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PREDICTED IMPACT OF POTENTIAL MANAGEMENT MEASURES ON STOCK STATUS AND CATCHES OF BIGEYE, SKIPJACK AND YELLOWFIN TUNAS IN THE WESTERN AND CENTRAL PACIFIC OCEAN

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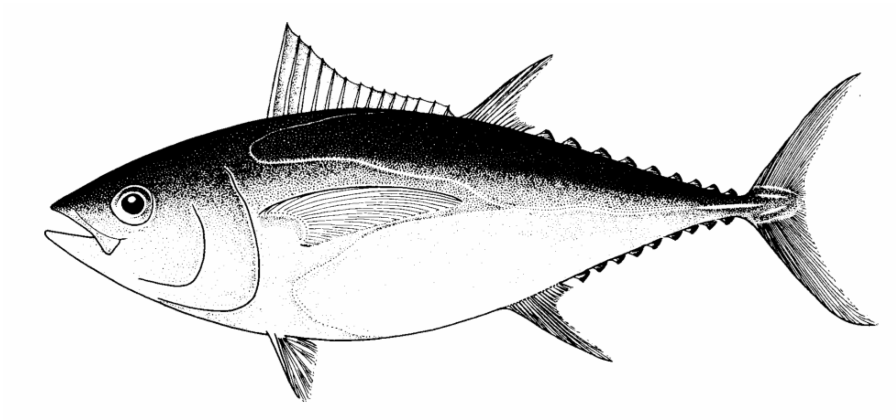
Predicted impact of potential management measures on stock status and catches of bigeye, skipjack and yellowfin tunas in the western and central Pacific Ocean



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Executive summary

At the request of the WCPFC Chair, a range of potential management measures were assessed using the most recent stock assessments for bigeye and skipjack (2008 assessments) and yellowfin tuna (2007 assessment) in the western and central Pacific Ocean. This paper firstly outlines the assumptions made in the process of implementing these potential measures into the MULTIFAN-CL stock assessment framework and, secondly, evaluates the predicted response of a range of key stock and fishery indicators to each of these measures.

Analyses were undertaken using the base case assessments for bigeye (WCPFC-SC4 SA-WP1) and yellowfin tuna (WCPFC-SC3 SA-WP1) and using the two-region *equatorial* assessment for skipjack tuna (WCPFC-SC4 SA-WP4). All data used and methodological approaches were the same as those reviewed at WCPFC-SC4.

The potential management measures that we were requested to evaluate were:

- A 12 month closure to purse seine fishing of the two high seas pockets[1];
- A three month ban during the third quarter on FAD sets within EEZs and on the high seas in the region between 20°N and 20°S (but excluding Indonesia and the Philippines and archipelagic waters);
- A staged reduction in longline catches of 30% over the period 2009-2011;
- A 30% reduction in effort from the Indonesian and Philippines (IND/PHI) fisheries; and
- Full retention of skipjack, bigeye, and yellowfin tuna catches by purse seine vessels.

To evaluate these potential measures it was also necessary to make some assumptions regarding how effort may be reallocated, e.g. what happens to high seas purse seine effort when the high seas pockets are closed and what might happen to purse seine effort during a three month ban on the use of FADs.

The main conclusions of the evaluation of potential options are as follows:

1. **Bigeye tuna** is currently experiencing overfishing and, if the current levels of fishing continue, the stock is predicted to decline to 35-45% below the MSY-related biomass reference points. The 30% longline reduction is the single measure that is predicted to provide the greatest reduction in fishing mortality, but it would be associated with a 7% reduction in MSY and a reduction in long term average catches. Measures directed at the surface fisheries could reduce fishing mortality to a lesser extent, but also result in increases in MSY and long term average catches from the stock.

   Even with a reduction in the order of 25-30% for all the main components of the fishery (including Indonesia and the Philippines), in the long term, the stock is still predicted to decline to a level slightly below that which would produce the MSY.

   While a transfer of fishing effort to unassociated sets during the three month ban on FAD sets would have little impact on bigeye tuna, an increased reliance on FADs throughout the year would result in increased overfishing and reductions in both MSY and long term average catches.

[1] These are: 1) the area of high seas bounded by the national waters of the Federated States of Micronesia, Indonesia, Palau and Papua New Guinea; and 2) the area of high seas bounded by the national waters of the Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Papua New Guinea, Solomon Islands and Tuvalu.

2. The 2007 assessment indicated that, although the point estimate for $F_{curr}/\tilde{F}_{MSY}$ is slightly below one, there was a 47% probability that **yellowfin tuna** is currently experiencing overfishing. Under current patterns of fishing mortality, total and adult biomass are predicted to remain slightly above the MSY-related levels. A reduction in effort by the IND/PHI fisheries would achieve the greatest reduction in fishing mortality of any of the measures considered, but would provide only modest increases in MSY and long term average catches.

   The implementation of all measures is predicted to reduce fishing mortality to well below the overfishing threshold ($F_{strat}/F_{MSY} \approx 0.7$) and result in biomass above the MSY-related levels. This would be associated with a 6% reduction in long term average catches.

   An increased reliance on FADs throughout the year would result in reductions in both MSY and long term average catches, but at a slightly lesser level than the reductions predicted for bigeye tuna. A transfer of fishing effort to unassociated sets during the three month ban on FAD sets would slightly increase the MSY and long term average catches.

3. The 2008 assessment indicated that overfishing is not occurring for **skipjack tuna** and neither is the stock in an overfished state. Therefore, the focus of the evaluations for skipjack was in terms of MSY and long term average catches.

   None of the measures, either individually or in combination are predicted to change MSY by more than 1.1%, but the three month ban on FAD sets is predicted to reduce long term average catches by 6.5%. All of the measures combined are predicted to result in a 16% reduction in long term average catches. This loss can be reduced to around 9% by transferring fishing effort to unassociated sets during the three month ban on FAD sets. There is little impact on any of the key indicators for skipjack of an increase in the proportion of total purse seine effort directed on FADs.

1 Introduction

At the request of the WCPFC Chair, a range of potential management options were assessed using the most recent stock assessments for bigeye and skipjack (2008 assessments) and yellowfin tuna (2007 assessment) in the western and central Pacific Ocean. This paper firstly outlines the assumptions made in the process of implementing these potential measures into the MULTIFAN-CL stock assessment framework and, secondly, evaluates the predicted response of a range of key stock and fishery indicators to each of these measures.

The underlying methodology used for the assessments is that commonly known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org), software that implements a size-based, age- and spatially-structured population model. Full details of these assessments are contained in WCPFC-SC working papers (WCPFC-SC4 SA-WP1, WCPFC-SC4 SA-WP4, and WCPFC-SC3 SA-WP1).

2 Data and model assumptions

2.1 Spatial stratification and fisheries

A six-region spatial stratification was adopted for the bigeye and yellowfin tuna assessments (Figure 1: top and middle panels) and the two regions critical to this evaluation are Regions 3 and 4 which span the breadth of the Convention Area between the latitudes of 10˚S and 20˚N. In the assessments of these two species, two purse seine fisheries are defined in each region, one for fishing on FADs and a second for fishing on unassociated schools.

For skipjack we have used the results from the equatorial model which considers only Regions 5 and 6 of the original six region skipjack assessment (Figure 1: bottom panel). In the assessment of skipjack, three purse seine fisheries are defined for modelling purposes for each region, one for fishing on logs, a second for FADs, and a third for fishing on unassociated schools. The log and FAD fisheries were treated the same for these analyses as logs are also considered FADs for the purpose of CMM2005-01.

2.2 Temporal stratification

The primary time period covered by the assessments were 1952–2006 (yellowfin tuna) and 1952-2007 (bigeye and skipjack tuna). Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

2.3 Catch and effort data

The stock assessments use catch and effort (days fished) for the purse seine fisheries in the key regions (see Section 2.1 above) each of the four fisheries. For the purpose of this evaluation it was necessary to further divide fishing effort into that occurring in the high seas pockets and within the archipelagic waters of Papua New Guinea and the Solomon Islands. Recent annual purse seine fishing effort (days) for FAD and unassociated sets (as used in the stock assessments) are provided in Table 1.

3 Potential Management Measures evaluated

3.1 Implementation of measures within MULTIFAN-CL

This section describes the potential management options that OFP-SPC was requested to consider and how they were implemented within the MULTIFAN-CL modelling framework. Briefly the measures considered were:

- A 12 month closure to purse seine fishing of the two high seas pockets[1];
- A three month ban during the third quarter on FAD sets within EEZs and on the high seas (but excluding Indonesia and the Philippines and archipelagic waters);
- A staged reduction in longline catches of 30% over the period 2009-2011;
- A 30% reduction in effort from the Indonesian and Philippines fisheries; and
- Full retention of skipjack, bigeye, and yellowfin tuna catches by purse seine vessels.

3.1.1 Closures to High Seas pockets

Average quarterly effort by set type was calculated for the period 2003-2006 for the two high seas pockets and this effort was subtracted from the relevant fisheries (e.g. Region 3 and 4 and FAD and unassociated effort for the bigeye and yellowfin assessments). The following assumptions were made:

- there would be no transfer of effort from the high seas pockets to EEZs or to other high seas areas (e.g. the eastern part of Region 4); and
- that within each region, biomass is uniformly distributed and catchability is constant (i.e. catchability and abundance of bigeye and yellowfin did not differ between EEZs and high seas pockets).

3.1.2 Three month ban on FAD use during the third quarter

Average purse seine effort in the third quarter by set type for areas outside archipelagic waters was calculated for the period 2003-2006. Three separate scenarios were modelled to investigate the potential impact of differing levels of effort transfer (0%, 50% and 100% transfers) to unassociated sets.

This measure was simulated by a reduction in FAD effort of around 25%, therefore if any of the assumptions listed below do not hold, the impact of the measure could be overestimated. These assumptions are that:

- there would be no transfer of the effort on FADs, during the third quarter, from EEZs and on the high seas to archipelagic waters;
- there would be no transfer of the effort on FADs during the third quarter to effort on FADs at other times of the year;
- the catchability of the species to FAD sets would not increase in the fourth quarter, e.g. if FADs were left in the water during part of the closure they might accumulate fish which could be caught shortly after the closure.

3.1.3 Longline catch reductions

As evaluation of the potential measures was through an equilibrium yield analysis rather than through projections (see Section 4 below), it was not possible to explicitly model a staged catch reduction (or in fact any catch reduction) so the potential measure was approximated via a 30% reduction in fishing mortality for the major longline fisheries.

Simulations undertaken at WCPFC-SC4 indicated that provided that the staged reduction was not too slow, the overall reduction in fishing mortality would be the same as that obtained through an immediate reduction.

3.1.4 Indonesia / Philippines reductions

Average quarterly effort for the within-zone fisheries were reduced by 30%. It is assumed that this effort is not transferred elsewhere.

3.1.5 Catch retention

This measure was not evaluated. While there are some observer-based estimates of discards of bigeye, yellowfin, and skipjack tuna, these have not been incorporated into the stock assessments. Until this is done, it is not possible evaluate how this measure could reduce overall fishing mortality within the stock assessment.

3.1.6 Transfer of fishing effort to FADs

In addition to the measures described above, we examined the impact of an increase from the current proportion of purse seine effort directed at sets on FADs (58%), to 75% and 100%.

3.2 Model scenarios

The potential measures were assessed individually and in combination. In total, 44 scenarios were considered for bigeye and yellowfin tuna and 34 for skipjack tuna (i.e. it was not necessary to evaluate for skipjack the measures that included longline) and these are outlined in Table 2.

4 Modelling approach

4.1 Yield analysis

There are two possible approaches for evaluating the impacts of the potential management options, these being standard yield analysis and stock projections. For this exercise we have used yield analysis. This is because the yield analysis is used to generate all the MSY-related reference points, and there are some differences in population dynamics assumptions between the two approaches that could potentially lead to different results. Furthermore, projections require strong assumptions to be made regarding future recruitment and can only really give a broad indication of the outcome of a particular management measure. The use of projections was discussed in detail at

WCPFC-SC4, but put aside in favour of the yield-based approach which was used to generate the results described in the Summary Report from that meeting.

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers, *fmult*, the natural mortality-at-age (M_a), the mean weight-at-age (w_a) and the SRR parameters α and β. All of these parameters, apart from *fmult*, which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to *fmult* can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as limit reference points. These ratios are also determined and their confidence intervals estimated using a profile likelihood technique, as noted above.

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In the bigeye assessment, we use the average over the period 2003–2006. The last year in which catch and effort data are available for all fisheries is 2007. We do not include 2007 and subsequent years in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis and the catch and effort data for this terminal year are usually incomplete (see Langley 2006a).

4.2 Reference points and indicators

In evaluating the various potential management measures, three types of indictors were considered relating to fishing mortality, biomass levels, and catches. These were then compared to the relevant MSY related reference points. Descriptions of the various reference points and indicators are provided in Table 3, but one term included there which could be new to many readers is F_{strat} which refers to the fishing mortality that is predicted to occur in the long term due to the new pattern of fishing resulting from (a) particular management measure(s).

5 Results

The main results are described in the text below and the main figures and tables. Full tables of the results for all model runs are provided in Attachment 1.

5.1.1 Fishing mortality levels

For bigeye tuna, the current levels of fishing mortality are estimated to be 44% higher than F_{MSY}. The individual measure predicted to achieve the greatest reduction in fishing mortality (and therefore overfishing) is the longline reduction, followed by the IND/PHI reductions, the three month ban on FAD sets, and the 12 month closure of the high seas pockets (Table 4 and Figure 2). If the IND/PHI restrictions are not included, it is not possible to reduce fishing mortality below a level 16% above F_{MSY}. Only when IND/PHI is included does fishing mortality get close to F_{MSY}.

For yellowfin tuna, the point estimate of F_{curr}/F_{MSY} is slightly less than 1, but there is still a 47% chance that overfishing is occurring. The individual measure with the greatest reduction in fishing mortality was the IND/PHI reductions, with the others all giving similar reductions (Table 5 and Figure 2). When all the measures are included, fishing mortality is predicted to be well below the overfishing threshold $\left(F_{strat}/F_{MSY} \approx 0.7\right)$.

5.1.2 Total and adult biomass

While the stock assessment for bigeye tuna indicates that current biomass levels are above the MSY-related reference points, under current fishing patterns it is predicted that total and adult biomass will decline to 67% and 54% of the MSY related levels respectively, indicating that in the long term that the stock is predicted to become overfished (Table 4, Figure 3, and Figure 4). For the measures considered individually, these increase slightly and it is only with all measures implemented together that it is predicted that the stock will approach MSY-levels in the long term (albeit still slightly below).

For yellowfin tuna it is predicted that total and adult biomass will remain slightly above the MSY levels under the status quo and will increase further above MSY levels under any of the management measures (Table 5, Figure 3, and Figure 4). When all measures are included, total and adult biomass increase to 32% and 42% above their respective MSY levels.

5.1.3 MSY and average catches

For bigeye tuna the longline reduction is predicted to reduce the MSY for the fishery by almost 7% as the fishery would be relatively more focused on fish of a size below that which would maximize the yield per recruit (Table 4 and Figure 5). Conversely, the combined purse seine measures are predicted to increase the MSY by 4.4%. For yellowfin and skipjack tuna, none of the measures are predicted to change MSY by more than 2.6% (Table 5, Table 6, and Figure 5).

As bigeye tuna is currently experiencing overfishing, long term average catches are predicted to increase under most scenarios where fishing mortality is reduced, particularly for those scenarios without a longline reduction component (Table 4 and Figure 6). A combined three month ban on FAD sets and a high seas pocket closure would increase long term average catches by 7%, but reducing longline effort would result in around a 3.7% reduction in long term average catches. Implementation of all measures is predicted to **increase** long term average catches by 5.9%.

For yellowfin tuna, small increases in long term average catches are predicted through the three month ban on FAD sets (0.6%) and the IND/PHI reductions (0.2%), but most other measures are predicted to reduce long term average catches (Table 5 and Figure 6). Implementation of all measures is predicted to **decrease** long term average catches by 6%.

For skipjack tuna, all measures (aside from the longline reduction) are predicted to result in a **decrease** in long term average catches ranging from 2.7% for the IND/PHI reductions to 16% with all the measures implemented together (Table 6 and Figure 6).

5.1.4 Sensitivity analysis: increasing FAD use

An increase in the proportion of the current purse seine effort on FADs (58%) to 100% would increase the level overfishing of bigeye tuna by 40%. This would, over time, result in biomasses at or below 50% of the MSY level (runs 1, 2, and 3 in Table 7 and Figure 7). Such a shift would also decrease the MSY and long term average catches by up to 11%. The reductions in MSY and long term average catches would be slightly less (up to 8%) for yellowfin tuna (runs 1, 2, and 3 in Table 8 and Figure 8), but there would be very little change for skipjack tuna (runs 1, 2, and 3 in Table 9 and Figure 9).

5.1.5 Sensitivity analysis: transfer of effort during the FAD closure

As only a small proportion of bigeye tuna is taken in unassociated sets, there is very little impact of a transfer of FAD effort to unassociated school sets during a three month ban on FAD sets (runs 4, 7, and 10 in Table 7 and Figure 10), but for yellowfin (runs 4, 7, and 10 in Table 8 and Figure 11) and skipjack tuna (runs 4, 7, and 10 in Table 9 and Figure 12) it would result in small increases in MSY and average catches. In particular for skipjack it could turn a 6.5% decrease in catch during the ban on FAD sets to a 0.5% increase.

6 Conclusions

The main conclusions of the evaluation for each species is provided below.

6.1.1 Bigeye tuna

Bigeye tuna is currently experiencing overfishing and, if the current levels of fishing continue, the stock is predicted to decline to 35-45% below the MSY-related biomass reference points. The 30% longline reduction is the single measure that is predicted to provide the greatest reduction in fishing mortality, but it would be associated with a 7% reduction in MSY and a reduction in long term average catches. Measures directed at the surface fisheries could reduce fishing mortality to a lesser extent, but also result in increases in MSY and long term average catches from the stock.

Even with a reduction in the order of 25-30% for all the main components of the fishery (including Indonesia and the Philippines), in the long term, the stock is still predicted to decline to a level slightly below that which would produce the MSY.

While a transfer of fishing effort to unassociated sets during the three month ban on FAD sets would have little impact on bigeye tuna, an increased reliance on FADs throughout the year would result in increased overfishing and reductions in both MSY and long term average catches.

6.1.2 Yellowfin tuna

The 2007 assessment indicated that, although the point estimate for $F_{curr}/\tilde{F}_{MSY}$ is slightly below one, there was a 47% probability that **yellowfin tuna** is currently experiencing overfishing. Under current patterns of fishing mortality, total and adult biomass are predicted to remain slightly above the MSY-related levels. A reduction in effort by the IND/PHI fisheries would achieve the greatest reduction in fishing mortality of any of the measures considered, but would provide only modest increases in MSY and long term average catches.

The implementation of all measures is predicted to reduce fishing mortality to well below the overfishing threshold ($F_{strat}/F_{MSY} \approx 0.7$) and result in biomass above the MSY-related levels. This would be associated with a 6% reduction in long term average catches.

An increased reliance on FADs throughout the year would result in reductions in both MSY and long term average catches, but at a slightly lesser level than the reductions predicted for bigeye tuna. A transfer of fishing effort to unassociated sets during the three month ban on FAD sets would slightly increase the MSY and long term average catches.

6.1.3 Skipjack tuna

The 2008 assessment indicated that overfishing is not occurring for **skipjack tuna** and neither is the stock in an overfished state. Therefore, the focus of the evaluations for skipjack was in terms of MSY and long term average catches.

None of the measures, either individually or in combination are predicted to change MSY by more than 1.1%, but the three month ban on FAD sets is predicted to reduce long term average catches by 6.5%. All of the measures combined are predicted to result in a 16% reduction in long term average catches. This loss can be reduced to around 9% by transferring fishing effort to unassociated sets during the three month ban on FAD sets. There is little impact on any of the key indicators for skipjack of an increase in the proportion of total purse seine effort directed on FADs.

7 Acknowledgements

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Table 1. Annual purse seine effort (days fished) for by set type for different areas within Regions 3 and 4 of the bigeye and yellowfin tuna assessments (see Figure 1).

Year	Associated					Unassociated				
	AP waters	EEZ	HS pockets	Other HS	TOTAL	AP waters	EEZ	HS pockets	Other HS	TOTAL
2003	3555	12474	3513	691	20233	0	14890	3533	194	18617
2004	2843	18790	5535	1257	28425	0	9398	2903	242	12544
2005	4600	13830	3525	1054	23009	0	16582	3158	429	20169
2006	3863	16263	2914	1013	24052	0	14325	1736	451	16512
Av 2003-06	3715	15339	3872	1004	23930	0	13799	2833	329	16960
2007	5145	11942	4197	404	21687	0	17359	2456	111	19925

Table 2. Full range of scenarios considered in the simulation study. "FAD% during open period" refers to the transfer of purse seine effort from unassociated sets to FAD sets during period of no FAD restriction (see Section 3.1.6); "Transfer to unass. during FAD closure" refers to the reallocation of purse seine effort on FADs to unassociated sets during the three month ban on FAD use during the third quarter (see Section 3.1.2).

Run	Measure	FAD % during open period	Transfer to unass. during FAD closure	Run	Measure	FAD % during open period	Transfer to unass. during FAD closure
1	Status quo	status quo	NA	25	30% longline effort reduction	NA	NA
2	Status quo	75%	NA	26	All PS & LL measures	status quo	0%
3	Status quo	100%	NA	27	All PS & LL measures	75%	0%
4	3 month FAD closure	status quo	0%	28		100%	0%
5		75%	0%	29		status quo	50%
6		100%	0%	30		75%	50%
7		status quo	50%	31		100%	50%
8		75%	50%	32		status quo	100%
9		100%	50%	33		75%	100%
10		status quo	100%	34		100%	100%
11		75%	100%	35	30% reduction in ID/PH	NA	NA
12		100%	100%	36	All PS, LL, PH/ID measures	status quo	0%
13	HS pockets closure	status quo	NA	37		75%	0%
14		75%	NA	38		100%	0%
15		100%	NA	39		status quo	50%
16	3 month FAD & HS pockets closure	status quo	0%	40		75%	50%
17		75%	0%	41		100%	50%
18		100%	0%	42		status quo	100%
19		status quo	50%	43		75%	100%
20		75%	50%	44		100%	100%
21		100%	50%				
22		status quo	100%				
23		75%	100%				
24		100%	100%				

Table 3. Description of quantities and associated symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2003–2006 from the stock assessment
F_{strat}	Average fishing mortality-at-age for a particular management strategy (e.g. set of measures)
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\left(\frac{F_{current}-F_{strat}}{F_{current}-1}\right)\times 100$	Percentage of the current overfishing reduced by a particular management strategy (for situations where $F_{current}/\tilde{F}_{MSY} > 1$)
$\tilde{Y}_{F_{strat}}$	Equilibrium yield at $F_{current}$ (the expected long term average annual catch under this pattern of fishing)
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY} (the maximum sustainable yield)
$\tilde{B}_{F_{strat}}$	Equilibrium total biomass at $F_{current}$ (expected long term total biomass level that results under this pattern of fishing)
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_{F_{strat}}$	Equilibrium adult biomass at $F_{current}$ (expected long term adult biomass level that results under this pattern of fishing)
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY

Table 4. Estimates of the management quantities for bigeye tuna for the main model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	Measure	$F_{strat}/\tilde{F}_{MSY}$	$\tilde{B}_{F_{strat}}/\tilde{B}_{MSY}$	$S\tilde{B}_{F_{strat}}/S\tilde{B}_{MSY}$	$\tilde{Y}_{F_{MSY}}$ (or MSY)	$\tilde{Y}_{F_{strat}}$	$\left(\frac{F_{current}-F_{strat}}{F_{current}-1}\right)\times 100$	% change MSY	% change $\tilde{Y}_{F_{strat}}$
1	Status quo	1.44	0.67	0.54	64600	60880	-	0	0
4	3 mo FAD closure	1.37	0.72	0.60	66400	63680	16.61	2.79	4.6
13	HS pockets closure	1.39	0.71	0.58	65880	62920	12.03	1.98	3.35
25	30% longline effort reduction	1.27	0.77	0.69	60120	58640	39.40	-6.93	-3.68
35	30% reduction in ID/PH	1.30	0.76	0.65	65960	64080	32.26	2.11	5.26
16	3 mo FAD & HS pockets closure	1.33	0.75	0.63	67440	65200	25.60	4.40	7.1
26	All PS & LL measures	1.16	0.86	0.80	62920	62360	63.77	-2.60	2.43
36	All PS, LL, PH/ID measures	1.02	0.98	0.97	64440	64440	95.97	-0.25	5.85

Table 5. Estimates of the management quantities for yellowfin tuna for the main model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	Measure	$F_{strat}/\tilde{F}_{MSY}$	$\tilde{B}_{F_{strat}}/\tilde{B}_{MSY}$	$S\tilde{B}_{F_{strat}}/S\tilde{B}_{MSY}$	$\tilde{Y}_{F_{MSY}}$ (or MSY)	$\tilde{Y}_{F_{strat}}$	$\left(\frac{F_{current}-F_{strat}}{F_{current}-1}\right)\times 100$	% change MSY	% change $\tilde{Y}_{F_{strat}}$
1	Status quo	0.96	1.04	1.05	399440	399000			
4	3 mo FAD closure	0.92	1.08	1.1	402800	401200		0.84	0.55
13	HS pockets closure	0.91	1.09	1.12	399320	396800		-0.03	-0.55
25	30% longline effort reduction	0.92	1.08	1.1	391440	389520		-2	-2.38
35	30% reduction in ID/PH	0.82	1.18	1.24	410000	399920		2.64	0.23
16	3 mo FAD & HS pockets closure	0.88	1.12	1.16	402000	397480		0.64	-0.38
26	All PS & LL measures	0.83	1.17	1.21	393280	385280		-1.54	-3.44
36	All PS, LL, PH/ID measures	0.69	1.32	1.42	404400	374880		1.24	-6.05

Table 6. Estimates of the management quantities for skipjack tuna for the main model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	**Measure**	**% change** MSY	**% change** $\tilde{Y}_{F_{strat}}$
1	Status quo		
4	3 mo FAD closure	-0.34	-6.45
13	HS pockets closure	-0.41	-7.08
25	30% longline effort reduction	0	0
35	30% reduction in ID/PH	0.84	-2.73
16	3 mo FAD & HS pockets closure	-0.75	-12.86
26	All PS & LL measures	-0.75	-12.86
36	All PS, LL, PH/ID measures	0.22	-16.35

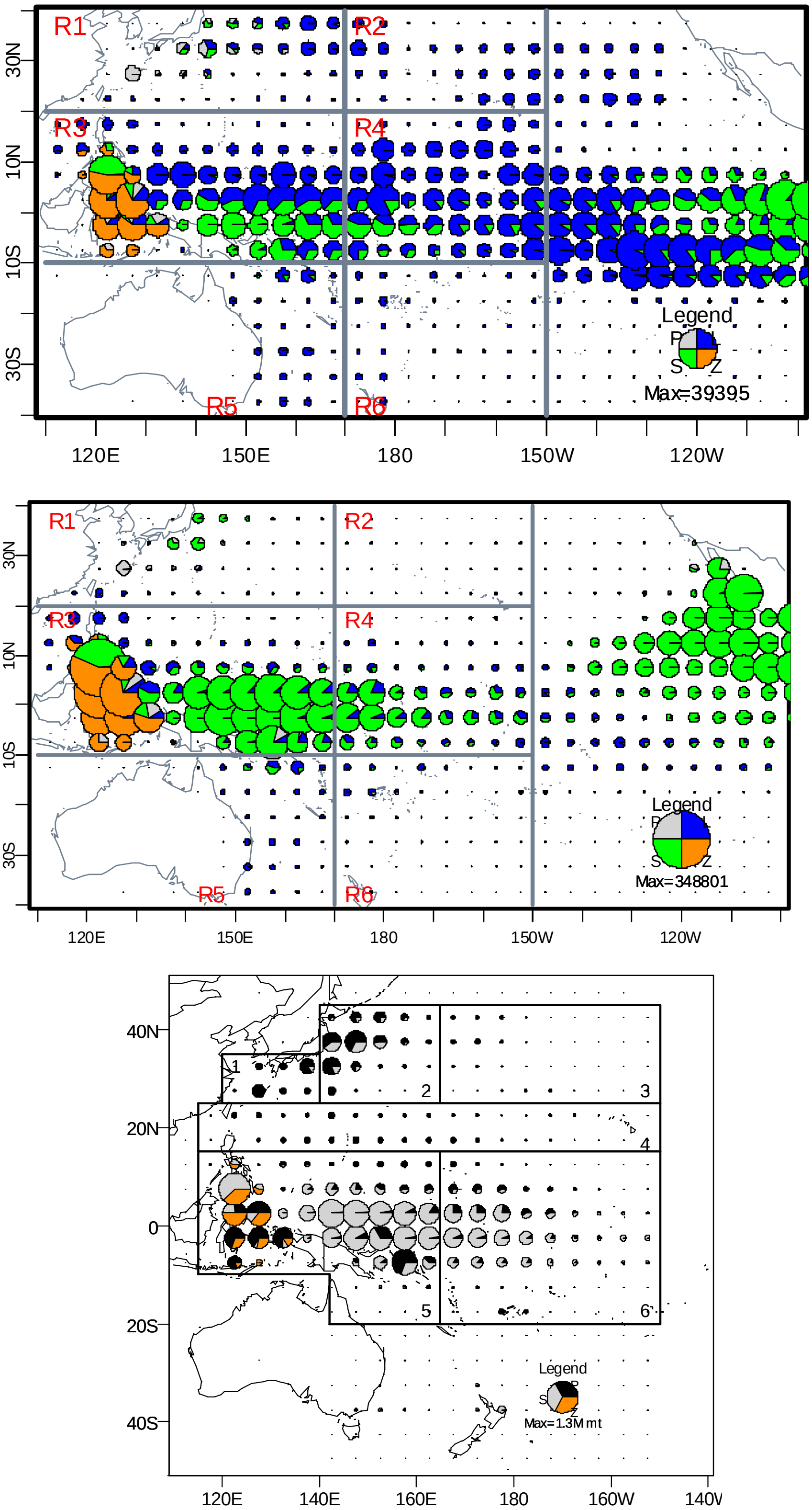

Figure 1. Distribution of catches and regional stratification for the bigeye (top), yellowfin (middle) and skipjack tuna (bottom) assessments. Regions considered for the purse seine measures were 3 and 4 for bigeye and yellowfin tuna and 5 and 6 for skipjack tuna.

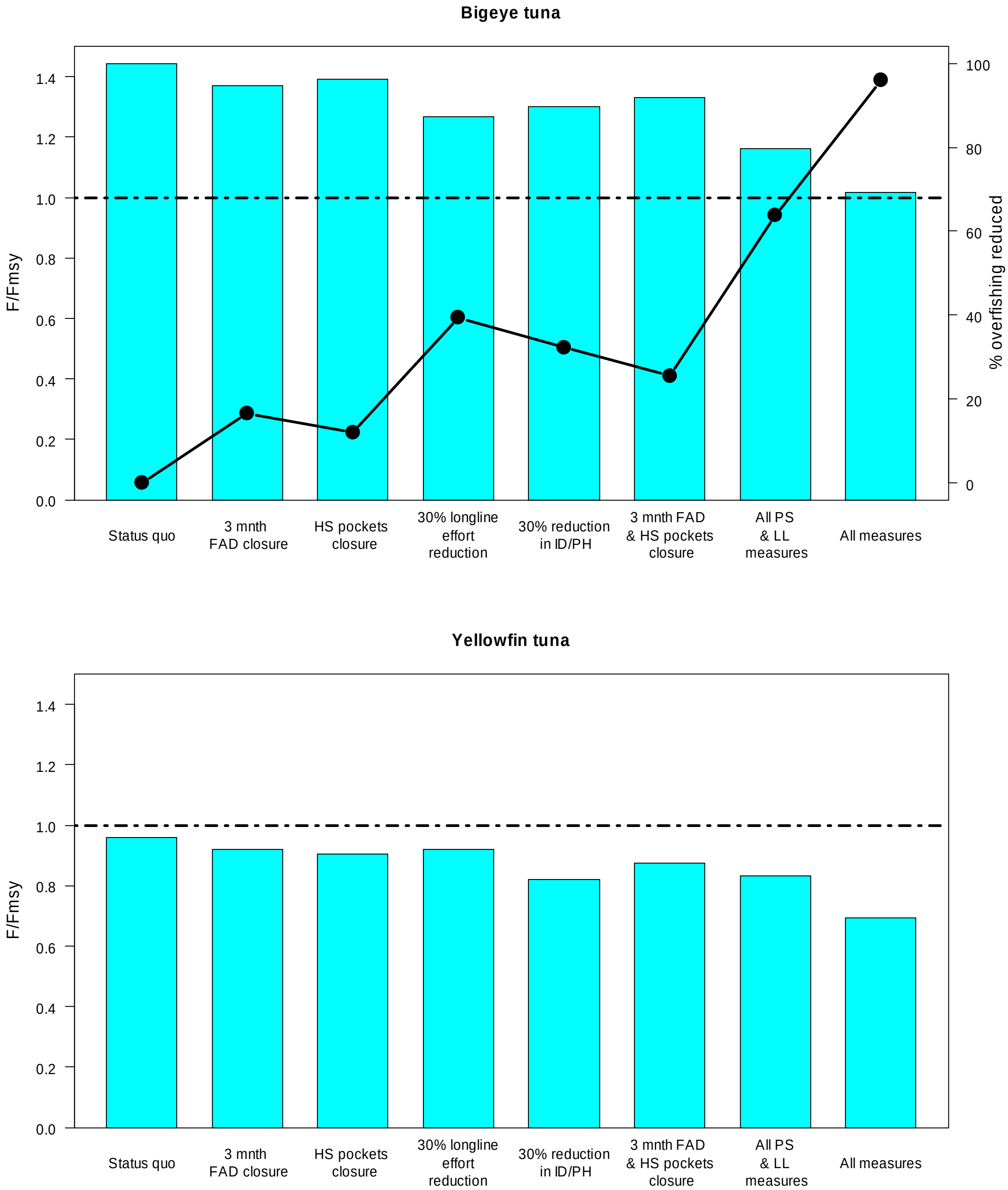

Figure 2. Estimated ratio of F/Fmsy for the various potential management measures separately and in combination for bigeye tuna (top) and yellowfin tuna (bottom). Bars **that cross** the horizontal line indicate that overfishing is still estimated to occur in that scenario. For bigeye tuna the secondary x-axis indicates the proportion of overfishing estimated for the status quo which is removed for each set of management measures.

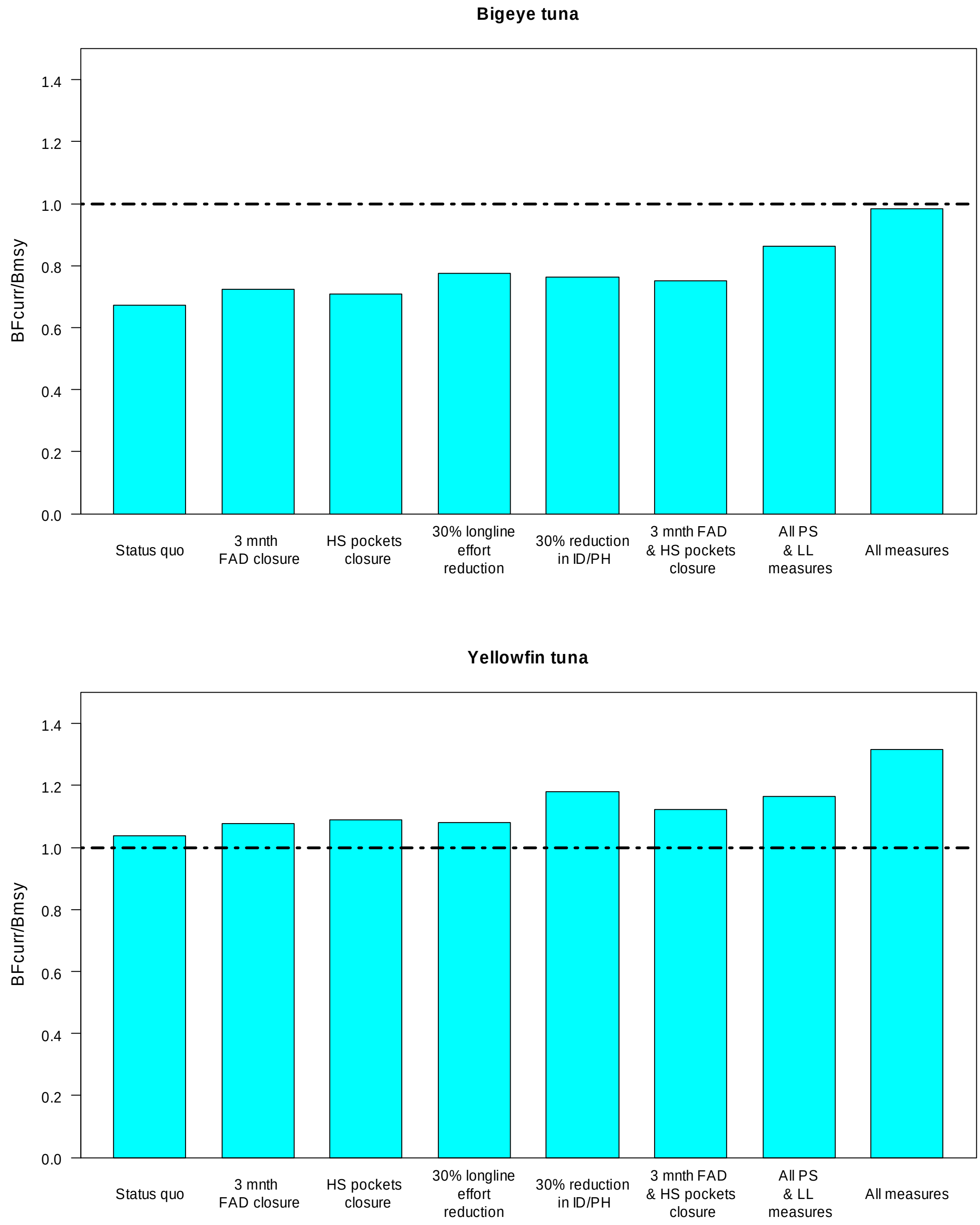

Figure 3. Estimated level of total biomass compared to $\widetilde{B}_{MSY}$ that is predicted to result on average as a result of each set of potential management measures for bigeye tuna (top) and yellowfin tuna (bottom). Bars that **do not** cross the horizontal line at one indicate that the stock is predicted to be in an overfished state.

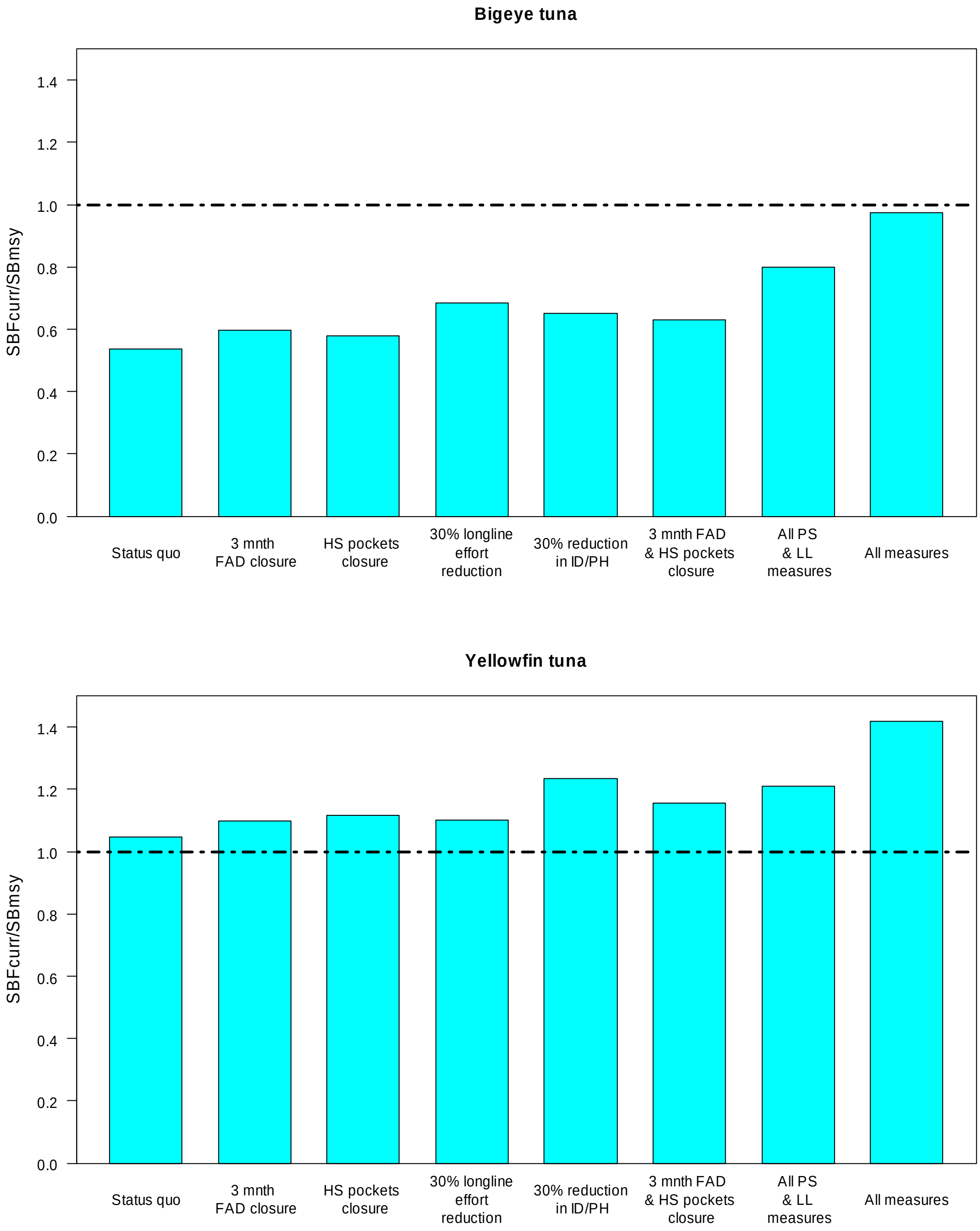

Figure 4. Average estimated level of spawning biomass compared to $\widetilde{SB}_{MSY}$ that is predicted as result of each set of potential management measures for bigeye tuna (top) and yellowfin tuna (bottom). Bars that **do not** cross the horizontal line at one indicate that the stock is predicted to be in an overfished state.

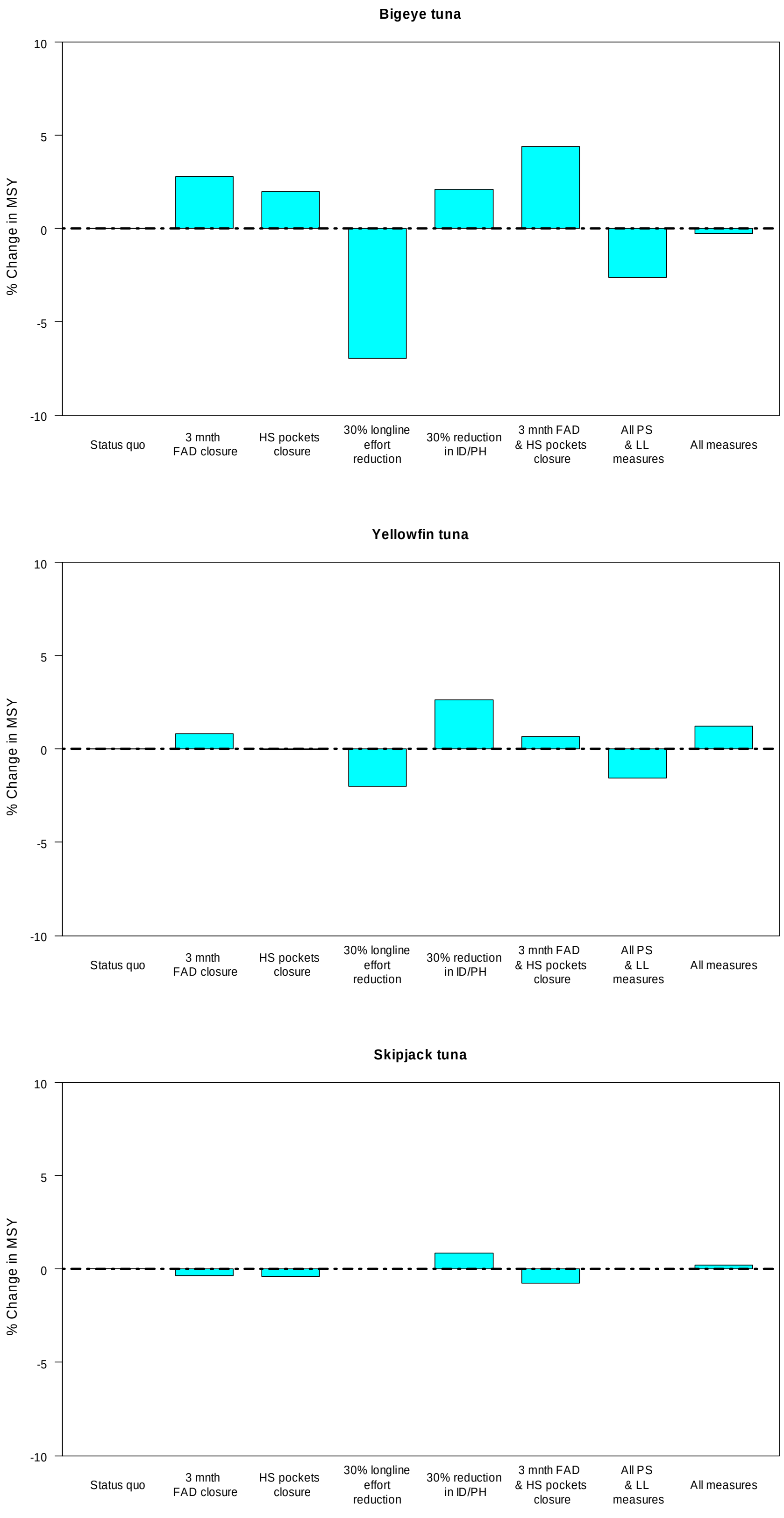

Figure 5. Estimated percentage change in MSY from the Status quo predicted as result of each set of potential management measures for bigeye (top), yellowfin (middle) and skipjack tunas (bottom).

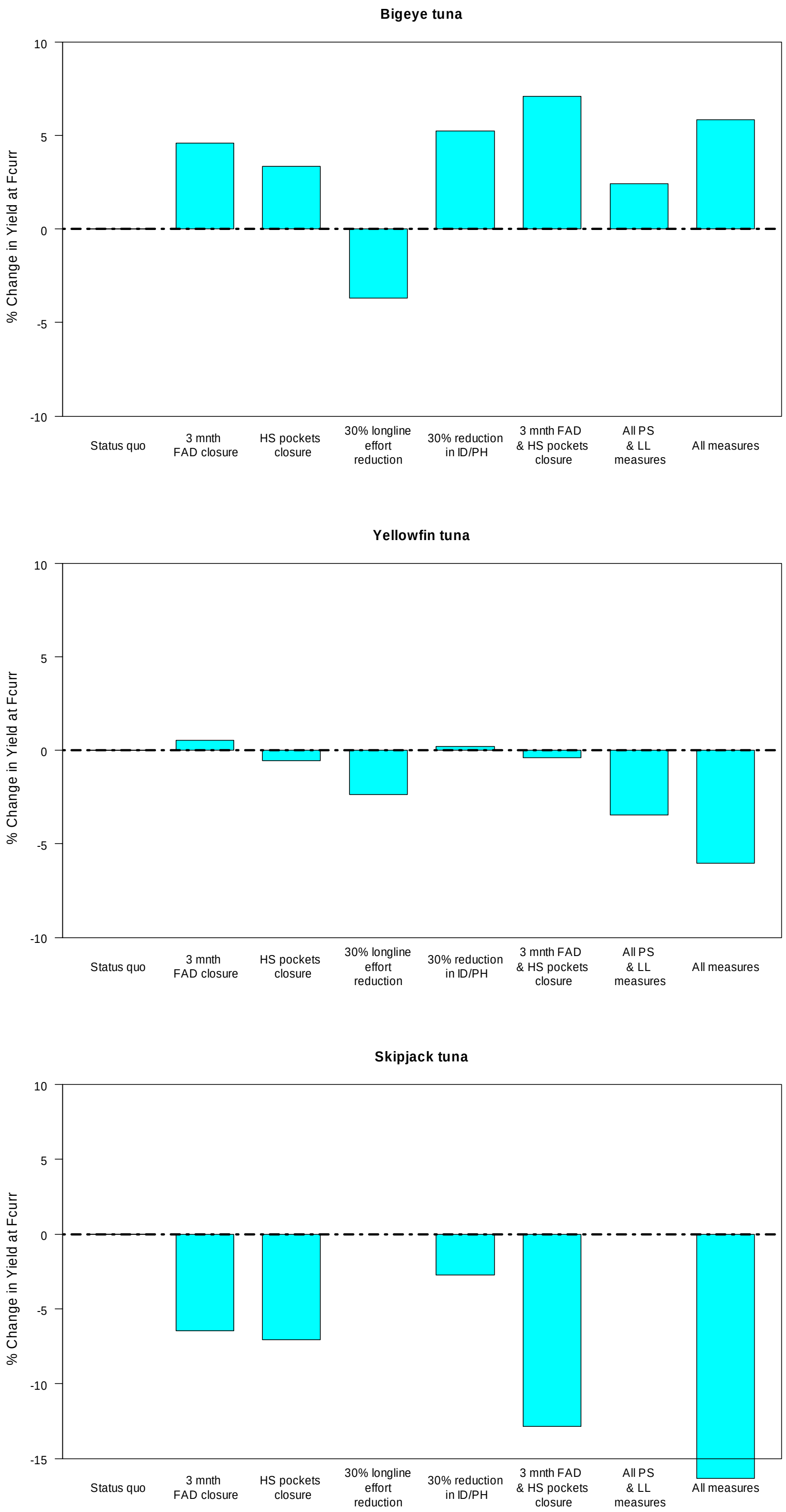

Figure 6. Estimated percentage change in long term average catch from the Status quo predicted as result of each set of potential management measures for bigeye (top), yellowfin (middle) and skipjack tunas (bottom).

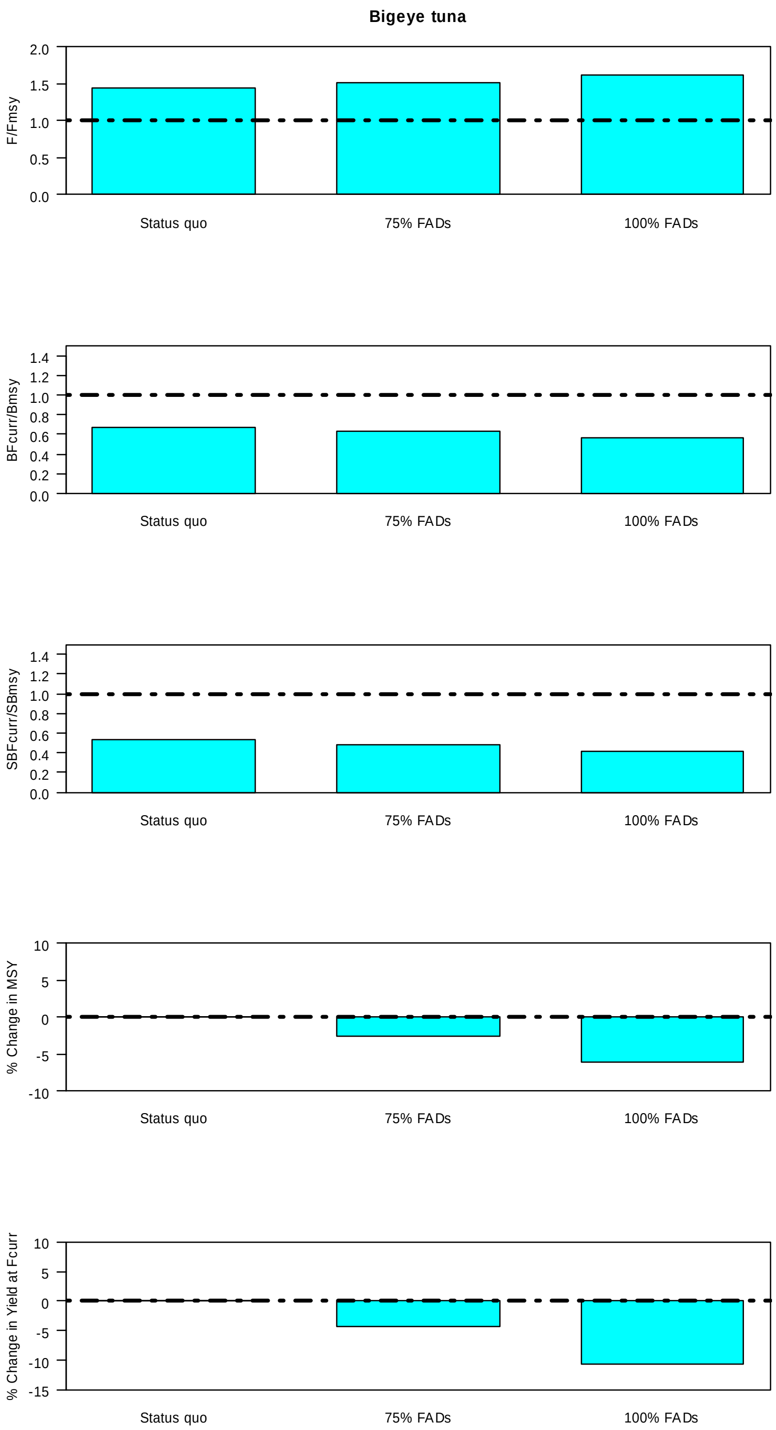

Figure 7. Sensitivity of the key performance indicators for bigeye tuna to an increase in the use of FADs. See captions for Figures 2-6 for more details of each plot.

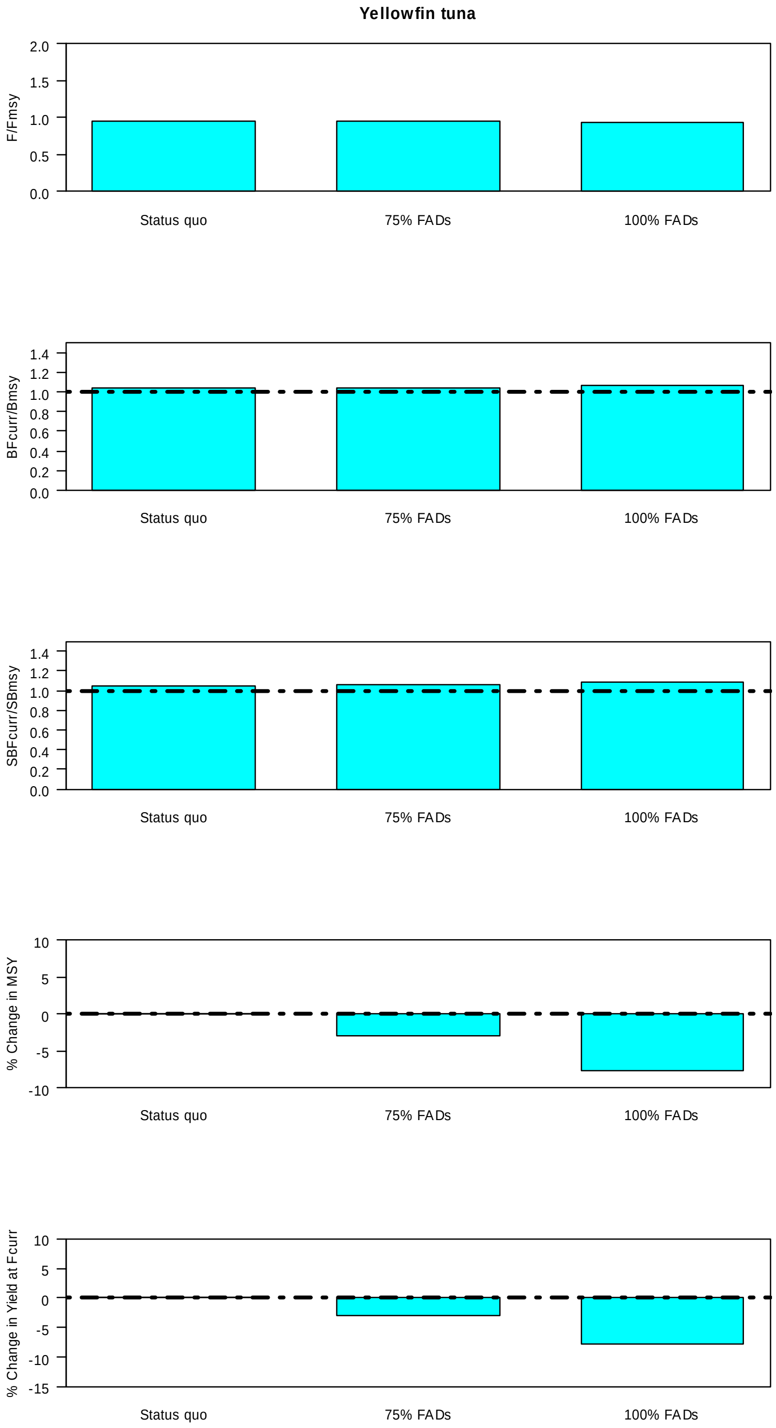

Figure 8. Sensitivity of the key performance indicators for yellowfin tuna to an increase in the use of FADs. See captions for Figures 2-6 for more details of each plot.

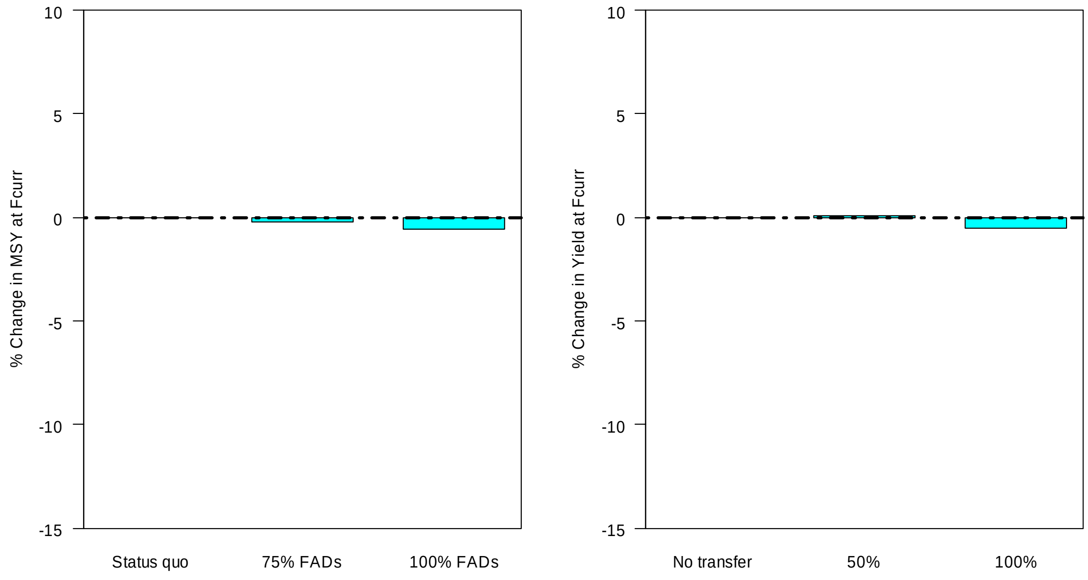

Figure 9. Sensitivity of the key performance indicators for skipjack tuna to an increase in the use of FADs. See captions for Figures 5-6 for more details of each plot.

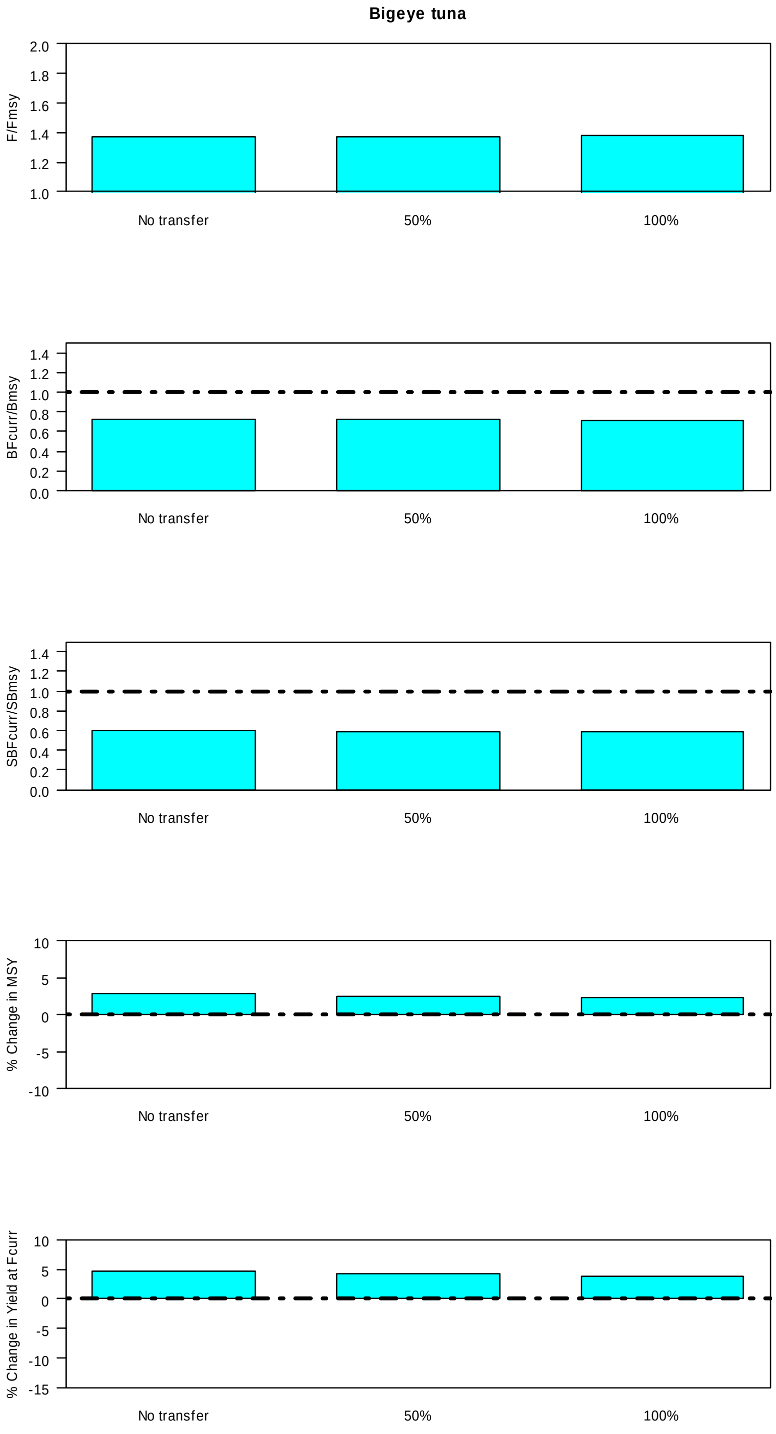

Figure 10. Sensitivity of the key performance indicators for bigeye tuna to a transfer of purse seine effort to unassociated sets during the three month FAD closure. See captions for Figures 2-6 for more details of each plot.

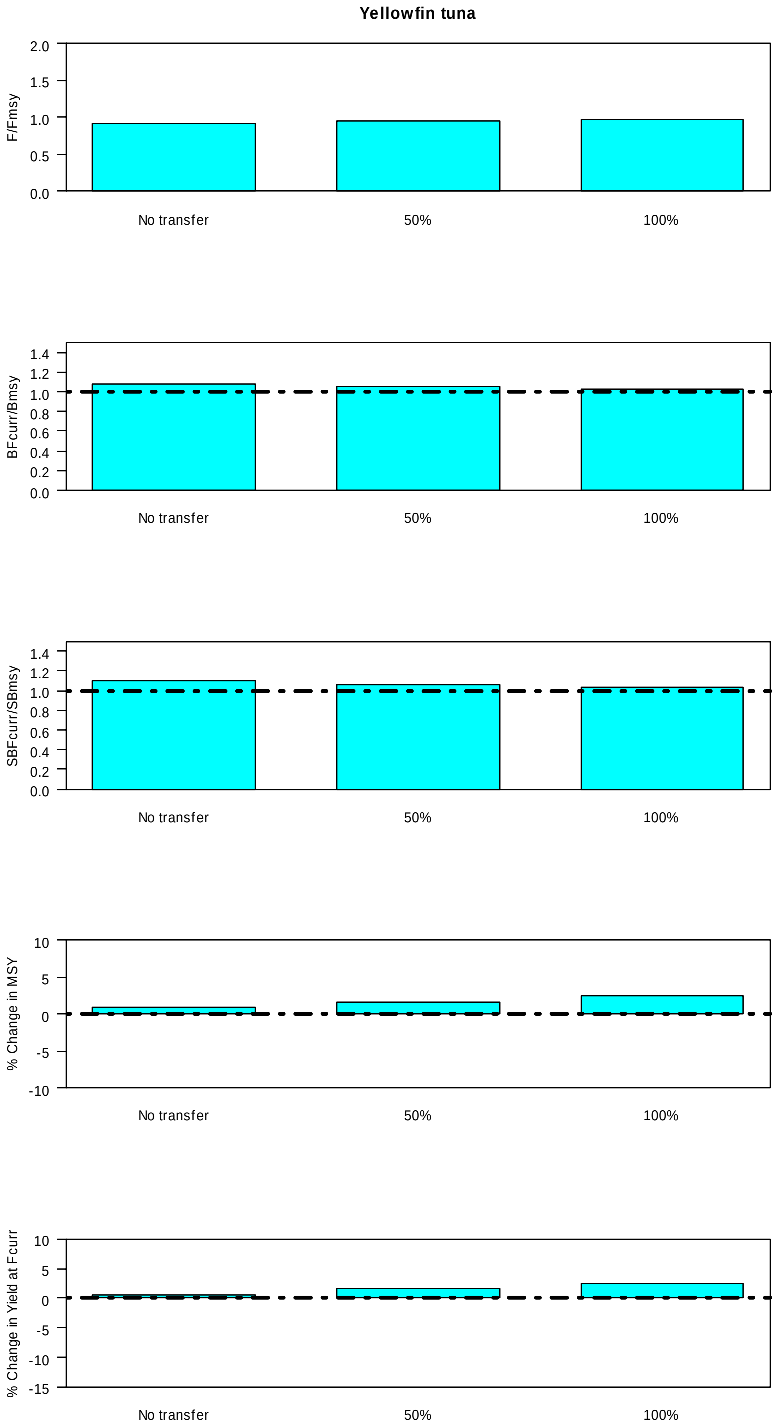

Figure 11. Sensitivity of the key performance indicators for yellowfin tuna to a transfer of purse seine effort to unassociated sets during the three month FAD closure. See captions for Figures 2-6 for more details of each plot.

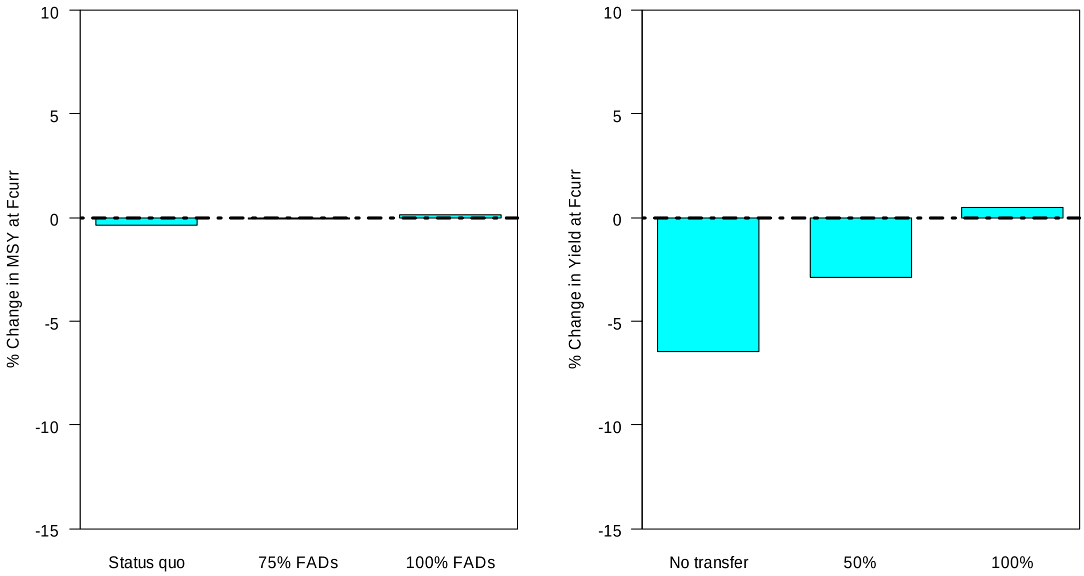

Figure 12. Sensitivity of the key performance indicators for skipjack tuna to a transfer of purse seine effort to unassociated sets during the three month FAD closure. See captions for Figures 2-6 for more details of each plot.

Attachment 1: Model results for all model runs.

Table 7. Estimates of the management quantities for bigeye tuna for all model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	Measure	**FAD % during open period**	**Transfer to unass. during FAD closure**	$F_{current}/\tilde{F}_{MSY}$	$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$	$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$	$\tilde{Y}_{F_{MSY}}$ (or MSY)	$\tilde{Y}_{F_{current}}$	**% overfishing reduced**	**% change** MSY	**% change** $\tilde{Y}_{F_{current}}$
1	Status quo	status quo	NA	1.44	0.67	0.54	64600	60880	0	0	0
2	Status quo	75%	NA	1.52	0.63	0.49	62960	58240	-16.01	-2.54	-4.34
3	Status quo	100%	NA	1.62	0.56	0.42	60680	54360	-40.2	-6.07	-10.71
4	3 mo FAD closure	status quo	0%	1.37	0.72	0.6	66400	63680	16.61	2.79	4.6
5		75%	0%	1.42	0.69	0.56	65120	61760	5.36	0.8	1.45
6		100%	0%	1.5	0.64	0.5	63200	58680	-12.99	-2.17	-3.61
7		status quo	50%	1.38	0.72	0.59	66240	63440	15.21	2.54	4.2
8		75%	50%	1.43	0.68	0.55	65000	61520	3.99	0.62	1.05
9		100%	50%	1.51	0.63	0.49	63080	58480	-14.31	-2.35	-3.94
10		status quo	100%	1.38	0.71	0.59	66120	63240	13.8	2.35	3.88
11		75%	100%	1.43	0.68	0.55	64840	61320	2.52	0.37	0.72
12		100%	100%	1.51	0.63	0.49	62960	58280	-15.7	-2.54	-4.27
13	HS pockets closure	status quo	NA	1.39	0.71	0.58	65880	62920	12.03	1.98	3.35
14		75%	NA	1.45	0.67	0.53	64400	60600	-1.6	-0.31	-0.46
15		100%	NA	1.55	0.61	0.47	62280	57120	-22.65	-3.59	-6.18
16	3 mo FAD & HS pockets closure	status quo	0%	1.33	0.75	0.63	67440	65200	25.6	4.4	7.1
17		75%	0%	1.37	0.72	0.59	66280	63520	15.94	2.6	4.34
18		100%	0%	1.45	0.67	0.54	64480	60800	-0.19	-0.19	-0.13
19		status quo	50%	1.34	0.75	0.63	67280	64960	24.2	4.15	6.7
20		75%	50%	1.38	0.72	0.59	66160	63320	14.53	2.41	4.01
21		100%	50%	1.45	0.67	0.53	64360	60560	-1.56	-0.37	-0.53
22		status quo	100%	1.34	0.74	0.62	67200	64840	23.23	4.02	6.5
23		75%	100%	1.38	0.71	0.59	66040	63160	13.58	2.23	3.75

24		100%	100%	1.46	0.67	0.53	64280	60440	-2.51	-0.5	-0.72
25	30% longline effort reduction	NA	NA	1.27	0.77	0.69	60120	58640	39.4	-6.93	-3.68
26	All PS & LL measures	status quo	0%	1.16	0.86	0.8	62920	62360	63.77	-2.6	2.43
27	All PS & LL measures	75%	0%	1.2	0.83	0.75	61760	60880	54.6	-4.4	0
28		100%	0%	1.27	0.77	0.68	60000	58520	39.25	-7.12	-3.88
29		status quo	50%	1.17	0.86	0.79	62760	62160	62.4	-2.85	2.1
30		75%	50%	1.21	0.82	0.75	61640	60720	53.23	-4.58	-0.26
31		100%	50%	1.28	0.77	0.68	59880	58360	37.9	-7.31	-4.14
32		status quo	100%	1.17	0.85	0.79	62680	62040	61.5	-2.97	1.91
33		75%	100%	1.21	0.82	0.74	61560	60600	52.34	-4.71	-0.46
34		100%	100%	1.28	0.77	0.68	59800	58240	37.06	-7.43	-4.34
35	30% reduction in ID/PH	NA	NA	1.3	0.76	0.65	65960	64080	32.26	2.11	5.26
36	All PS, LL, PH/ID measures	status quo	0%	1.02	0.98	0.97	64440	64440	95.97	-0.25	5.85
37		75%	0%	1.06	0.95	0.92	63080	63000	86.7	-2.35	3.48
38		100%	0%	1.13	0.88	0.83	61000	60640	71.28	-5.57	-0.39
39		status quo	50%	1.02	0.98	0.97	64280	64280	94.59	-0.5	5.58
40		75%	50%	1.07	0.94	0.91	62920	62840	85.36	-2.6	3.22
41		100%	50%	1.13	0.88	0.83	60880	60480	69.96	-5.76	-0.66
42		status quo	100%	1.03	0.97	0.96	64160	64160	93.69	-0.68	5.39
43		75%	100%	1.07	0.94	0.91	62840	62720	84.44	-2.72	3.02
44		100%	100%	1.14	0.88	0.82	60760	60360	69.09	-5.94	-0.85

Table 8. Estimates of the management quantities for yellowfin tuna for all model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	Measure	**FAD % during open period**	**Transfer to unass. during FAD closure**	$F_{current}/\tilde{F}_{MSY}$	$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$	$S\tilde{B}_{F_{current}}/S\tilde{B}_{M}$	$\tilde{Y}_{F_{MSY}}$ (or MSY)	$\tilde{Y}_{F_{current}}$	**% overfishing reduced**	**% change** MSY	**% change** $\tilde{Y}_{F_{current}}$
1	Status quo	status quo	NA	0.96	1.04	1.05	399440	399000		0	0
2	Status quo	75%	NA	0.95	1.05	1.06	387800	387160		-2.91	-2.97
3	Status quo	100%	NA	0.93	1.07	1.08	368760	367560		-7.68	-7.88
4	3 mo FAD closure	status quo	0%	0.92	1.08	1.1	402800	401200		0.84	0.55
5		75%	0%	0.92	1.08	1.1	394560	392600		-1.22	-1.6
6		100%	0%	0.9	1.1	1.12	380400	377880		-4.77	-5.29
7		status quo	50%	0.95	1.05	1.07	406000	405200		1.64	1.55
8		75%	50%	0.94	1.06	1.07	398040	397120		-0.35	-0.47
9		100%	50%	0.93	1.07	1.09	384280	382960		-3.8	-4.02
10		status quo	100%	0.97	1.03	1.03	409200	409200		2.44	2.56
11		75%	100%	0.97	1.03	1.04	401600	401200		0.54	0.55
12		100%	100%	0.96	1.04	1.05	387960	387480		-2.87	-2.89
13	HS pockets closure	status quo	NA	0.91	1.09	1.12	399320	396800		-0.03	-0.55
14		75%	NA	0.9	1.1	1.13	388880	385960		-2.64	-3.27
15		100%	NA	0.88	1.12	1.15	371840	368000		-6.91	-7.77
16	3 mo FAD & HS pockets closure	status quo	0%	0.88	1.12	1.16	402000	397480		0.64	-0.38
17		75%	0%	0.87	1.13	1.16	394600	389880		-1.21	-2.29
18		100%	0%	0.86	1.14	1.17	381800	376400		-4.42	-5.66
19		status quo	50%	0.9	1.1	1.12	405600	402800		1.54	0.95
20		75%	50%	0.9	1.1	1.13	398240	395240		-0.3	-0.94
21		100%	50%	0.89	1.11	1.14	385840	382320		-3.4	-4.18
22		status quo	100%	0.92	1.08	1.1	407600	405600		2.04	1.65
23		75%	100%	0.92	1.08	1.1	400800	398560		0.34	-0.11
24		100%	100%	0.9	1.09	1.12	388360	385800		-2.77	-3.31

25	30% longline effort reduction	NA	NA	0.92	1.08	1.1	391440	389520		-2	-2.38
26	All PS & LL measures	status quo	0%	0.83	1.17	1.21	393280	385280		-1.54	-3.44
27	All PS & LL measures	75%	0%	0.83	1.17	1.22	385520	377280		-3.48	-5.44
28		100%	0%	0.82	1.18	1.23	372080	362960		-6.85	-9.03
29		status quo	50%	0.86	1.14	1.18	397120	391440		-0.58	-1.89
30		75%	50%	0.86	1.14	1.18	389600	383680		-2.46	-3.84
31		100%	50%	0.85	1.16	1.2	376560	369920		-5.73	-7.29
32		status quo	100%	0.88	1.12	1.15	399560	395120		0.03	-0.97
33		75%	100%	0.87	1.13	1.16	392240	387640		-1.8	-2.85
34		100%	100%	0.86	1.14	1.17	379360	374040		-5.03	-6.26
35	30% reduction in ID/PH	NA	NA	0.82	1.18	1.24	410000	399920		2.64	0.23
36	All PS, LL, PH/ID measures	status quo	0%	0.69	1.32	1.42	404400	374880		1.24	-6.05
37		75%	0%	0.69	1.33	1.43	395080	365320		-1.09	-8.44
38		100%	0%	0.68	1.34	1.44	378840	347960		-5.16	-12.79
39		status quo	50%	0.72	1.29	1.38	408800	383880		2.34	-3.79
40		75%	50%	0.72	1.3	1.39	399640	374640		0.05	-6.11
41		100%	50%	0.71	1.31	1.4	384040	357880		-3.86	-10.31
42		status quo	100%	0.74	1.27	1.36	411200	389280		2.94	-2.44
43		75%	100%	0.73	1.27	1.36	402400	380440		0.74	-4.65
44		100%	100%	0.72	1.29	1.38	387240	363840		-3.05	-8.81

Table 9. Estimates of some management quantities for skipjack tuna for all model runs. Descriptions of the various reference points are provided in **Table 3**.

Run	Measure	**FAD % during open period**	**Transfer to unass. during FAD closure**	**% change** MSY	**% change** $\tilde{Y}_{F_{current}}$
1	Status quo	status quo	NA	0	0
2	Status quo	75%	NA	-0.22	0.09
3	Status quo	100%	NA	-0.56	-0.54
4	3 mo FAD closure	status quo	0%	-0.34	-6.45
5		75%	0%	-0.5	-6.27
6		100%	0%	-0.75	-6.54
7		status quo	50%	-0.06	-2.87
8		75%	50%	-0.22	-2.69
9		100%	50%	-0.47	-2.96
10		status quo	100%	0.16	0.49
11		75%	100%	0.06	0.76
12		100%	100%	-0.19	0.4
13	HS pockets closure	status quo	NA	-0.41	-7.08
14		75%	NA	-0.59	-7.12
15		100%	NA	-0.94	-7.75
16	3 mo FAD & HS pockets closure	status quo	0%	-0.75	-12.86
17		75%	0%	-0.88	-12.81
18		100%	0%	-1.13	-13.08
19		status quo	50%	-0.44	-8.92
20		75%	50%	-0.56	-8.83
21		100%	50%	-0.78	-9.05
22		status quo	100%	-0.22	-6.41
23		75%	100%	-0.34	-6.23
24		100%	100%	-0.56	-6.54

25	30% longline effort reduction	NA	NA	NA	NA
26	All PS & LL measures	status quo	0%	NA	NA
27	All PS & LL measures	75%	0%	NA	NA
28		100%	0%	NA	NA
29		status quo	50%	NA	NA
30		75%	50%	NA	NA
31		100%	50%	NA	NA
32		status quo	100%	NA	NA
33		75%	100%	NA	NA
34		100%	100%	NA	NA
35	30% reduction in ID/PH	NA	NA	0.84	-2.73
36	All PS, LL, PH/ID measures	status quo	0%	0.22	-16.35
37		75%	0%	0.09	-16.26
38		100%	0%	-0.19	-16.58
39		status quo	50%	0.53	-12.14
40		75%	50%	0.38	-12.05
41		100%	50%	0.13	-12.32
42		status quo	100%	0.72	-9.5
43		75%	100%	0.56	-9.32
44		100%	100%	0.31	-9.68