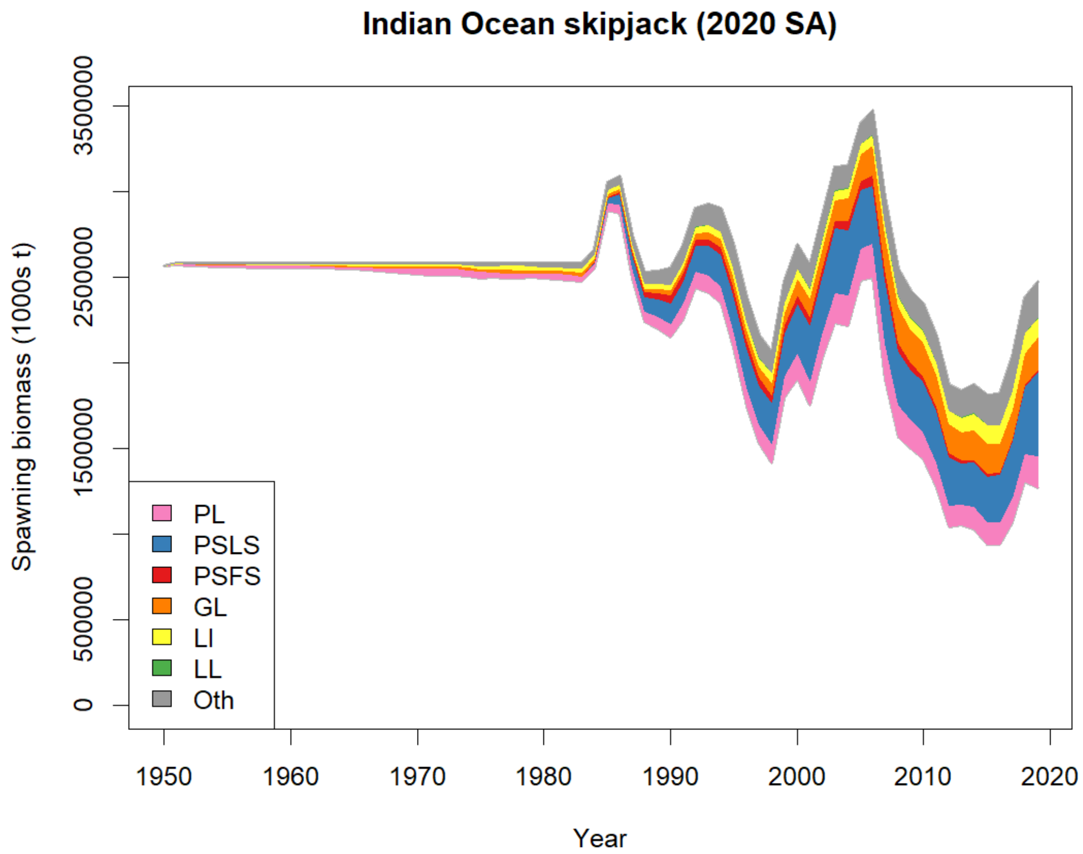

Figure 3. Impact plot for skipjack. This plot shows the change in spawning biomass if a specific fleet is removed from the stock assessment model.

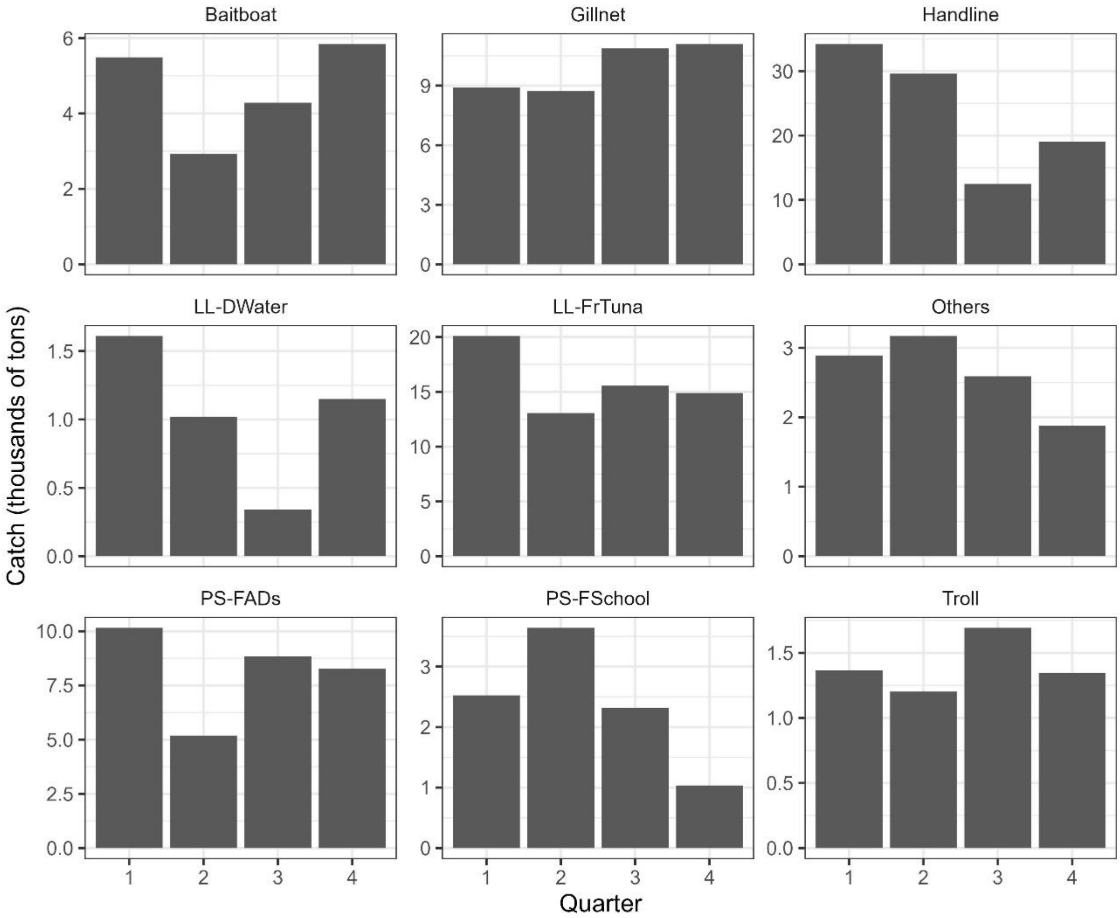

Figure 4. Yellowfin tuna. Observed catch per quarter and per fleet for the last three years of the model period (2018-2020). These catches were used for every year of the projection period.

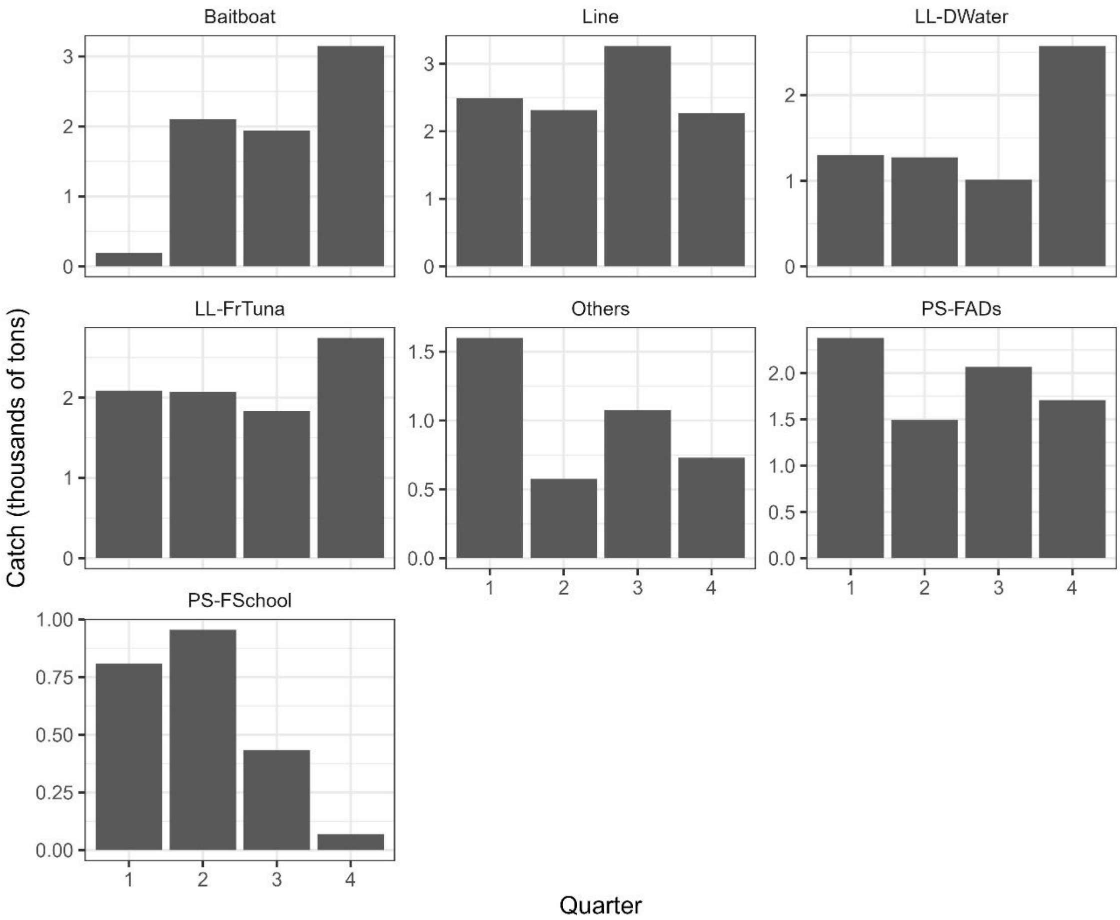

Figure 5. Bigeye tuna. Observed catch per quarter and per fleet for the last three years of the model period (2019-2021). These catches were used for every year of the projection period.

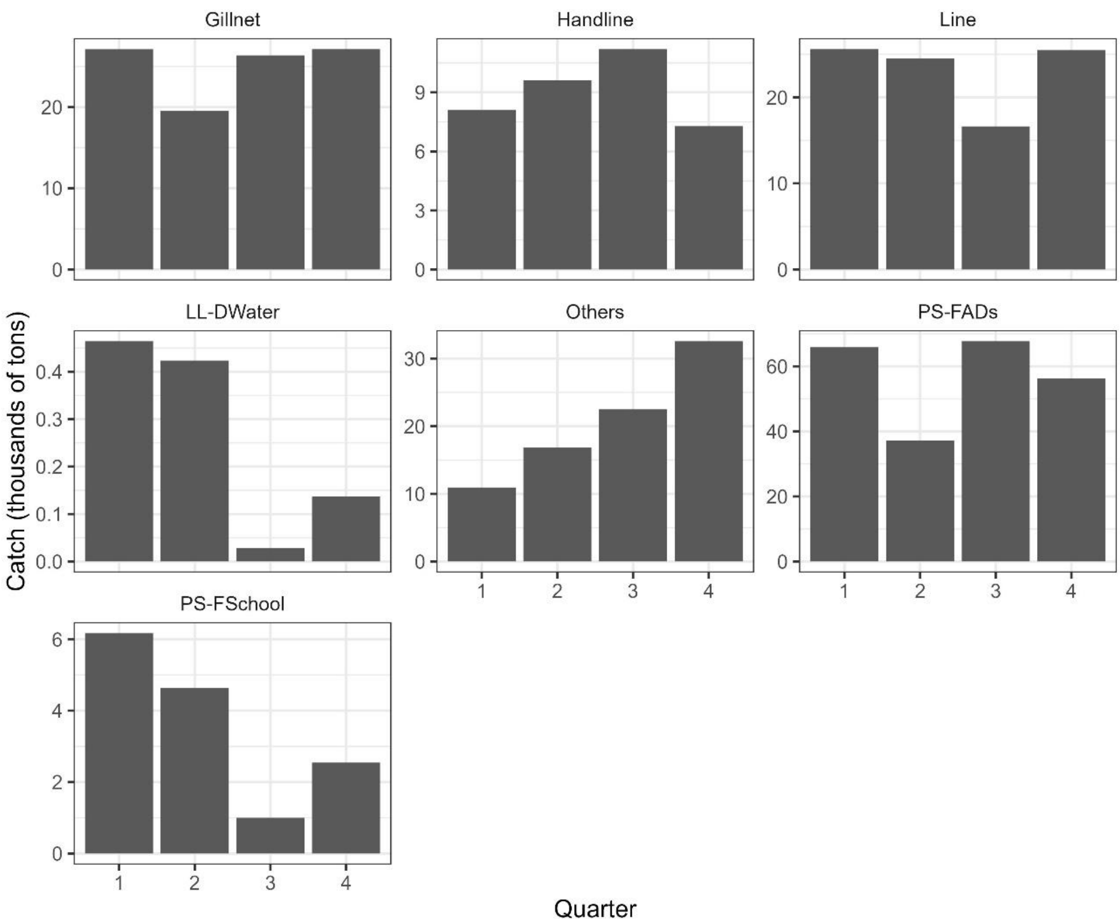

Figure 6. Skipjack. Observed catch per quarter and per fleet for the last three years of the model period (2017-2019). These catches were used for every year of the projection period.

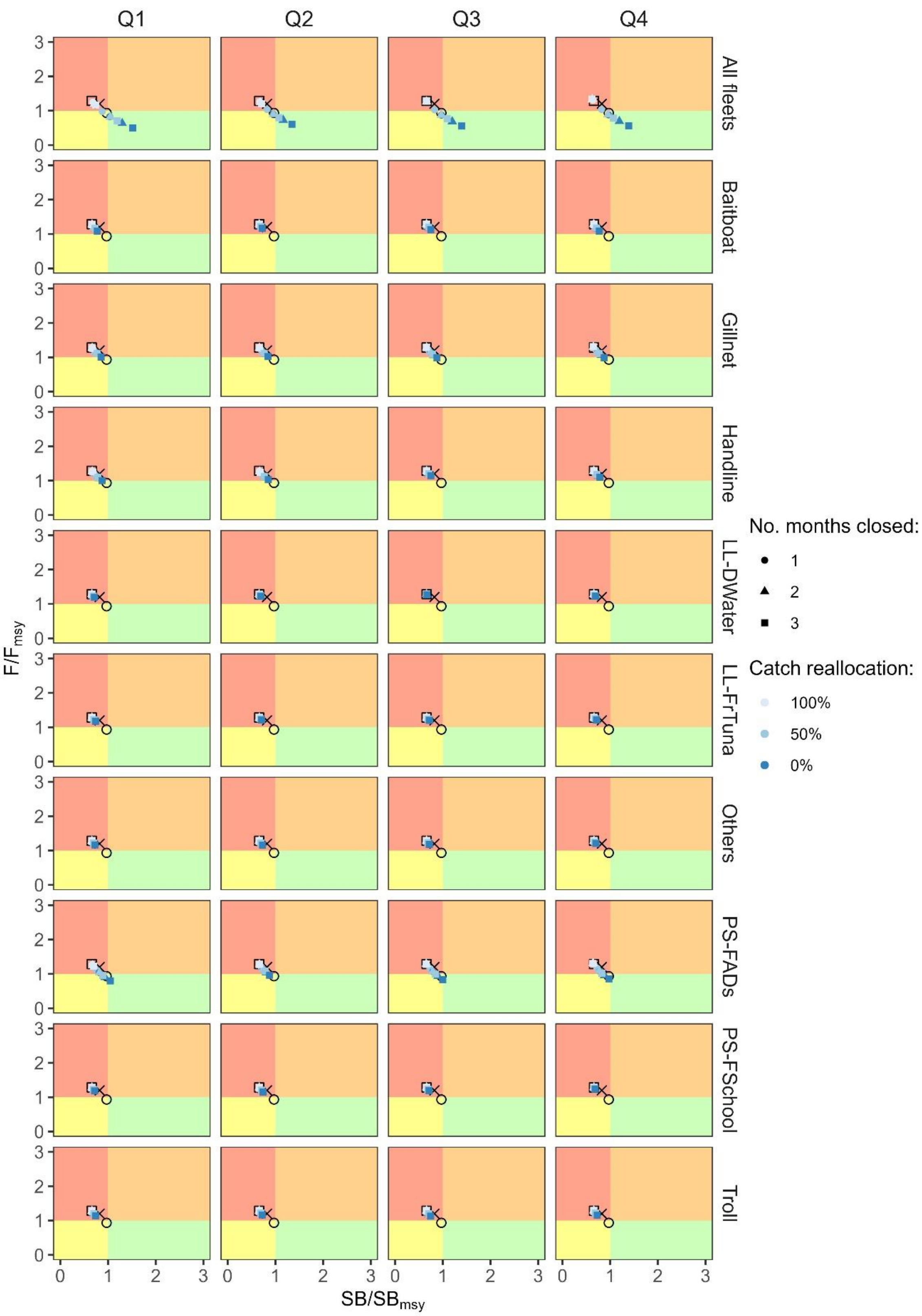

Figure 7. Yellowfin tuna. Effects of closure strategies on the stock status in the terminal year of the projection period. Columns indicate the quarter that is closed, and rows indicate the fishery that is closed. The 'X' indicates the stock status in the terminal year of the model period (i.e., at the start of the projections). The black open square and circle

indicate the stock status in the terminal year of the projection period for the base and TAC scenarios (all quarters open), respectively.

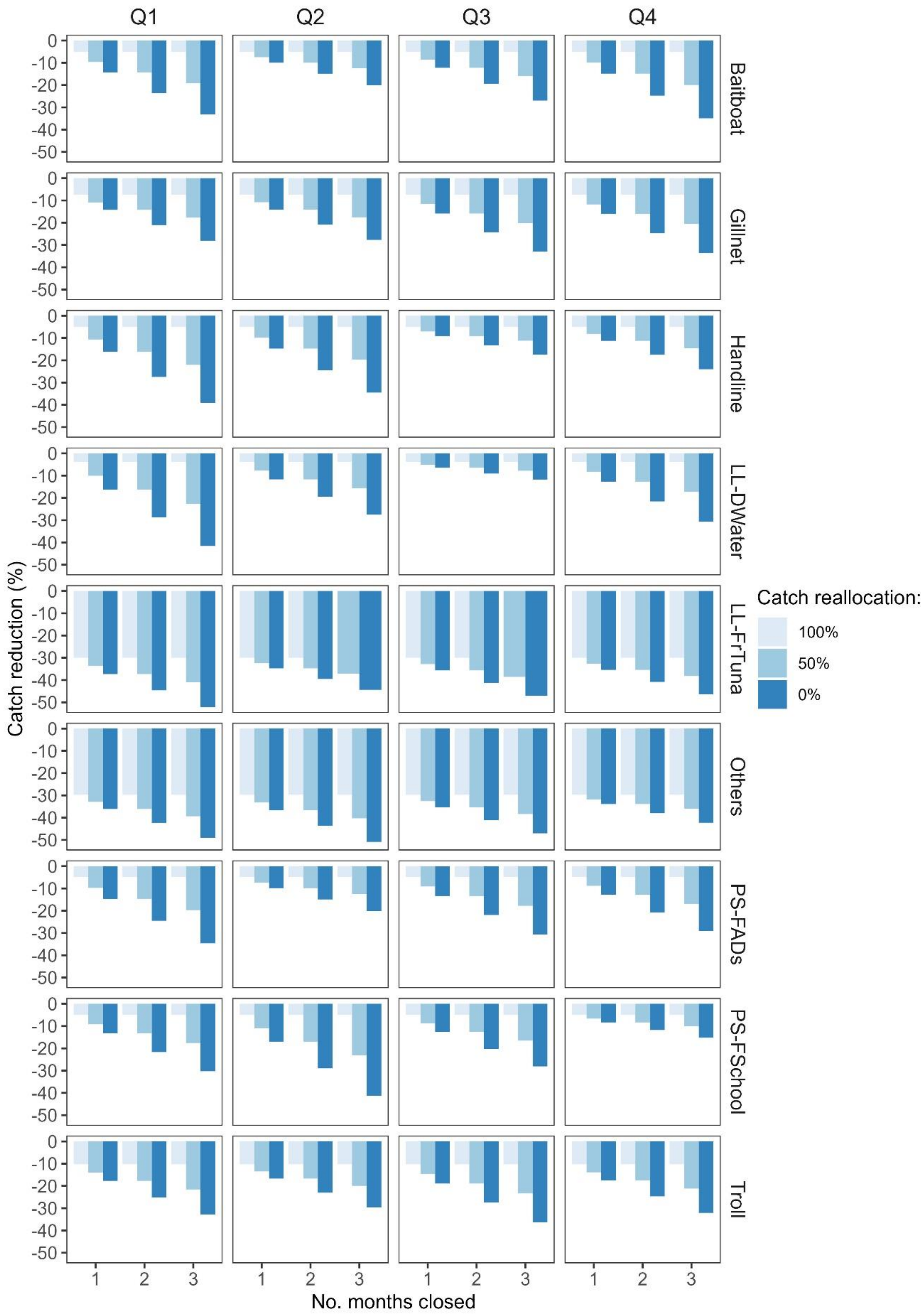

Figure 8. Yellowfin tuna. Annual catch reduction (%) by fleet (rows) for the projection period with respect to the average catch observed in the last three years of the model

period (2018-2020), already considering the catch reduction applied to some fisheries to obtain a feasible base scenario. Columns indicate the quarter that is closed.

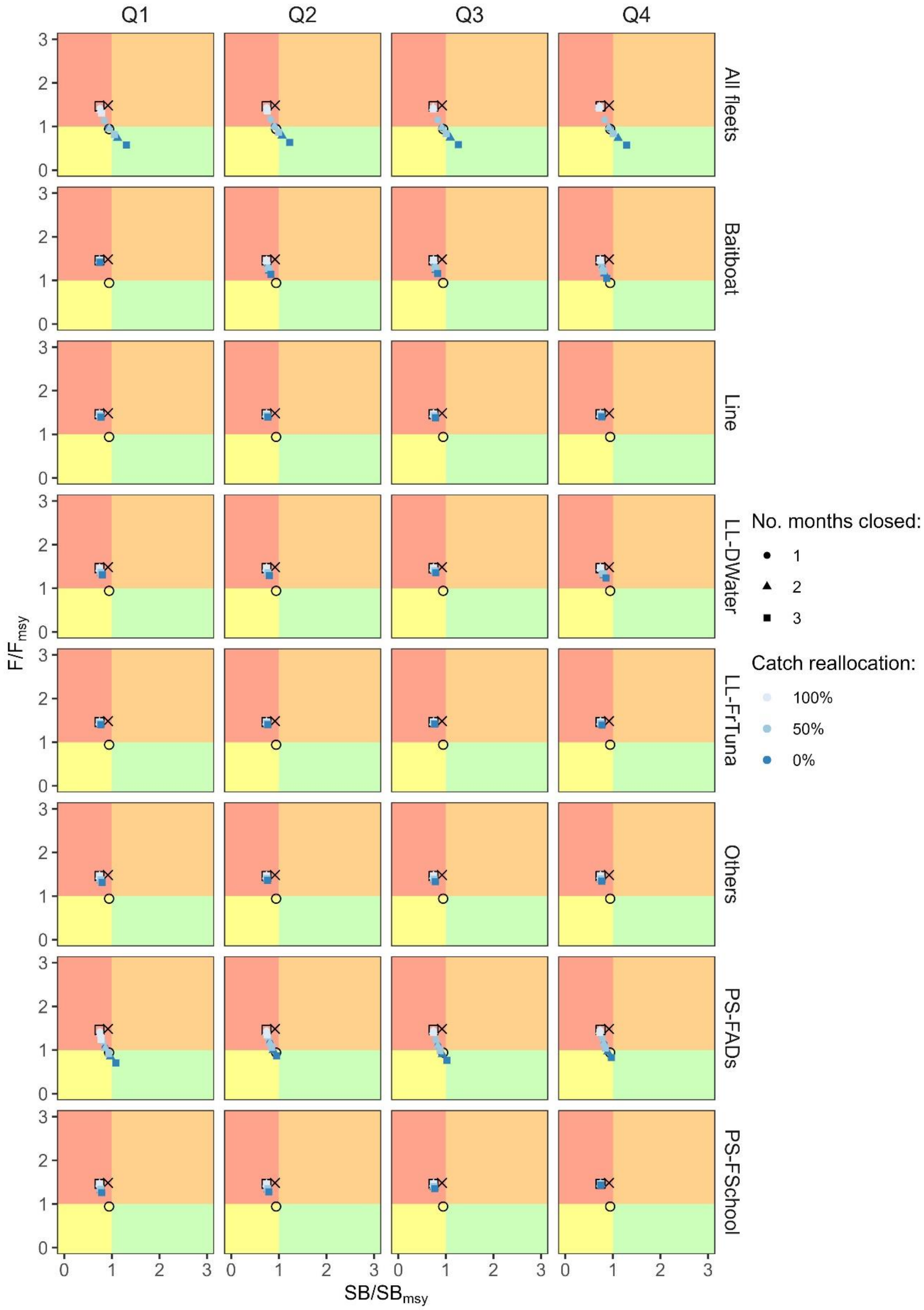

Figure 9. Bigeye tuna. Effects of closure strategies on the stock status in the terminal year of the projection period. Columns indicate the quarter that is closed, and rows indicate the fishery that is closed. The 'X' indicates the stock status in the terminal year of the model period (i.e., at the start of the projections). The black open square and

circle indicate the stock status in the terminal year of the projection period for the base and TAC scenarios (all quarters open), respectively.

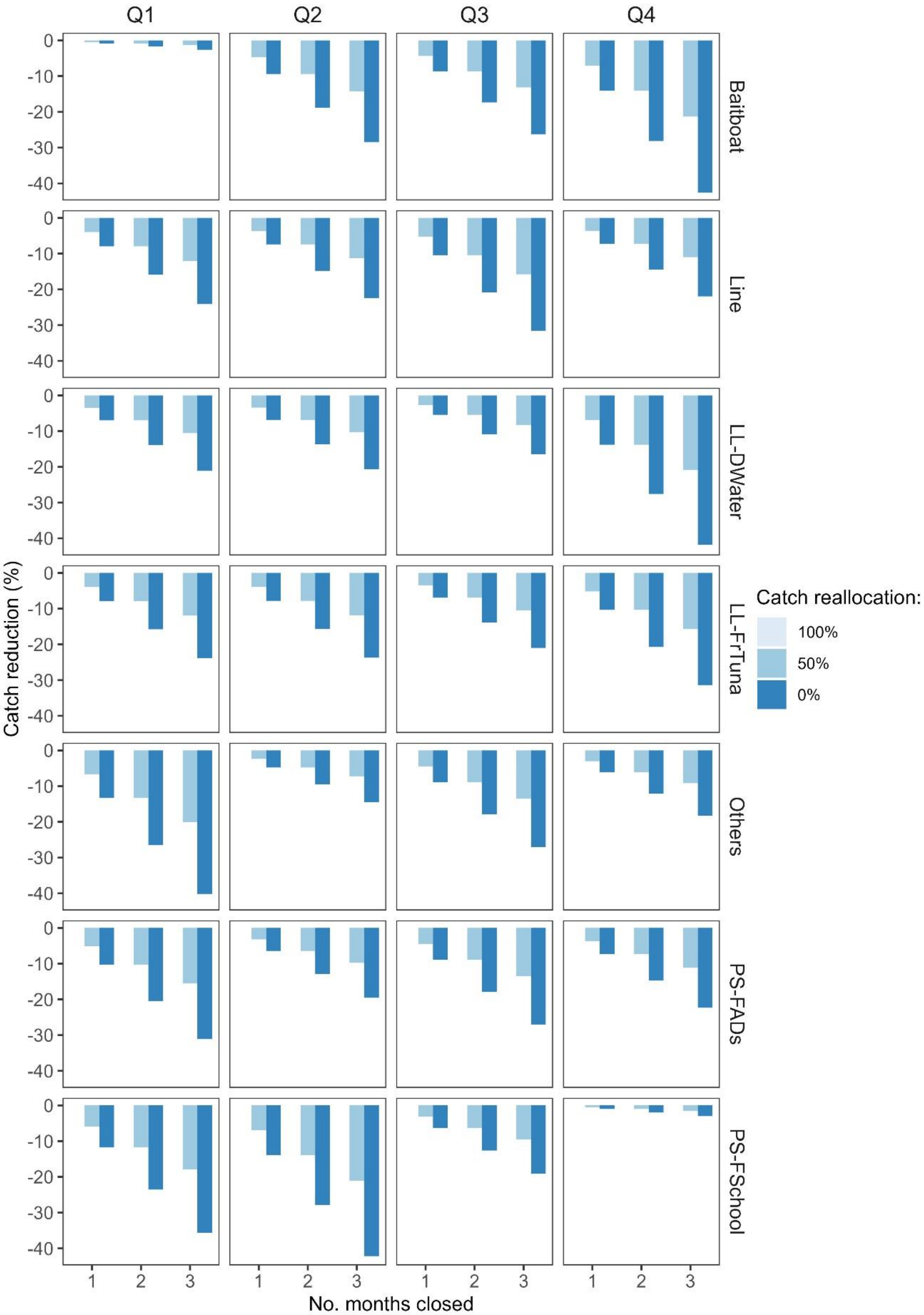

Figure 10. Bigeye tuna. Annual catch reduction (%) by fleet (rows) for the projection period with respect to the average catch observed in the last three years of the model period (2019-2021). Columns indicate the quarter that is closed.

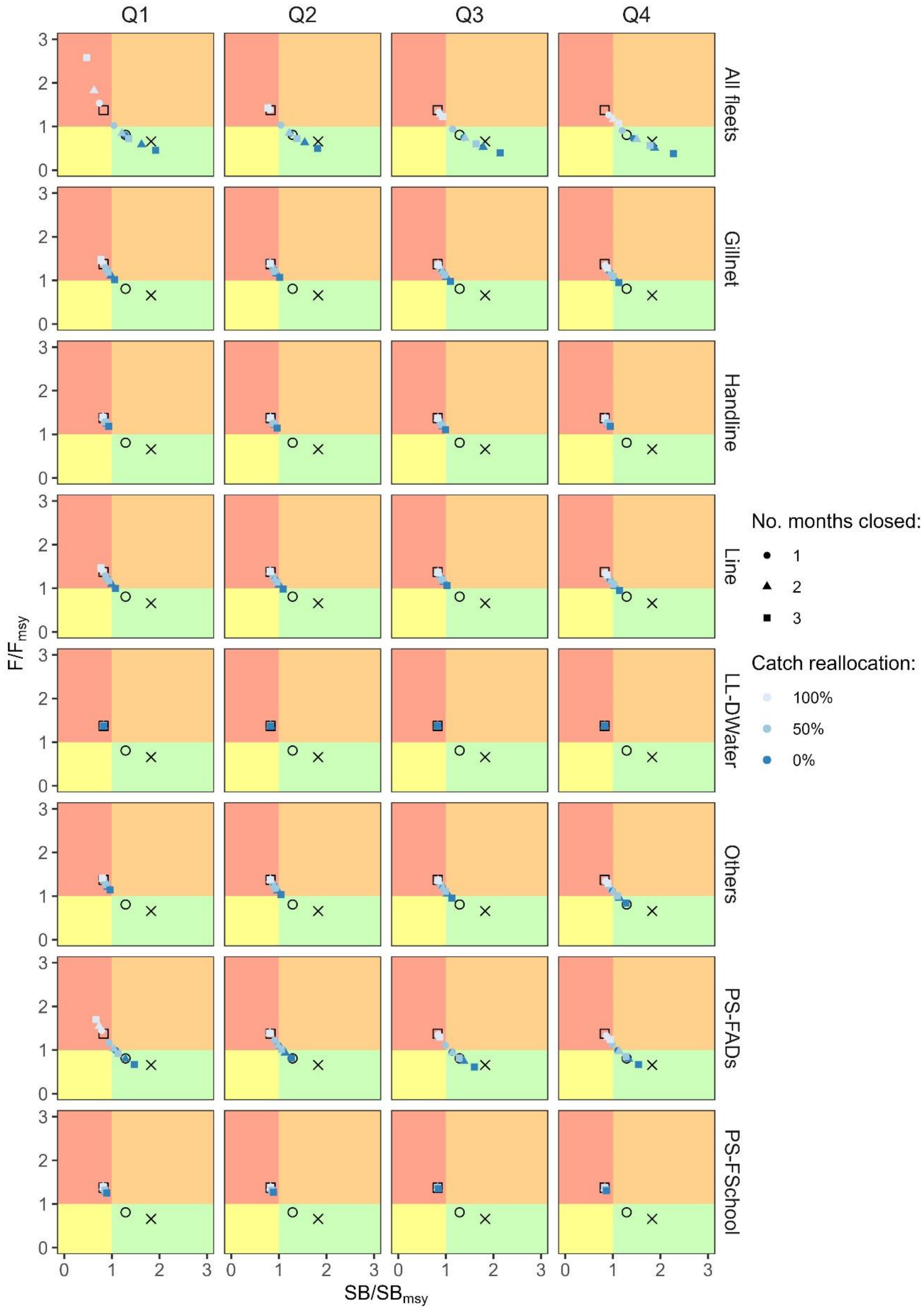

Figure 11. Skipjack. Effects of closure strategies on the stock status in the terminal year of the projection period. Columns indicate the quarter that is closed, and rows indicate the fishery that is closed. The 'X' indicates the stock status in the terminal year of the model period (i.e., at the start of the projections). The black open square and circle

indicate the stock status in the terminal year of the projection period for the base and TAC scenarios (all quarters open), respectively.

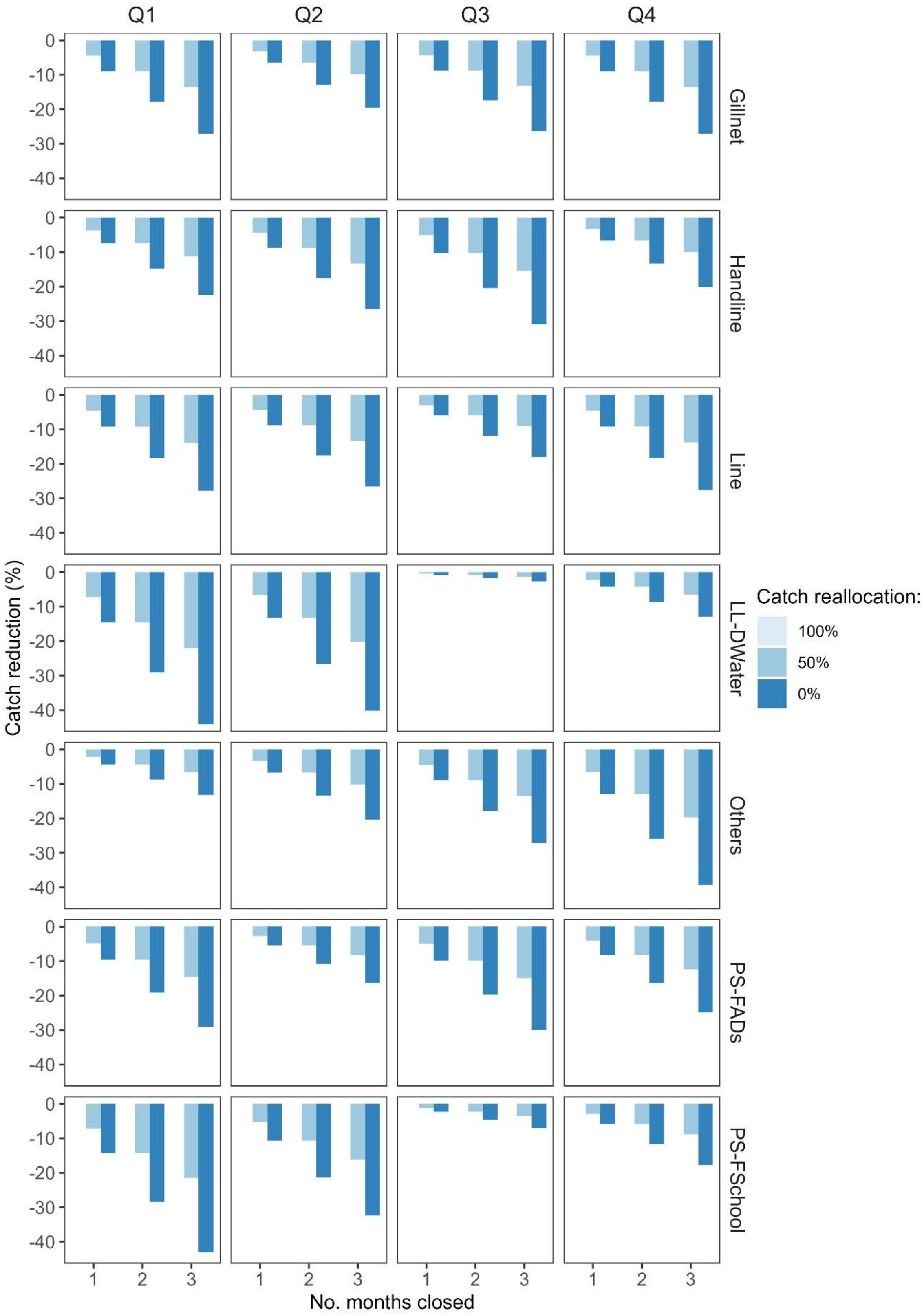

Figure 12. Skipjack. Annual catch reduction (%) by fleet (rows) for the projection period with respect to the catch observed in the last three years of the model period (2017-2019) for all closure strategies. Columns indicate the quarter that is closed.