Using effort control measures to implement catch limits in IOTC purse seine fisheries

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Extended Abstract

In 2016, the IOTC adopted a rebuilding plan in order to address overfishing of the stock of yellowfin tuna (YFT), through the implementation of catch limits for some fisheries and additional measures to reduce the capacity of industrial purse seine fisheries. However, catch controls, while ensuring that overall fishing mortalities are not exceeded, are not implemented properly because some IOTC CPCs exceed targets on a regular basis and not all fisheries are covered by the measures. This is an issue in multi-species fisheries where monitoring of catch in near-real time is complex, especially for industrial tuna purse seine and pole-and-line fisheries, that very often catch juvenile yellowfin tuna and bigeye tuna (BET) when targeting skipjack tuna (SKJ), as those species tend to aggregate forming mixed schools. In other multi-species fisheries, the adoption of measures on one stock may prompt changes of target to other stocks, with a potential to undermine the status of those, -e.g. longline fisheries changing gear configuration, purse seine fisheries shifting from free-school to associated sets, or the contrary, and multi-gear fisheries moving from a gear targeting a stock (pole-and-line targeting skipjack tuna) to another (handline targeting yellowfin tuna).

We examined the historic data series of catch and effort for the Purse seine fleet on tropical tuna in the Indian Ocean. Based on the information numerous models were developed to predict how much would be caught at a particular effort target. While these catch targets may vary by time and area, the implementation of time-area closures by the IOTC has not been successful, mostly due to effort redistribution and catches in areas outside the closure making up for the catch reduction expected from it or an unwanted increase in the catches of other stocks (IOTC 2018).

The purpose of this study is to explore how full seasonal closures (monthly measures), where vessels remain in port, may better assist multi-species fisheries, such as purse seine, in achieving the levels of catch reduction sought by the IOTC. We developed a model based on parameter estimates of individual models to estimate catches by time as a function of available biomass for YFT, effort by strata (month), and month-effort interactions to estimate YFT catch targets (and associated BET and SKJ as a result). While estimates from these models are subject to various levels of precision, depending on the stock, they provide managers with the ability to predict catches over a time-period, thereby facilitating monitoring and the use of a more precautionary adaptive approach in attaining catch targets with a desired precision level.

In addition, the implementation of seasonal fishery closures has proved successful at the IATTC, which has been using a Control Rule based on this principle for over fifteen years with stocks maintained by the target reference level in recent years. Management systems based on seasonal fishery closures have also proved to be more efficient than those based on catch limits, due to the latter leading to underreporting unless extensive monitoring is in place. Some examples of how the Control Rule may be implemented are provided. A decision support tool is developed based on the

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data and proposed season closures to implement an overall target catch on yellowfin tuna, which is subject to a catch limit by IOTC.

Introduction

In recent years, all tuna-Regional Fishery Management Organisations (tRFMO) have adopted various management measures intended to maintain tropical tuna stocks at the target sustainable biomass levels. To ensure those levels are maintained, tRFMOs have agreed to carry Management Strategy Evaluation (MSE) and move towards the adoption of Harvest Control Rules (HCR) for their stocks (Hillary et. al. 2015). At present, the Indian Ocean Tuna Commission (IOTC) has only adopted a Harvest Control Rule (HCR) for its skipjack tuna (SKJ) stock, while other stocks are subject to various interim measures, including TACs, catch limits, FAD closures, limits on active Fish Aggregating Devices (FADs), limits on support vessels, and limits on fishing capacity for partial or complete coverage of a fleet (subset of fleets in CPC's IOTC SC 2017). However, these measures have not been effective at maintaining the catches of YFT and SKJ at the agreed levels. The same applies to the International Commission for the Conservation of Atlantic Tunas (ICCAT) where recent catch levels for three over the four stocks of tropical tunas have been well over adopted TACs (YFT & BET) and scientific advice (SKJ-East).

In the Indian Ocean, the IOTC adopted catch limits for some fisheries catching yellowfin tuna, applicable since 2017, and some additional measures for purse seiners (IOTC Resolution 18-01). In purse seine fisheries, catch limits are intended to reduce catches of yellowfin tuna by 15% for selected purse seine fisheries (those that reported catches of YFT over 5,000 MT in 2014), using 2015 (Seychelles) or 2014 (all other fleets) as reference year. However, catch limits have been breached over the first two years of implementation, with 2018 YFT catches[3] well above those recorded for 2017 and over 85,000 tonnes (in excess by 25%) over the scientific advice (a 15% reduction over the 2014 YFT catch is recommended). FAD closures have also been evaluated as ineffective in the IOTC and ICCAT areas, mainly due to redistribution of effort to areas outside the closure and catch rates in those areas at similar levels than those attained in the past inside the closure area. The multispecies nature of purse seine fisheries also makes it difficult to obtain catch estimates by species in real time. In addition, the quality of catch estimates may be compromised as a consequence of various potential sources of bias associated with the sampling scheme and/or estimation procedures used by some CPCs (Herrera & Baez 2018a, 2018b; Hoyle *et al.* 2019).

In the eastern Pacific Ocean, the Inter-American Tropical Tuna Commission (IATTC) adopted a measure that contemplates two closures of the purse seine fishery, with the length of those closures adjusted using a Control Rule that relies on the most recent assessments of the stocks of tropical tunas and potential overall levels of capacity of purse seiners estimated for the following year(s). At the start of each year, purse seine companies have to indicate which of their purse seiners will adhere to the first closure and which to the second (Squires et. al. 2016). In addition, IATTC has implemented a ban on support vessels, FAD limits, a FAD closure and input capacity limits for purse seiners, and TACs for longliners (Squires et. al. 2016).

OPAGAC is currently implementing a Fishery Improvement Project (FIP) and has adopted an action plan that includes actions to assist in the evaluation of stock status and monitoring in all oceans, the former through assisting on the implementation of HCR and the latter through assisting improvements in compliance monitoring. Considering that the performance reviews of ICCAT and IOTC have recommended that both organisations improve their management framework for tropical

[3] https://www.iotc.org/WPTT/21/Data/03-NC

tunas, we would like to explore the effectiveness of alternative management measures, along the lines of those adopted by the IATTC, in improving the efficiency of management in IOTC and ICCAT.

As for the IOTC area, the goal is to explore if purse seine fisheries would be better managed through a system similar to the one used by the IATTC, rather than through output measures, which have proved to be ineffective in most oceans. This includes the IATTC , which recently shifted from fishery closures to TACs, to realise, in less than one year, that monitoring of catch against TAC levels was too complex and ineffective, deciding to revert back to fishery closures.

The main objective of this analysis is to explore to which extent a similar approach to the one taken by the IATTC can be successfully used to manage tropical tunas at the IOTC (in terms of efficiency of management, including its monitoring and compliance components) and, if so, provide a Control Rule that would allow converting from a YFT catch limit into a number of closure days, including a proposal of suitable time-periods for the closure; this is done bearing in mind not only the YFT stock but also potential impacts of the measure on other target stocks (BET and SKJ) and main bycatch species (e.g. silky shark). In addition, the report recommends actions that IOTC would need to undertake to assist in the implementation of the Control Rule proposed here.

Materials & Methods

Effort is assumed to be proportional to fishing mortality. Hence, effort closures temporally would have the same net effect as catch limits. The reason is simply shown below in eq. 1:

$$qE_t = F_t \qquad \text{(eq. 1)}$$

Where *q* is catchability and *E* is the effort in the fishery, and *F*, fishing mortality in the fishery. The assumption essentially is that if we can parse effort by different time periods in a year and close some periods, we would essentially have a net limit of fishing mortality (*F*). Note that, implicitly we assume that *q* will remain constant through the unit of fishing effort measured (in fishing hours, as reported to IOTC).

If we have a standardized unit of effort for all fleets, then we could estimate an optimal effort, E_{opt} capacity for the fleet, as a function of optimal fishing mortality, F_{opt} by looking at the following equation

$$E_{opt} = \frac{-ln(1-F_{opt})}{q} \qquad \text{(eq. 2)}$$

Essentially, when we have an over capacity fleet, the yield would be less than optimal as shown below (Figure 0) as discussed in Squires et. al. (2016)

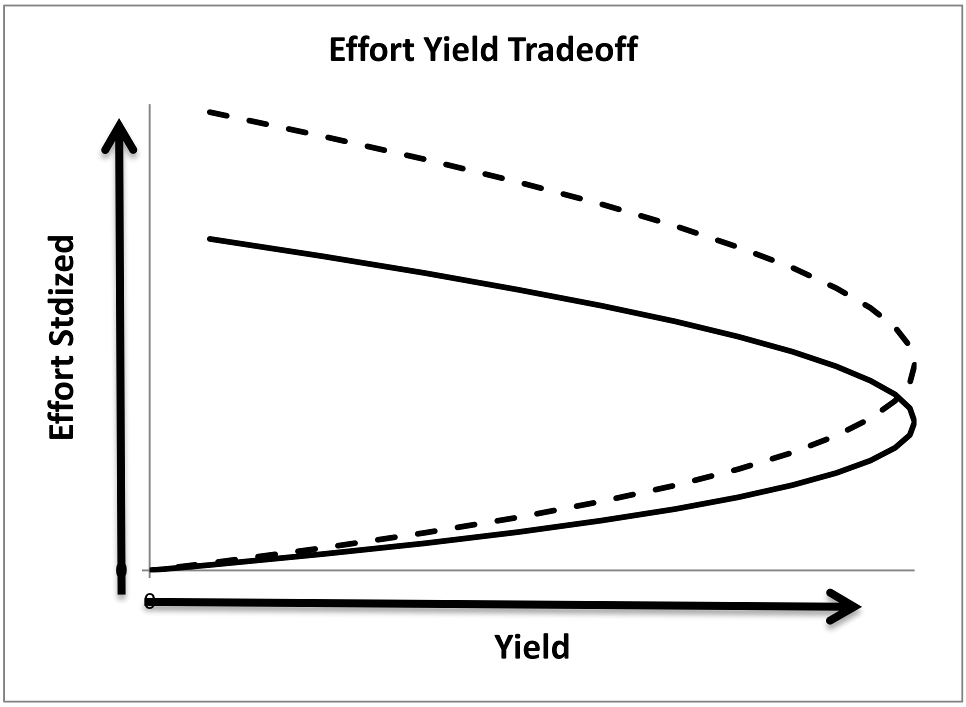

Figure 0: Optimal effort related to yield with different *q*'s.

Once effort exceeds optimal capacity, at some assumed *q*, the ability to get a profitable fishery declines substantially. Hence limiting effort would make sense to some effect on a fishery, especially if it operates at levels over its optimal capacity, as indicated in the SC report for YFT (IOTC SC 2018).

We stratified effort data by time and area, and assess its relationship to catch assuming a 1-1 relationship with YFT catch by year and area (GLM model developed eq. 3). Essentially, if we can limit effort for a portion of days based on the IOTC dataset, we would estimate a substantial reduction in catch and thereby achieve the reliable target that is determined pre-season.

So, we will try and estimate the following

$$YFT_{PSCatch_t} = \alpha + \beta PS_{Effort_t} + \varepsilon \qquad \text{eq.3}$$

Where $YFT_{PSCatch}$ is a function of the PS_{Effort}. We could look at both log response and normal response. Based on slope values by time-period, we can limit overall effort by area to limit catch. This can be related eventually to PS well capacity and number of trips (fishing hours by month and if needed by area) which could be estimated and controlled for.

Datafiles Used and Data Preparation

The PS data used was downloaded from the IOTC website in November 2018. The following datasets were used to build the file for the analysis:

- IOTC-2018-WPTT20-DATA03a: Refers to IOTC's Nominal Catch Data as prepared for the 20th Session of the IOTC Working Party on Tropical Tunas, in MS Excel format, which contains nominal catches of Indian tuna and tuna-like fish, by year (1950-2017), gear, region and flag [compressed MS Excel; version 01/10/2018[4]];

- IOTC-2018-WPTT20-DATA05: Refers to IOTC's Catch & Effort for surface fisheries (1982-2017) [compressed csv file; version 27/09/2018[5]];
- IOTC-2018-WPTT20-DATA09: Refers to IOTC's Size frequency data for the bigeye tuna (BET), as produced by the IOTC Secretariat for the WPTT in 2018 (various formats, 1952-2017) [compressed csv file; version 27/09/2018[6]];
- IOTC-2018-WPTT20-DATA10: Refers to IOTC's Size frequency data for the skipjack tuna (SKJ), as produced by the IOTC Secretariat for the WPTT in 2018 (various formats, 1980-2017) [compressed csv file; version 27/09/2018[7]]
- IOTC-2018-WPTT20-DATA11: Refers to IOTC's Size frequency data for the yellowfin tuna (YFT), as produced by the IOTC Secretariat for the WPTT in 2018 (various formats, 1980-2017) [compressed csv file; version 27/09/2018[8]]
- IOTC-2018-WPTT20-DATA15: Includes the set of equations used by the IOTC Secretariat to convert from length to weight and other types of conversions (pdf file; version 28/09/2018[9])

It is important to note that the main CPC having purse seine fisheries in the Indian Ocean report catch-and-effort and length frequency data raised to total [nominal] catch for their fisheries.

The above data were used to produce a file that contained catch and effort of tropical tunas in the Indian Ocean, for the period 1981-2017, in weight (kilograms). For this all purse seine data were extracted and used to produce:

- **VBA_OUTPUTMT.csv**: File containing Catch (in metric tons) and effort (in number of fishing days or fishing hours) data for PS fisheries separated by school type (associated/free) and maturity (immature/mature), by species (YFT/BET/SKJ), 5 degree square, year (1981-2017), and month.

The number of fish recorded under each length class bin was converted to weight using IOTC's length-weight equations, as included in Table 2 (Page 3) IOTC-2018-WPTT20-DATA15[10]:

- Yellowfin tuna: $W_{kg} = 2.459*10^{-5}*FL_{cm}^{2.9667}$
- Bigeye tuna: $W_{kg} = 2.217 *10^{-5}* FL_{cm}^{3.01211}$
- Skipjack tuna: $W_{kg} = 4.97*10^{-6}* FL_{cm}^{3.39292}$

The amount of fish immature and mature was assigned using IOTC's length-at-first-maturity for each of IOTC's tropical tuna stocks, as used for the assessments of each tropical tuna stock:

4 https://www.iotc.org/sites/default/files/documents/2018/10/IOTC-2018-WPTT20-DATA03a_-_NC_scenario1_0.zip
5 https://www.iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPTT20-DATA05_-_CEPSBB.zip
6 https://www.iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPTT20-DATA09_-_SF_BET_FL.zip
7 https://www.iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPTT20-DATA10_-_SF_SKJ_FL.zip
8 https://www.iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPTT20-DATA11_-_SF_YFT_FL.zip
9 https://www.iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPTT20-DATA15_-_Equations.pdf
10 *Ibid*. 8; length-weight equations for all three tropical tuna species as in Chassot, E. et al. 2016 (IOTC-2016-WPDSC12-INF05)

- Yellowfin tuna[11]: 50% of mature females measuring 102 cm (Zudaire *et al*. 2013);
- Bigeye tuna[12]: 50% mature females measuring 110 cm (Zudaire *et al*. 2013);
- Skipjack tuna[13]: 50% mature females measuring 38 cm (Grande *et al*. 2010, Indian). Used for the stock assessment of skipjack tuna in 2017 (SS3).

The data for the different purse seine fleets were aggregated as follows:

- PS-EU: Purse seine fleets operating under EU flags (France, Spain and Italy) or other flags that operate as EU purse seiners (e.g. France Overseas Territories and other flags recorded as NEIPS in the IOTC database mainly Netherland Antilles and Panama);
- PS-Seychelles: Purse seine vessels flagged in Seychelles: they operate in a way similar to EU fleets;
- PS-Other: Purse seine vessels flagged to other countries and for which catch and effort and length frequency data may not be raised to represent total catch(Mauritius, Japan, Thailand, ex-Soviet Union and other assimilated).

All effort data recorded in fishing days was converted into fishing hours considering that each fishing days consisted on 13 hours of activity in average. These included all available data for Thailand, Japan, ex-Soviet Union and assimilated, and part of the Spanish and Seychelles data.

Although the final file contained information for 1981-2017, only data from the EU-PS and Seychelles fleets, for the period 2002-2017 were used for the analysis. This is because the EU-PS, assimilarted and Seychelles fleets have reported the highest catches in recent years and are the only fleets for which catch, effort, and size data are fully available.

The final file used for the analysis contained total catches of tropical tunas in metric tons taken by EU, assimilated and Seychelles purse seiners, total effort in fishing hours, and total catches broken by fishing mode, species and maturity stage (immature & mature), by year (2002-17), month, and 5 degree square grid.

Generalized Linear Models Examined

Three basic models were examined that looked at response of BET/SKJ/YFT by main effects. We have control on only two of the main effects in terms of management and focus on those (time and/or area), as such models examined only looked at main effects and interactions of these terms with estimated effort (McCullagh and Nelder 1989). The models examined are the following:

$$SPP_{Catch_t} = \alpha + \sum_{i=1}^{n} \beta_i Y_i + \sum_{s=1}^{12} \beta_s M_s + E_t + B_t + \varepsilon_t \qquad (4)$$

[11] Zudaire *et al*. 2013. Reproductive potential of Yellowfin Tuna (*Thunnus albacares*) in the western Indian Ocean. Fishery Bulletin- National Oceanic and Atmospheric Administration 111(3):252-264 · June 2013

[12] Updated ogive taken from Zudaire, *et al*. 2016, 'Sex-ratio, size at maturity, spawning period and fecundity of bigeye tuna (*Thunnus obesus*) in the western Indian Ocean', IOTC–2016–WPTT18–37. Table 4, Page 30 http://www.iotc.org/sites/default/files/documents/2017/11/IOTC-2017-WPTT19-RE_-_FINAL_DO_NOT_MODIFY_0.pdf

[13] Table 9, Page 43 http://www.iotc.org/sites/default/files/documents/2017/11/IOTC-2017-WPTT19-RE_-_FINAL_DO_NOT_MODIFY_0.pdf

$$SPP_{Catch_{t,a}} = \alpha + \alpha_1 B_t + \sum_{s=1}^{12} \beta_s M_s + \sum_{a=1}^{67} \beta_a A_a + \alpha_2 E_t + \varepsilon_{t,a} \quad (5)$$

Where SPP is species (BET, YFT or SKJ), Y is a year effect, M is month effect, and B is the Biomass estimated from the assessment (shown in Figures 7 based on the assessment conducted in 2018. Since Year is confounded with assessment biomass, we chose to use on Biomass as a continuous measure (eq. 5 as it would get rid of 11 degrees of freedom).

Finally, since area controls are not a factor to account for, because the consequences of effort redistribution over the target and other stocks are difficult to assess, we analysed the data based on month and effort only, - i.e. full stop of industrial tuna purse seiners for tropical tunas in the IOTC Area of competence, mainly the western central and subtropical Indian Ocean.

$$SPP_{Catch_{t,a}} = \alpha + \alpha_1 B_t + \sum_{s=1}^{12} \beta_s M_s + \alpha_2 E_t + \varepsilon_{t,a} \quad (6)$$

The final model used month:effort interactions so a variation in slopes for each month could be accounted for (eq. 7). This is eventually the resolution with which they could plan for.

$$SPP_{Catch_{t,a}} = \alpha + \alpha_1 B_t + \sum_{s=1}^{12} \beta_s M_s + \sum_{s=1}^{12} \beta_s M_s E_s + \alpha_2 E_t + \varepsilon_{t,a} \quad (7)$$

Results

Exploratory Data Analysis

Since we are interested in overall patterns in the fishery over time, we compiled some simple plots looking at overall proportions for YFT, BET and SKJ between 2002-2017 (aggregated, Figure 1 & 2) for Mature and Immature and school type. Decadal effort is shown for all PS fleets in Figure 3 some of effort monthly variations in landings between 2002-2017 by area (Figure 4). Figure 5 displays the abundance trends over time, by quarter and since the PS fleet is largely active in Area 1 & 2 (Figure 5 bottom half), biomass in those areas are calculated and used in the GLM as a continuous variable to account for year effects.

Generalized Linear Models Examined

The data were conditioned first on YFT and then applied to BET using large fish as the dependent variable. The aim was to assess loss in catch of large BET and SKJ on each of the time-periods (months) selected for the closure. A log response model as well as a model for non-linear relationships (log catch related to log effort) were also assessed but both models performed poorly with respect to diagnostics. Table 1 summaries results using ANOVAs on the 3 species described above.

Diagnostic fits to models 1 and 2 for YFT (Figure 6 & 7) examine effect of year versus Month:Effort interactions. The final model chosen was of the form of Figure 7, and diagnosed with residuals (Figures 7-10). Final Model 2 with parameter values of the coefficients is shown in Table 1 (Figure 7-10). Similar parameter values for SKJ and BET are shown in Table 2. Diagnostic fits on these models were examined showing similar results to those obtained from the final models chosen for YFT.

Table 1: ANOVAS on models examined for BET, YFT and SKJ by mature and immature and by log school and free school

YFT IMMATURE FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	11978540		
factor(Year)	15	159531	7687	11819009	8.3993	< 2.2e-16
BiomassArea12	1	26666	7686	11792343	21.0594	4.52E-06
factor(MonthStart)	11	94568	7675	11697775	6.7895	1.79E-11
FhoursE	1	1980759	7674	9717017	1564.301	< 2.2e-16

YFT IMMATURE FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	11978540		
BiomassArea12	1	80936	7701	11897604	70.8264	< 2.2e-16
factor(MonthStart)	11	98271	7690	11799333	7.8178	1.23E-13
FhoursE	1	1970203	7689	9829129	1724.108	< 2.2e-16
factor(MonthStart):Fhours	11	1055190	7678	8773940	83.9443	< 2.2e-16

YFT_MATURE_FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	2.58E+09		
BiomassArea12	1	36764605	7701	2.54E+09	244.391	< 2.2e-16
factor(MonthStart)	11	73997307	7690	2.47E+09	44.718	< 2.2e-16
FhoursE	1	8.6E+08	7689	1.61E+09	5714.704	< 2.2e-16
factor(MonthStart):Fhours	11	4.53E+08	7678	1.16E+09	273.702	< 2.2e-16

YFT_IMMAT_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	4.81E+08		
BiomassArea12	1	4466	7701	4.81E+08	0.1751	0.6757
factor(MonthStart)	11	17608389	7690	4.63E+08	62.7375	<2e-16
FhoursE	1	1.95E+08	7689	2.68E+08	7640.959	<2e-16
factor(MonthStart):Fhours	11	72040147	7678	1.96E+08	256.6741	<2e-16

YFT_MAT_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	92115730		
BiomassArea12	1	396421	7701	91719309	54.771	1.50E-13
factor(MonthStart)	11	1344098	7690	90375211	16.882	< 2.2e-16
FhoursE	1	30654179	7689	59721032	4235.311	< 2.2e-16
factor(MonthStart):Fhours	11	4149490	7678	55571542	52.119	< 2.2e-16

BET_IMMATURE_FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	813091		
BiomassArea12	1	34	7701	813057	0.3745	0.5406
factor(MonthStart)	11	8246	7690	804811	8.3042	1.13E-14
FhoursE	1	81928	7689	722883	907.6199	< 2.2e-16
factor(MonthStart)	11	29815	7678	693068	30.0273	< 2.2e-16

BET_MATURE_FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	28649177		
BiomassArea12	1	7523	7701	28641653	3.5456	0.05974
factor(MonthStart)	11	612212	7690	28029442	26.2297	< 2e-16
FhoursE	1	6710913	7689	21318528	3162.752	< 2e-16
factor(MonthStart)	11	5026895	7678	16291634	215.3727	< 2e-16

BET_IMMATURE_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	42992896		
BiomassArea12	1	2653	7701	42990243	1.2391	0.2657
factor(MonthStart)	11	1267519	7690	41722724	53.8168	<2e-16
FhoursE	1	20358369	7689	21364355	9508.22	<2e-16
factor(MonthStart)	11	4924730	7678	16439624	209.0961	<2e-16

BET_MATURE_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	148341		
BiomassArea12	1	2053.3	7701	146287	139.767	< 2.2e-16
factor(MonthStart)	11	2775.5	7690	143512	17.175	< 2.2e-16
FhoursE	1	19022.8	7689	124489	1294.864	< 2.2e-16
factor(MonthStart)	11	11691.9	7678	112797	72.351	< 2.2e-16

SKJ_IMMATURE_FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	1300		
BiomassArea12	1	1.937	7701	1298.1	12.0364	0.000525
factor(MonthStart)	11	9.684	7690	1288.4	5.4712	9.34E-09
FhoursE	1	39.11	7689	1249.3	243.0553	< 2.2e-16
factor(MonthStart):FhoursE	11	13.844	7678	1235.5	7.8215	1.20E-13

SKJ_MATURE_FS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	2.21E+08		
BiomassArea12	1	2038250	7701	2.19E+08	112.6721	< 2.2e-16
factor(MonthStart)	11	1199170	7690	2.18E+08	6.0262	6.86E-10
FhoursE	1	45843882	7689	1.72E+08	2534.198	< 2.2e-16
factor(MonthStart):FhoursE	11	33192605	7678	1.39E+08	166.8045	< 2.2e-16

SKJ_IMMATURE_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	1059174		
BiomassArea12	1	92	7701	1059082	1.1018	0.2939
factor(MonthStart)	11	32461	7690	1026621	35.1925	<2e-16
FhoursE	1	207086	7689	819534	2469.636	<2e-16
factor(MonthStart):FhoursE	11	175711	7678	643823	190.4967	<2e-16

SKJ_MATURE_LS

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			7702	3.45E+09		
BiomassArea12	1	6226661	7701	3.44E+09	42.69	6.83E-11
factor(MonthStart)	11	1.4E+08	7690	3.3E+09	87.432	< 2.2e-16
FhoursE	1	1.64E+09	7689	1.66E+09	11265.75	< 2.2e-16
factor(MonthStart):FhoursE	11	5.35E+08	7678	1.12E+09	333.716	< 2.2e-16

Model Developed

Based on the ANOVAS in Table 1, parameter estimates were obtained for all the models and a general model was developed based on average effort between 2002 and 2017 for the EU and Seychelles fleets. The models predictive capability of catches for the EUPS fleet is shown in Figure 11-13 for BET, YFT and SKJ by school type. The predictive capability of the model with CV's on overall targets is shown in Table 2 below. For illustrative purposes two other models are developed with differential closure patterns, one in the austral winter months of January and February whereas the other was in March through June. Effects of these closures are shown in Figures 14 and 15 and the effort, as compared to 2016 effort, is shown in Figure 16. This model can be used as the basis for planning seasonal closures with some desired objective.

Table 2: Catch Estimated with uncertainty based on effort distribution for YFT in 2016

Month	Avg Eff	Fishing (on=1)	=	Estimated Immature FS_YFT	Estimated Mature FS_YFT	Estimated Immature LS_YFT	Estimated Mature_LS_YFT	SE (Immature FS_YFT)	SE (Estimated Mature FS_YFT)	SE Estimated Immature LS_YFT	SE Estimated Mature_LS_YFT
1	13490	1	1060000	459	19580	1545	701	40	454	187	100
2	11827	1	1060000	496	15600	2427	935	80	914	376	200
3	12954	1	1060000	234	5020	5092	1614	91	1042	429	229
4	11459	1	1060000	383	4974	2767	1920	80	916	377	201
5	11013	1	1060000	460	3790	1708	968	76	874	360	192
6	10604	1	1060000	427	12067	1475	1042	72	825	340	181
7	11519	1	1060000	176	8064	2539	1822	80	914	376	200
8	12665	1	1060000	73	811	6003	1906	84	969	399	212
9	12238	1	1060000	62	2005	7685	2108	82	938	386	206
10	11807	1	1060000	285	2658	7904	2232	82	940	387	206
11	12318	1	1060000	461	6282	4581	2109	92	1056	435	232
12	13350	1	1060000	1309	14172	1977	834	93	1067	439	234
			TOTAL CATCH (T)	4824	95023	45703	18191				
			cv	0.20	0.11	0.10	0.13				

Table 3: Catch estimated with uncertainty based on effort distribution for BET in 2016

Month	Avg Eff	Fishing (on=1)	=	Estimated Immature FS_BET	Estimated Mature FS_BET	Estimated Immature LS_BET	Estimated Mature_LS_BET	SE Estimated Immature FS_BET	SE Estimated Mature FS_BET	SE Estimated Immature LS_BET	SE Estimated Mature_LS_BET
1	13490	1	1060000	159	1310	832	20	11	54	54	4
2	11827	1	1060000	108	1142	962	26	22	109	109	9
3	12954	1	1060000	38	459	1844	15	26	124	124	10
4	11459	1	1060000	81	417	998	6	22	109	109	9
5	11013	1	1060000	65	267	534	5	21	104	104	9
6	10604	1	1060000	153	1850	428	11	20	98	98	8
7	11519	1	1060000	61	864	921	44	22	109	109	9
8	12665	1	1060000	30	101	1962	57	24	115	116	10
9	12238	1	1060000	28	160	2256	57	23	111	112	9
10	11807	1	1060000	47	154	1968	110	23	112	112	9
11	12318	1	1060000	42	412	1417	67	26	125	126	10
12	13350	1	1060000	88	837	719	45	26	127	127	11
			TOTAL CATCH (T)	900	7971	14840	462				
			cv	0.30	0.16	0.09	0.23				

Table 4: Catch estimated with uncertainty based on average effort distribution for SKJ

Month	Avg Eff	Fishing (on=1)	=	Estimated Immature FS_SKJ	Estimated Mature FS_SKJ	Estimated Immature LS_SKJ	Estimated Mature_LS _SKJ	SE Estimated Immature FS_SKJ	SE Estimated Mature FS_SKJ	SE Estimated Immature LS_SKJ	SE Estimated Mature_LS _SKJ
1	13490	1	1060000	2	1248	26	5083	0	158	11	447
2	11827	1	1060000	3	1529	26	7442	1	317	22	900
3	12954	1	1060000	4	1494	92	15234	1	361	25	1026
4	11459	1	1060000	3	2918	93	9549	1	318	22	902
5	11013	1	1060000	2	5957	35	5509	1	303	21	860
6	10604	1	1060000	1	1307	56	3440	1	286	19	812
7	11519	1	1060000	1	520	83	7984	1	317	22	900
8	12665	1	1060000	1	878	195	18278	1	336	23	954
9	12238	1	1060000	1	1087	302	20178	1	325	22	923
10	11807	1	1060000	1	1732	384	22316	1	326	22	926
11	12318	1	1060000	1	2231	129	12033	1	366	25	1040
12	13350	1	1060000	1	1060	38	5419	1	370	25	1051
			TOTAL CATCH (T)	21	21960	1459	132465				
			cv	0.55	0.17	0.18	0.08				

For example if we wanted to estimate a total catch of 100,000 tons for YFT with one seasonal closure at different times, it could be implemented with Table 5 or Table 6 below resulting in catch distribution pattern shown in Figure 14 and 15. Note, that the estimated catch is the measure that controls a portion of the fleet (i.e. EUPS and Seychelles fleet that is the EST TOTAL CATCH that can be explained by the model). If we want to expand it to the observed data, we need to expand what this measure would do to the whole fleet based on the ratio of catch that it represents of the whole fleet, i.e. the expanded total catch (EXP Total Catch). So, the estimated (EST) catch is what is explained by the model, has to then be raised to what the total catch of the EUPS fleet is for that period (on average).

Table 5: Catch Estimated with uncertainty based on one closure and target of 100,000 YFT with 2 month closure.

Month	Avg Eff	Fishing (on=1)	=	Estimated Immature FS_YFT	Estimated Mature FS_YFT	Estimated Immature LS_YFT	Estimated Mature_LS _YFT	SE (Immature FS_YFT)	SE (Estimated Mature FS_YFT)	SE Estimated Immature LS_YFT	SE Estimated Mature_LS _YFT
1	13490	0	1060000	0	0	0	0	0	0	0	0
2	11827	0	1060000	0	0	0	0	0	0	0	0
3	11106	1	1060000	201	4299	4364	1383	79	904	372	198
4	9699	1	1060000	324	4202	2343	1623	69	786	324	173
5	9753	1	1060000	407	3352	1513	857	68	782	322	172
6	7759	1	1060000	311	8797	1080	763	54	623	257	137
7	9332	1	1060000	142	6521	2063	1476	66	754	311	165
8	11281	1	1060000	65	722	5347	1698	76	871	359	191
9	10301	1	1060000	52	1683	6467	1776	70	801	330	176
10	9592	1	1060000	231	2155	6421	1813	68	778	320	171
11	10133	1	1060000	379	5156	3772	1734	77	882	363	193
12	10603	1	1060000	1037	11232	1575	663	75	863	355	189
			TOTAL CATCH (T)	3149	48121	34946	13784				
			cv	0.22	0.17	0.09	0.13				

Table 6: Catch Estimated with uncertainty based on two closures and target of 100,000 YFT with 4 month closures (Figure 15).

Month	Avg Eff	Fishing (on=1)	=	Estimated Immature FS_YFT	Estimated Mature FS_YFT	Estimated Immature LS_YFT	Estimated Mature_LS _YFT	SE (Immature FS_YFT)	SE (Estimated Mature FS_YFT)	SE Estimated Immature LS_YFT	SE Estimated Mature_LS _YFT
1	10853	1	1060000	369	15727	1252	567	33	375	154	82
2	9193	1	1060000	384	12091	1895	729	63	727	299	159
3	12954	0	1060000	0	0	0	0	0	0	0	0
4	11459	0	1060000	0	0	0	0	0	0	0	0
5	11013	0	1060000	0	0	0	0	0	0	0	0
6	10604	0	1060000	0	0	0	0	0	0	0	0
7	9774	1	1060000	149	6833	2159	1546	69	787	324	173
8	11561	1	1060000	66	740	5480	1740	78	891	367	195
9	10692	1	1060000	54	1748	6713	1843	72	829	341	182
10	10040	1	1060000	242	2257	6721	1897	71	810	334	178
11	10575	1	1060000	395	5383	3935	1810	80	917	378	201
12	11158	1	1060000	1092	11826	1656	697	79	904	372	198
			TOTAL CATCH (T)	2753	56606	29811	10829				
			cv	0.20	0.11	0.09	0.13				

Implementation of closures in the context of the IOTC

The model presented can be used to assess the time-period and number of fishing days of closure required in order to replace the existing or any future YFT Catch limits recommended by the IOTC for the industrial tuna purse seine component. Other than the recommended catch limit, the following information will be required to estimate the number of closure days for a given year:

1. Number of industrial tuna purse seiners to be in operation, by IOTC CPC, and the expected total number of days that will be fished by those: The number of tuna seiners can be obtained from the latest list of active vessels and fishing craft statistics reported by each CPC, and the total number of fishing days from past reports of vessel numbers and catch-and-effort data by each CPC as part of IOTC's data requirements;

2. Trend in the total number of active support vessels / FADs used by purse seiners, or any other new piece of technology that could contribute to an increase in effective fishing effort directed at the YFT stock (i.e. effort creep)[14];

3. Any other management measure the IOTC has implemented in complement to the fishery closure that could contribute to a decrease in effective fishing effort directed at the YFT stock (e.g. limits on numbers of active FADs and support vessels).

4. YFT Biomass value estimate from the latest stock assessment.

While most of the information covered in 1-4 can be obtained from the IOTC this does not apply to the numbers of active purse seiners and support vessels that will operate in the future in the IOTC Convention Area as, at present, IOTC CPCs not covered by the capacity limitation are not obliged to provide this information in advance to the IOTC. However, IOTC could contemplate to make it a requirement for CPC to provide this information, including fish carrying capacity, if this measure is

[14] Note that the IOTC has adopted limits on the numbers of FADs and vessels that act in support of purse seiners and therefore this trend can only increase through the entry of new purse seiners into the fishery.

implemented in substitution of the existing catch limit. Appendix I presents an attempt to estimate levels of capacity for the purse seine fleet since 2014.

Discussion

IATTC's system currently uses effort in fishing hours to incorporate increases in fishing capacity. This system could easily be adapted to that as Fishing hours estimated across all fleets, could easily be converted to units of fleet/well capacity times the number of trips to overall well capacity for the fleet for that month. Some work would be needed to account for which fleets are fishing at which month and to incorporate an effort measure that is in units of well capacity. We could then limit the overall well capacity instead of hours to estimate the overall impact using this approach. However, it is important to note that the purse seine fleets operating in the Atlantic and Indian oceans are less heterogeneous than the one operating in the Eastern Pacific ocean.

Squires et. al. (2016) argue for a case where Effort Rights Based Management has received considerably less conceptual or empirical attention in the literature than transferable catch quota approaches. Rather than having open access, race-horse derby type fisheries, where fishers normally don't get optimal price for their catch, Squires et. al. (2016) argue that effort control type fisheries closely align the private behaviour of fishers with society's desired social–economic–ecological objectives of harvests satisfying a sustainable yield or effort target and sustainable social and economic benefits. Squires et. al. (2016) cover 37 different studies where these approaches have worked and also provided a right to the resource using responsible effort based management measures. Squires et. al. (2016) dispel a number of myths about effort-based fisheries, as discussed below.

Effort controls, in contrast to catch controls, create incentives to increase input use and costs in an attempt to maximize individual vessel catches and revenues. This incentive in turn raises, rather than minimizes, input usage and costs, at least collectively for the fleet. As a fleet becomes more efficient it tends to overfish and catch more with the same input (i.e. effort measure). However, controlling that measure can then keep fleets fishing at sustainable levels (e.g. capacity limitation, FAD limits, etc.). In contrast TAC based measures tend to provide stronger incentives to reduce effort and costs and to increase price. Catch rights thereby increase revenue through improved quality or smoothing out seasonality of production (as there is a limited catch). This was the case with halibut ITQ's (Grafton et al. 2000). However, for tuna fisheries this is far from the case and unless a particular fleet catch is in high demand and not affected by supply from other oceans or sectors (longline, pole-and-line and artisanal which is not the case), so this argument would not work for having a TAC based control rather than an effort-based control.

Other issues such as technological creep will provide incentives for the fleet to maximize catch with better efficiency (the case for PS). However, if we update our analysis with the latest information the relationship would be valid for the latest technology and could be updated every 5 years to give a new measure of effort in line with the recommended TAC. Although that is a serious criticism of effort-based measures to control output from the fisheries, especially if the technological creep increase so that more fish is caught every year that planned with a particular opener (Squires et. al. 2016), IATTC has been implementing such a system for over 15 years and has achieved maintaining the tropical tuna stocks to the target reference points over the entire period (never breaching limit reference points for those stocks).

As for the advantages ascribed to effort controls Squires et. al. (2016) mention that those systems are recommended in the case that catches cannot be estimated properly and/or compliance monitoring is poor. This is, to a different degree depending on the fleet, the case of industrial tuna purse seine fisheries because: catches for some CPC can be very uncertain (e.g. Ghana in ICCAT, Chassot *et al*. 2014); catches by species cannot be estimated in near real-time or be estimated by vessel to a known precision (e.g. EU fleet, Herrera & Báez 2018); the adoption of TACs has led to gross underreporting of catches by some fleets (e.g. Chinese Taipei longline fleet, ICCAT 2015, IOTC 2018; IOTC 2019); the IOTC has not set any mechanism to independently monitor CPC compliance with the catch limits of yellowfin tuna or the TAC issuing from the HCR for skipjack tuna; the costs of such a mechanism will be extremely high, well beyond the cost of monitoring through a full closure, which only requires control through VMS and/or Inspection in Port.

Conclusions

This study shows the potential benefits for IOTC's management to consider replacing the existing catch limits of yellowfin tuna with fishery closures for its purse seine component, and extend this measure to other fleets that fail to comply with IOTC Data Collection and Reporting requirements.

There are many possible scenarios of developing solutions to achieve a certain YFT target with certain monthly closures. However, we may have conflicting objectives as seen that don't allow the catch to exceed some threshold tonnage of SKJ while keeping YFT targets low. In optimizing to one target the catches of other species may not reach the target levels set, as seen above. However, considering the multi-species nature of surface fisheries at the IOTC and the fact that the skipjack tuna is subject to a HCR and catch limits could exist for both bigeye tuna and yellowfin tuna, it would only be reasonable that the closure adopted seeks a reduction in the catches of all three stocks, or at least that increases in catches of other stocks that may put at risk their sustainability are prevented . In addition, the catch limit adopted by the IOTC for the yellowfin tuna stock has proved to have a adverse effect on fishing behaviour as it has prompted fishermen to avoid catching adult YFT on free-schools towards fishing on FADs, where YFT, mostly juvenile, only represents a fraction of the total catch. Therefore, there is a potential for effort limits to be more effective in addressing catch limits for multi-species fisheries in which catch limits have been adopted for more than one stock (IOTC, ICCAT) or those fisheries that operate over its optimum capacity and target stocks that have been assessed to be fully exploited or above such levels, as it is the case of purse seine fisheries in the ICCAT and IOTC areas.

Thus, the choice of closures will be dependent on an iterative discussion between the managers and ship operators as shown in situations presented above. In addition, it is evident in certain months (shoulder seasons March April, and September to November) that catch rates of directed species are lower and closures in those months would benefit YFT reductions while not compromising the catches of BET or SKJ.

Given the large uncertainties in achieving catch limits and the failure shown in IOTC, ICCAT and IATTC to do so, effort controls with large industrial fleets like the PS fleet are considered a better alternative. The ability to do so is entirely dependent on the data and management to implement these closures in an effective manner and has already proved effective in the case of the IATTC.

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APPENDIX I
Implementation of Effort Controls

This section presents an example about how the Model presented in this document can be used to set Fishery Closures for industrial tuna purse seiners in the Indian Ocean.

This is done on the assumption that purse seine effort levels in 2020 will not be higher than those recorded in 2016, which is used in the Model as reference for effort. This is because 2016 was the year in which the highest effort was recorded in the Indian Ocean for the reference fleet (EU plus Seychelles flag), over the period 2002-2017.

The first section of Appendix I contains information about levels of purse seine effort in the Indian Ocean since 2014. This is done to justify the statement that effort levels in the Indian Ocean have not increased since 2016, nor are they likely to grow over 2016 levels in 2020. The second section of the Appendix shows an example of implementation of Fishery Closures using the Sharma & Herrera (2019) Model.

Review of industrial tuna purse seine [fishing] capacity in the IOTC Area of Competence

This section contains an overview of levels of capacity of purse seiners in the IOTC Area of Competence over the years 2014-2020. The following elements are reviewed:

- *Total number and capacity of active purse seiners*: The total number and capacity of active purse seiners was obtained from the IOTC Record of Active Vessels[15], which contains information up to 2018. The list was completed in 2019 adding a new Spanish purse seiner, which joined the fishery during the last quarter of 2019. Information for this vessel was obtained from the IOTC Record of Authorised Vessels[16]. Table 7 present total number of vessels and GT for purse seiners whose catch-and-effort data was used for the model (7a. EU and Seychelles), and for other purse seiners operating in the Indian Ocean (7b. various flags), respectively. Data from the latter was not used for the model because it was incomplete, or estimates were not corrected using data from port sampling.

Table 7a: Purse seiners for which data was used for the Model. Number of purse seiners active (no.) in the IOTC Area of Competence and total tonnage (GT) for those over the period 2014-2019; and purse seiners expected to operate in 2020. Red font represents estimates.

	2014		2015		2016		2017		2018		2019		2020	
Flag	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT
France (EU)	13	29366	12	27229	**12**	**27196**	12	27196	12	27196	12	27196	**12**	**27196**
Italy (EU)	0	0	1	2137	**1**	**2137**	1	2137	1	2137	1	2137	**1**	**2137**
Spain (EU)	15	45958	15	45201	**18**	**51598**	14	46715	14	46715	14	46715	**15**	**49504**
Seychelles	8	24443	13	39982	**13**	**39982**	13	39982	13	39982	13	39982	**13**	**39982**
TOTAL	36	99767	41	114549	**44**	**120913**	40	116030	40	116030	40	116030	**41**	**118819**

[15] https://www.iotc.org/sites/default/files/documents/compliance/vessel_lists/GetActiveVesselListE.zip (Downloaded on 8-October-2019)
[16] https://www.iotc.org/vessels/history/124090/17253 (Aterpe Alai; Downloaded on 8-October-2019)

Table 7b: Purse seiners for which data were not used for the Model. Number of purse seiners active (no.) in the IOTC Area of Competence and total tonnage (GT) for those over the period 2014-2019; and purse seiners expected to operate in 2020. Red font represents estimates. Values in *italics* are excluded from the total (see text for details).

Flag	2014		2015		2016		2017		2018		2019		2020	
	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT
Australia	*5*	*1915*	*6*	*2524*	*6*	*2624*	*7*	*2487*	*6*	*2368*	*6*	*2368*	*6*	*2368*
Indonesia	*0*	*0*	*18*	*2353*	*6*	*870*	*29*	*4544*	*65*	*10169*	*65*	*10169*	*65*	*10169*
Iran	5	7847	5	7847	**8**	**11570**	5	7847	5	7847	5	7847	**5**	**7847**
Japan	2	3672	2	3672	**2**	**3672**	2	3672	2	3672	2	3672	**2**	**3672**
Korea Rep.	4	8352	4	8352	**5**	**10759**	3	6835	2	4634	2	4634	**2**	**4634**
Mauritius	7	8589	7	8589	**2**	**5334**	2	5334	2	5334	2	5334	**2**	**5334**
Sri Lanka	*7*	*4557*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Thailand	*0*	*0*	*0*	*0*	*1*	*200*	*1*	*200*	*1*	*200*	*1*	*200*	*1*	*200*
TOTAL	18	28460	18	28460	**17**	**31335**	12	23688	11	21487	11	21487	**11**	**21487**

As shown in Table 7a, the number of vessels and GT in the reference year used for the model (2016) was higher than the number of vessels and GT estimated for 2020. The number of vessels and GT for France, Italy and Seychelles in 2019 was projected into 2020. On the contrary, Spain added a vessel by the end of 2019, the purse seiner *Aterpe Alai*. This vessel and its GT were added in 2020.

Table 7b contains purse seiners under other flags that were active in the IOTC Area over the same period. However, the purse seiners and GT reported by Australia, Indonesia, Sri Lanka and Thailand were not accounted for in the Total because vessels do not target tropical tunas (Australia; Sri Lanka; Thailand) or are of small size (GT<250; Indonesia, Thailand). On the other hand, the number of purse seiners and GT for Iran, Japan, the Republic of Korea and Mauritius was much higher in 2014 (reference year for the catch limits of yellowfin) than the projected number for 2020.

- *Total levels of purse seine Catch and Effort*: Table 8 presents levels of catch of yellowfin tuna, in metric tons, and effort, in number of hours fishing for EU and Seychelles (Table 8a), and other purse seiners (Table 8b). Levels of effort (8a) expected for 2020 are similar than those recorded for 2016 (reference year for the model). The catches of yellowfin tuna for EU and Seychelles purse seine fleets have represented over 85% of the total catches of yellowfin tuna by the purse seine fishery in recent years.

Table 8a: Purse seiners for which data was used for the Model. Total Effort (number of hours fishing; Fhours) in the IOTC Area of Competence and total catch of yellowfin tuna (metric tons; MT) over the period 2014-2019; and levels of effort [and catch] expected for the year 2020. Red font represents estimates.

Flag	2014		2015		2016		2017		2018		2019		2020
	Fhours	MT	Fhours	MT	Fhours	MT	Fhours	MT	Fhours	MT	Fhours	MT	Fhours
France (EU)	45077	33513	41178	31047	**40981**	**33720**	38256	29960	42030	28971	42030	28971	**40981**
Italy (EU)	0	0	3688	2471	**3688**	**1868**	3688	2418	0	0	0	0	**0**
Spain (EU)	55088	57892	49894	52631	**51129**	**51489**	42148	54513	44623	45309	44623	45309	**54781**
Seychelles	25312	23449	39156	39015	**53135**	**40007**	42499	41688	36227	35018	36227	35018	**53135**
TOTAL	125477	114854	133916	125163	**148934**	**127687**	126591	128632	122881	109298	122881	109298	**148897**

Table 8b: Purse seiners for which data were not used for the Model. Total catch of yellowfin tuna (metric tons; MT) in the IOTC Area of Competence over the period 2014-2019. Red font represents estimates. Levels of effort are lacking or incomplete for some fleets and therefore not recorded in the Table. Values in *italics* are excluded from the total (see text for details).

Flag	2014 MT	2015 MT	**2016 MT**	2017 MT	2018 MT	2019 MT
Australia	*0*	*0*	***0***	*0*	*0*	*0*
Indonesia	*5598*	*5493*	***5214***	*5214*	*9564*	*9564*
Iran	4832	3842	**3465**	1764	3898	3898
Japan	433	338	**422**	712	404	404
Korea Rep.	8852	7509	**10347**	6362	5415	5415
Mauritius	4844	5448	**7404**	7681	11322	11322
Sri Lanka	*0*	*0*	***0***	*0*	*0*	*0*
Thailand	*0*	*0*	***0***	*0*	*0*	*0*
TOTAL	18961	17137	**21639**	16520	21039	21039

- *Total number and capacity of vessels acting in support of purse seiners*: Table 9 shows the total number of vessels that operated in support of purse seiners, and total tonnage (GT), over the period 2014-2019, and estimates of the number of support vessels for 2020. The number of support vessels is subject to limits since 2018 (ratio 1 support vessel for 2 purse seiners is applicable in 2018 and 2019). The ratio 2 support vessels for 5 purse seiners will be effective as from 2020 (IOTC Resolution 19/01). This is the reason why the number of support vessels projected for 2020 is much lower than the number existing in 2016. Therefore, future levels of support vessel capacity are expected to be lower than those existing in 2016. As for other fleets, only one support vessel has been registered, although it is not clear if that vessel is in operation.

Table 9: Purse seiners for which data was used for the Model. Number of support vessels active (no.) in the IOTC Area of Competence and total tonnage (GT) for those over the period 2014-2019; and support vessels expected to operate in 2020. Red font represents estimates.

	2014		2015		2016		2017		2018		2019		2020	
Flag	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT	no.	GT
France (EU)	0	0	0	0	**0**	**0**	0	0	0	0	4	1643	**4**	1643
Italy (EU)	0	0	0	0	**0**	**0**	0	0	0	0	0	0	**0**	0
Spain (EU)	10	3661	10	3716	**9**	**3589**	10	4108	6	2465	6	2465	**4**	1643
Seychelles	7	2603	7	2603	**7**	**2603**	8	3260	5	2038	5	2038	**4**	1630
TOTAL	17	6264	10	6319	**16**	**6192**	18	7368	11	4503	15	6146	**12**	4916

- *Total number of active FADs used by purse seiners*: Table 10 shows the number of active EU and Seychelles purse seiners (#PS) over the years 2014 to 2019, and estimates of the total number of active FADs per day monitored by each fleet, over the same period. Estimates of the number of purse seiners and active FADs for 2020 are also shown. The number of active FADs was estimated on the basis of previous levels of FAD usage by fleet and the limits on active FADs adopted by the IOTC, which are applicable since 2017. The following average number of active FADs per vessel per day was used for each fleet:

- France and Italy: The number of active purse seiners was multiplied by an average number of 175 FADs per vessel for the years 2014 to 2017 (French companies were subject to limits on the use of FADs, to 200 active FADs per vessel per day), and 250 FADs from 2018 to 2020. The reason for using these numbers is that French and Italian vessels have increased FAD usage in recent years.
- Spain: The number of active purse seiners was multiplied by an average number of 450 FADs per vessel for the years 2014 to 2017. The number of FADs since 2018 was estimated according to the FAD limits in place, assuming that the average number of active FADs used by purse seiner was 5% below the limits set by the IOTC for each year (i.e. 425 in 2018, 350 in 2019, and 300 in 2020).
- Seychelles: The eight purse seiners flagged in Seychelles in 2014 operate like the Spanish and therefore the same number of FADs than for Spain was used in this case. Since 2015, the Seychelles fleet consists on 13 purse seiners, 11 that operate like the Spanish and 2 like the French. Therefore, the total number of FADs for Seychelles was estimated according to the numbers used for French (2 vessels) and Spanish (11 vessels) purse seiners.

The number of active FADs estimated for 2020 is well below that estimated for 2016 and therefore future FAD capacity can be assumed to be below the one in the year used as reference for the model. As for other purse seine fleets, it is known that the number of FADs used by Japan, the Republic of Korea and Iran has been low over the entire period. While the actual numbers of FADs cannot be estimated, it can be assumed that those numbers have been stable over time and therefore the total number in 2020 should be lower than that in 2014 or 2016, where there were more purse seiners active. The Mauritius fleet operates as the French and therefore may have increased FAD usage in recent years. However, the number of vessels in 2020 is the same as the one in 2016 and lower than that recorded for 2014. For this reason, it can be assumed that the total number of FADs has not increased from previous levels.

Table 10: Purse seiners for which data was used for the Model. Number of active purse seiners (#PS) in the IOTC Area of Competence over the period 2014-2019 and number of active FADs per day used by the fleet estimated according to previous levels of FAD usage and the limits on active FADs adopted by the IOTC; and number of purse seiners and active FADs expected for 2020. Red font represents estimates.

	2014		2015		2016		2017		2018		2019		2020	
Flag	#PS	#FAD	#PS	#FAD	#PS	#FAD	#PS	#FAD	#PS	#FAD	#PS	#FAD	#PS	#FAD
France (EU)	13	2275	12	2100	**12**	**2100**	12	2100	12	3000	12	3000	**12**	**3000**
Italy (EU)	0	0	1	175	**1**	**175**	1	175	1	250	1	250	**1**	**250**
Spain (EU)	15	6750	15	6750	**18**	**8100**	14	6300	14	5653	15	4988	**15**	**4275**
Seychelles	8	4000	13	5850	**13**	**5850**	13	5850	13	4941	13	4158	**13**	**3635**
TOTAL	36	13025	41	14875	**44**	**16225**	40	14425	40	13844	41	12395	**41**	**11160**

- *Other considerations*: In addition to the above, the IOTC adopted additional measures to limit future increases in capacity of purse seine fleets. This includes a ban on the use of aircraft or unmanned aerial vehicles to aid fishing operations (IOTC Resolution 16/08); and a ban on the use of artificial lights to attract fish (IOTC Resolution 16/07). In particular, the latter measure led to the removal of support vessels from the *Coco de Mer* sea mounts, limiting the capacity of purse seiners to catch fish in that area.

Figure 17 summarises what future levels of purse seine capacity might be as compared with those recorded in 2016, which is the year that was used as reference for the effort input in the model. Purse seine Capacity has therefore decreased for all the components of capacity reviewed, with the highest reductions recorded for support vessels (21% reduction in support vessel GT); and FADs (31% reduction in the number of active FADs). While changes in fishing technology may also contribute to *effort creep* (e.g. through the increased use of buoys with echo-sounder) they have not been evaluated here. However, the sharp decrease in support vessel and FAD usage is expected to compensate for any future increases in efficiency of the fleet.

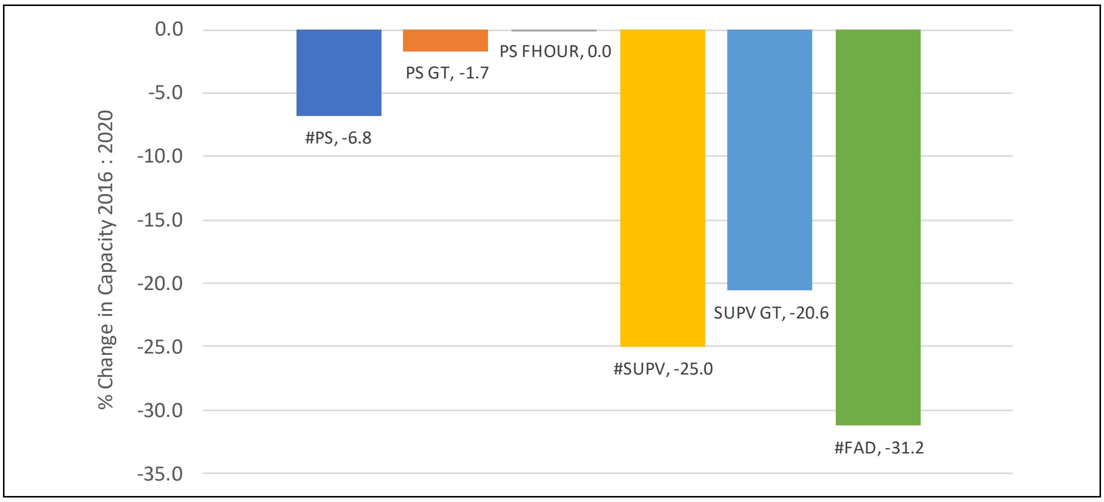


Figure 17: Purse seiners for which data was used for the Model. Changes in the capacity of industrial purse seiners active in the IOTC Area of Competence. The change is expressed (in %) as the difference between levels of purse seine capacity in 2016 and those projected for 2020, for the following components: Number of active purse seiners (#PS); total Gross Tonnage of active purse seiners (PS GT); Total number of hours fished by purse seiners (PS FHOUR); number of vessels operated in support of purse seiners (#SUPV); total Gross Tonnage of support vessels (SUPV GT); and total number of active FADs used per day (#FAD).

Implementation of the Closures to Purse Seine activity

The following steps show how the effort decision support tool can be used to implement the closures:

1. Setting the target reduction in catch required for the stock of Indian Ocean yellowfin tuna (YFT): IOTC Resolution 19/01 sets a target reduction in catches of yellowfin tuna, to achieve a 15% reduction in catch from the levels of catch recorded in 2015 (Seychelles) or 2014 (other purse seine fleets). Thus, we estimate the target catch using the figures in Table 8a:
    a. YFT Catch EU purse seiners (2014): 33513 + 57892 = 91405 tons
    b. YFT Catch Seychelles (2015): 39015 tons
    c. Reference YFT catch: 91405 + 39015 = 130420 tons
    d. YFT target catch: 130420 – (130420*15%) = 110857 tons
    e. Target reduction in YFT catch using the catches estimated by the Model, which uses effort levels in 2016 (Table 8a).
        i. YFT Catch EU and Seychelles purse seiners (Model): 141743 tons
        ii. Reduction required from 2016 YFT catch (1.e.i.) to achieve the 110857 tons catch target (1.d.): 141743-110857 = 30886 tons

iii. **Percentage YFT catch reduction required** = 30886 * 100 / 141743 = **21.8%**

Therefore, we should use the model to seek a 21.8% reduction in the catch of YFT.

2. Estimating the proportion catch reduction which is obtained for each tropical tuna stock and maturity group using the effort decision support tool: Table 11 presents the reduction in catches of tropical tunas, expressed as a percentage, that the model estimates for one day closure in each month. FHOUR refers to the number of hours fished per day in each month (estimated dividing the total monthly effort by the number of days in each month). %YFT, %BET & %SKJ refer to the contribution of the catches of each stock in one fishing day over the total catches of such stock for the whole year[17]. The two columns to the right of each stock refer to the proportion (%) that the catches of mature (M) and immature (I) fish in each day represent over the total catches of mature and immature fish estimated by the model for the whole year. Table 12 presents the values that would correspond to full monthly closures, as estimated by the model.

Table 11: Number of fishing hours (FHOUR) and levels of expected reduction (expressed as a %) in the catches of yellowfin tuna (YFT), bigeye tuna (BET) and skipjack tuna (SKJ) for each fishing day in each month estimated using the model. The two columns to the right of each %-stock show the contribution of one fishing day in each month to the reduction of catches of Mature (M) and Immature (I) fish for that stock.

MONTH	FHOUR	%YFT	%YFTM	%YFTI	%BET	%BETM	%BETI	%SKJ	%SKJM	%SKJI
JAN	435	0.51	0.67	0.15	0.36	0.60	0.23	0.15	0.15	0.07
FEB	422	0.49	0.60	0.24	0.38	0.58	0.28	0.24	0.24	0.08
*FEB**	*408*	*0.48*	*0.58*	*0.23*	*0.37*	*0.56*	*0.27*	*0.23*	*0.23*	*0.08*
MAR	358	0.23	0.19	0.34	0.31	0.18	0.38	0.35	0.35	0.21
APR	323	0.20	0.20	0.21	0.20	0.17	0.22	0.27	0.27	0.21
MAY	315	0.14	0.14	0.14	0.12	0.11	0.13	0.25	0.25	0.08
JUN	259	0.26	0.33	0.11	0.29	0.64	0.10	0.09	0.09	0.11
JUL	301	0.23	0.26	0.16	0.24	0.33	0.19	0.17	0.17	0.18
AUG	364	0.18	0.08	0.41	0.30	0.06	0.42	0.42	0.42	0.46
SEP	343	0.24	0.12	0.51	0.34	0.08	0.47	0.45	0.45	0.69
OCT	309	0.24	0.13	0.50	0.29	0.10	0.39	0.48	0.48	0.81
NOV	338	0.26	0.24	0.32	0.26	0.18	0.30	0.30	0.30	0.28
DEC	342	0.33	0.39	0.19	0.21	0.32	0.15	0.12	0.12	0.08

* Applies to leap years (e.g. 2020)

[17] Refer to the Tables 2 (YFT), 3 (BET) & 4 (SKJ) for details about the total effort and catch estimated by the model, by stock, fishing mode and maturity stage.

Table 12: Number of fishing hours (FHOUR) and levels of expected reduction (expressed as a %) in the catches of yellowfin tuna (YFT), bigeye tuna (BET) and skipjack tuna (SKJ) corresponding to full month closures, as estimated using the model. The two columns to the right of each %-stock show the contribution of full month closures to the reduction of catches of Mature (M) and Immature (I) fish for that stock.

MONTH	FHOUR	%YFT	%YFTM	%YFTI	%BET	%BETM	%BETI	%SKJ	%SKJM	%SKJI
JAN	13490	15.8	20.7	4.6	11.1	18.5	7.2	4.7	4.7	2.1
FEB	11827	13.8	16.9	6.7	10.8	16.3	7.8	6.7	6.7	2.2
MAR	11106	7.3	5.8	**10.6**	9.7	5.6	**11.9**	10.8	10.9	6.6
APR	9699	6.0	6.0	6.2	6.1	5.0	6.7	8.0	8.0	6.4
MAY	9753	4.3	4.3	4.5	3.7	3.3	3.9	7.7	7.7	2.6
JUN	7759	7.8	9.8	3.2	8.7	19.1	3.1	2.6	2.6	3.3
JUL	9332	7.2	8.2	5.1	7.4	10.2	5.8	5.2	5.2	5.4
AUG	11281	5.5	2.4	**12.6**	9.2	1.9	**13.2**	13.0	12.9	14.1
SEP	10301	7.1	3.5	**15.2**	10.2	2.5	**14.2**	13.6	13.6	20.6
OCT	9592	7.5	4.0	**15.5**	8.9	3.0	**12.1**	14.9	14.8	25.2
NOV	10133	7.8	7.1	**9.6**	7.7	5.5	**8.9**	8.9	8.9	8.5
DEC	10603	10.3	12.2	6.0	6.5	9.8	4.7	3.9	3.9	2.4
TOTAL	124875	100	101	100	100	101	100	100	100	100

3. Setting up scenarios of catch reduction for the closures: Table 13 shows the scenarios of YFT catch reductions used. The number of days closure were estimated using the model, to achieve the target catch reductions in the Table. Scenario 1, in bold, refers to the base case, which contemplate a 21.8% reduction in YFT catch from the catch in the reference year(s). The other two scenarios contemplate set asides of -2% and -5% of the catch limits. These scenarios are used to account for the lower fishing capacity that purse seiners will have in 2020 as compared with the reference year used for the model (as presented in the previous section). Set aside scenarios are used to account for changes in efficiency of purse seiners (*effort creep*). Negative scenarios are used because purse seine efficiency is thought to have decreased through the adoption of regulations to limit support vessel and FAD capacity, at levels of effort similar to those existing in 2016.

Table 13: Catch limit scenarios used for purse seine fisheries.

Stock	Ref. Catch YFT 2016 (Model)	Scenario	% Set Aside	Target Catch	Catch Red.	Actual % Red.
YFT	141,743	**1**	**0.0**	110,857	30,886	21.8
		2	-2.0	113,074	28,669	20.2
		3	-5.0	116,400	25,343	17.9

4. Obtaining all individual Closures from which the expected reduction in YFT catch would be achieved for each scenario: The following step looks for Closures through which the catch reductions recorded in Table 13 are achieved. This is done using the data in Table 11, assuming that purse seine catch and effort is spread evenly over each month (i.e. the reduction in catch

achieved in all days of a specific month is the same[18]). An example of the effort reductions required to achieve the catch reduction in Table 13, Scenario 1, is presented in **Table 14** below. The levels of catch reduction by stock, fishing mode and maturity stage, as estimated from the Model, are also presented. The shortest Closures estimated by the Model are 72 days long (7-Feb to 18-Apr 2020), through which the catch target would be achieved, representing a 21.8% reduction in catches of YFT. The Model also presents the catch and % reductions expected for SKJ and BET.

Table 14: Example of Model set up to achieve the target reduction in catch expected for the yellowfin tuna stock. The top table shows an example of the number of days fished over the year, in particular over the period in which the number of days fished shall be reduced to achieve the target reduction (Feb to Apr). The table at the bottom shows the gain in terms of catch reduction for each stock and maturity stage, as estimated by the model.

Month	DAYS FISHED	MONTH DAYS	Closure From To	Ref. Fishing Days	Eff Scaling	INPUT eff
Jan	31	31		13490	1.00	13490
Feb	**6**	**29**	**7-Feb**	**11827**	**0.21**	**2447**
Mar	**0**	**31**	**: :**	**11106**	**0.00**	**0**
Apr	**12**	**30**	**18-Apr**	**9699**	**0.40**	**3880**
May	31	31		9753	1.00	9753
: :	: :	: :		: :	: :	: :
Dec	31	31		10603	1.00	10603

↓

Stock-Fishing_Mode-Maturity	Catch Model	Catch Closure (Model)	%Red	%Red Mat / Imm	Est. Catch (Model)	%Sp Red	%Red Tcatch
YFT_Free_Mature	83,301	63,919	23.27	**22.77**	**110,800**	**21.83**	22.31
YFT_Associated_Mature	15,421	12,319	20.11				
YFT_Free_Immature	4,104	3,310	19.35	**19.66**			
YFT_Associated_Immature	38,918	31,252	19.70				
BET_Free_Mature	6,832	5,314	22.22	21.40	16,189	21.93	
BET_Associated_Mature	390	354	9.27				
BET_Free_Immature	779	621	20.29	22.15			
BET_Associated_Immature	12,737	9,901	22.26				
SKJ_Free_Mature	18,939	14,942	21.11	21.02	105,412	20.94	
SKJ_Associated_Mature	113,139	89,378	21.00				
SKJ_Free_Immature	18	11	40.56	12.24			
SKJ_Associated_Immature	1,226	1,081	11.81				

The Model estimates as many Closures as possible in each year and for each of the scenarios in **Table 13** (i.e. the outcome is 365/6 scenarios per year and scenario in **Table 13**).

[18] For more precise estimates daily catches could be used. However, EU and Seychelles purse seiners use quarterly time-steps to adjust logbook catches, using data from sampling in port. Therefore, the assumption made here that effort is equally distributed over all fishing days within a month is a plausible one.

5. Obtaining scenarios of Pairs of Closures through which the expected reduction in catches of yellowfin tuna is achieved: Once that all the scenarios are estimated, the process searches for pairs of scenarios, according to the following criteria:
    a. The scenarios have the same duration in terms of total number of closure days;
    b. The two scenarios making up each pair do not overlap and are separated by at least 30 days.

   The process picks then closures which do not differ more than 5% in terms of the number of days closure estimated (e.g. 80 days closures are matched with closures ranging from 76 to 84 days), adding days to the shortest closure and removing days from the largest until the closures have the same size and the expected catch reduction is achieved. At the end of the process all those closures for each a pair is not found are removed (this normally refers to the shortest closures in the year, for which a second window is difficult to find). **Figure 18** shows a summary of the closures identified for the three scenarios in Table 13, their duration, and the gain in terms of reduction in catches of yellowfin tuna and other stocks, by maturity stage.

6. Sorting the Closures according to the expected targets: All the scenarios of pairs of Closures identified were sorted according to the following:
    a. The number of days closure were scaled to represent values between 0 and 100, with 0 assigned to the Closure representing the maximum number of days and 100 to that representing the minimum number of days; all remaining values were scaled to values between 0 and 100; [${}^{100}_{1}ndClose$]
    b. The gains in terms of reduction of catches of each stock and maturity stage were scaled to represent values between 0 and 100, according to the following criteria:
        i. Total catch by stock and catches of Mature fish (YFT; YFT_Mature; BET; BET_Mature; SKJ; SKJ_Mature): The lowest % of catch reduction of each category was set to 100 while the highest was made 0; all remaining values were scaled to values between 0 and 100; (${}^{100}_{1}YFT$; ${}^{100}_{1}YFT_M$; ${}^{100}_{1}BET$; ${}^{100}_{1}BET_M$; ${}^{100}_{1}SKJ$; ${}^{100}_{1}SKJ_M$)
        ii. Total catch of Immature fish (YFT_Immature; BET_Immature): The highest % of catch reduction of each category was scaled up to represent 100 while the lowest was scaled to 0; all remaining values were scaled to values between 0 and 100; (${}^{100}_{1}YFT_I$; ${}^{100}_{1}BET_I$)

    The following function was used to assign scores to each scenario:

$${}^{100}_{1}ndClose + ((({}^{100}_{1}YFT + ({}^{100}_{1}BET * 3) + ({}^{100}_{1}SKJ * 3) + ({}^{100}_{1}YFT_M * 3) + {}^{100}_{1}BET_M + {}^{100}_{1}SKJ_M + ({}^{100}_{1}YFT_I * 6) + ({}^{100}_{1}BET_I * 4)) / 22) * 2)$$

    Therefore, the length of the closure in terms of number of days represents one third of the total score, with the proportion catch reduction representing two thirds of the score. Catch reductions are weighted according to the following:

    - Scenarios with the lowest reduction in catch of BET and SKJ are promoted (i.e. $({}^{100}_{1}BET * 3) + ({}^{100}_{1}SKJ * 3)$)
    - Scenarios with the lowest reduction of mature YFT are promoted (i.e. $({}^{100}_{1}YFT_M * 3)$);
    - Scenarios with the highest reduction of immature YFT and BET are promoted (i.e. $({}^{100}_{1}YFT_I * 6) + ({}^{100}_{1}BET_I * 4)$).

Finally, all scenarios are sorted from the one getting the highest score to the one getting the lowest. An example of this is presented in **Table 15**.

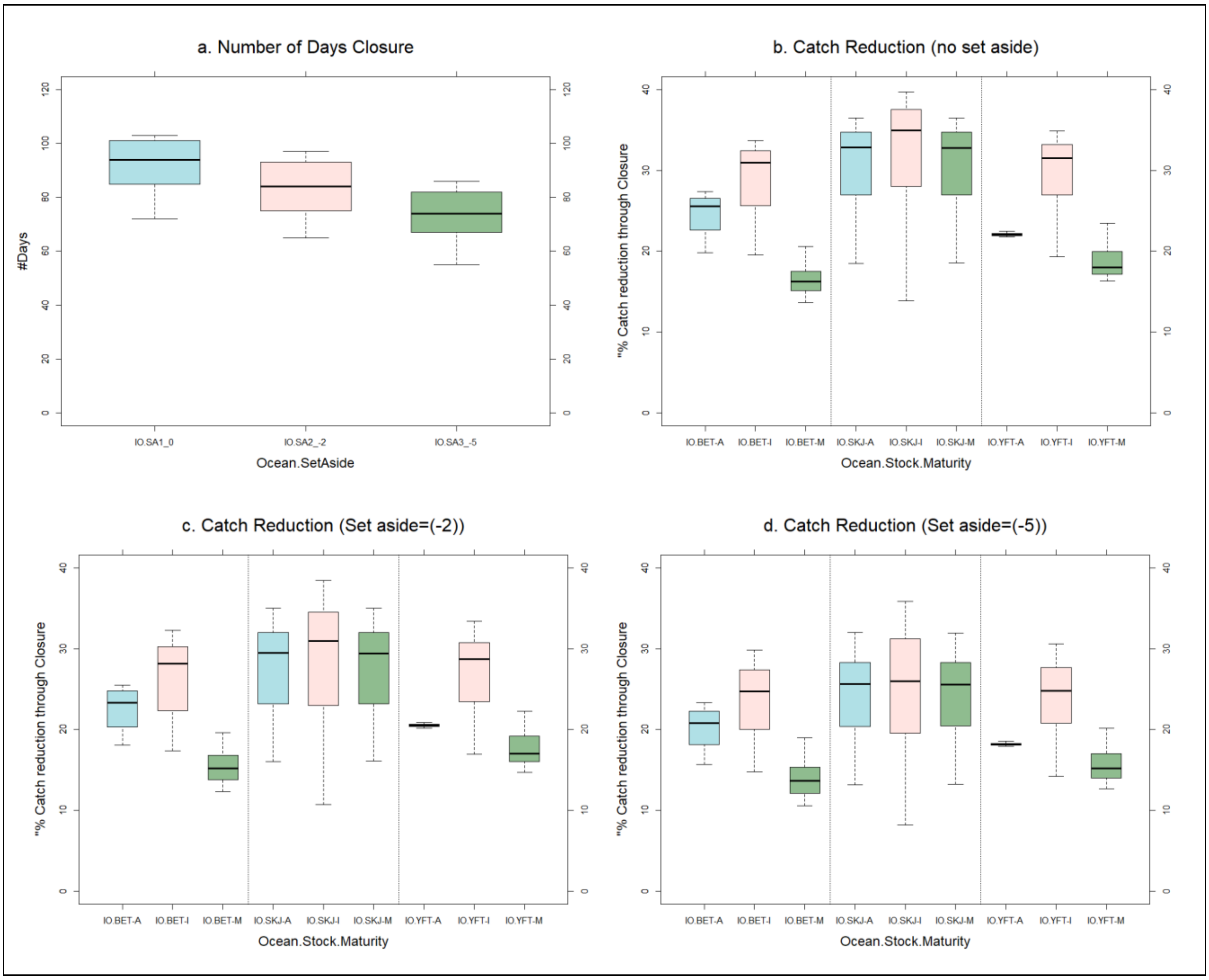


Figure 18. Box plots showing all scenarios of pairs of closures from which the expected 21.8% reduction in catches of yellowfin tuna can be obtained, according to the three scenarios presented in Table 13.

a. Length of each of the two closures, in number of days, for scenario 1 (no set aside; IOSA1_0), scenario 2 (set aside is -2%; IOSA2_-2), and scenario 3 (set aside is -5%; IOSA3_-5);
b. Reduction (%) in catches of yellowfin tuna, skipjack tuna and bigeye tuna expected for all pairs of closures identified for scenarios with no set aside: overall by stock (IO.BET-A; IO.SKJ-A; IO.YFT-A); and for Immature (IO.BET-I; IO.SKJ-I; IO.YFT-I) and Mature fish (IO.BET-M; IO.SKJ-M; IO.YFT-M);
c. Reduction in catches of yellowfin tuna, skipjack tuna and bigeye tuna expected for all pairs of closures identified for scenarios with set aside -2; refer to b. for label description;
d. Reduction in catches of yellowfin tuna, skipjack tuna and bigeye tuna expected for all pairs of closures identified for scenarios with set aside -5; refer to b. for label description.

The bottom and top of the box represent the 25th and 75th percentile (the lower and upper quartiles, respectively), and the band near the middle of the box is the 50th percentile (the median); default R boxplot settings apply to whiskers and notches.

Table 15. Example of resulting scenarios of pairs of Closures sorted according to its scoring with the highest scores shown at the top of the table and the lowest at the bottom. The gain in terms of reduction of catches of each stock and maturity stage are also shown (bold font was used to highlight the stock that is the target of the measure (YFT-A) and immature YFT (YFT-I) and BET (BET-I) for which the highest reductions are promoted (further details are presented in the text).

Stock	nD Close	Score	Cls1F	Cls1T	Cls2F	Cls2T	BET-A	BET-I	BET-M	SKJ-A	SKJ-I	SKJ-M	YFT-A	YFT-I	YFT-M
YFT	74	266.7	20-Feb	03-May	27-Aug	08-Nov	0.21	**0.26**	0.12	0.27	0.32	0.27	**0.18**	**0.27**	0.14
YFT	76	266.7	21-Feb	06-May	21-Aug	04-Nov	0.22	**0.27**	0.12	0.28	0.33	0.28	**0.18**	**0.28**	0.14
YFT	72	266.3	19-Feb	30-Apr	03-Sep	13-Nov	0.21	**0.25**	0.12	0.26	0.31	0.26	**0.18**	**0.27**	0.14
YFT	74	266.3	20-Feb	03-May	28-Aug	09-Nov	0.21	**0.26**	0.12	0.27	0.32	0.27	**0.18**	**0.27**	0.14
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
YFT	103	210.3	04-Jul	15-Oct	23-Feb	05-Jun	0.27	0.32	0.18	0.34	0.34	0.34	0.23	0.32	0.19
YFT	98	209.5	17-Feb	24-May	27-Jun	02-Oct	0.26	0.30	0.19	0.30	0.29	0.30	0.22	0.29	0.19

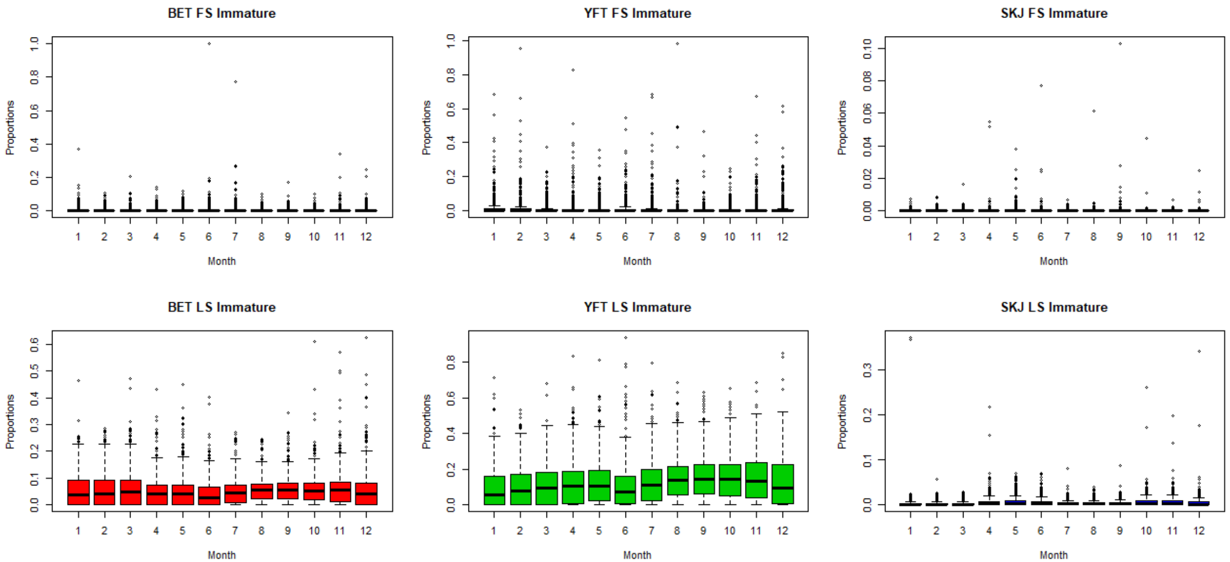


Figure 1: Seasonal proportions of BET, YFT and SKJ for Immature fish by Free school and log school

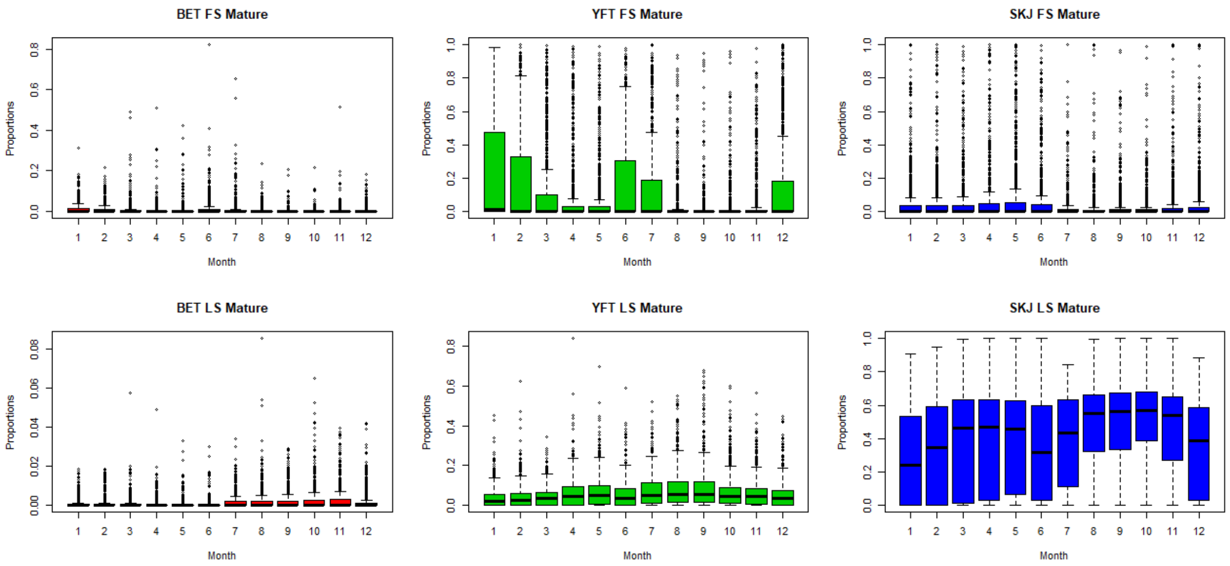


Figure 2: Seasonal proportions of BET, YFT and SKJ for Mature fish by Free school and log school

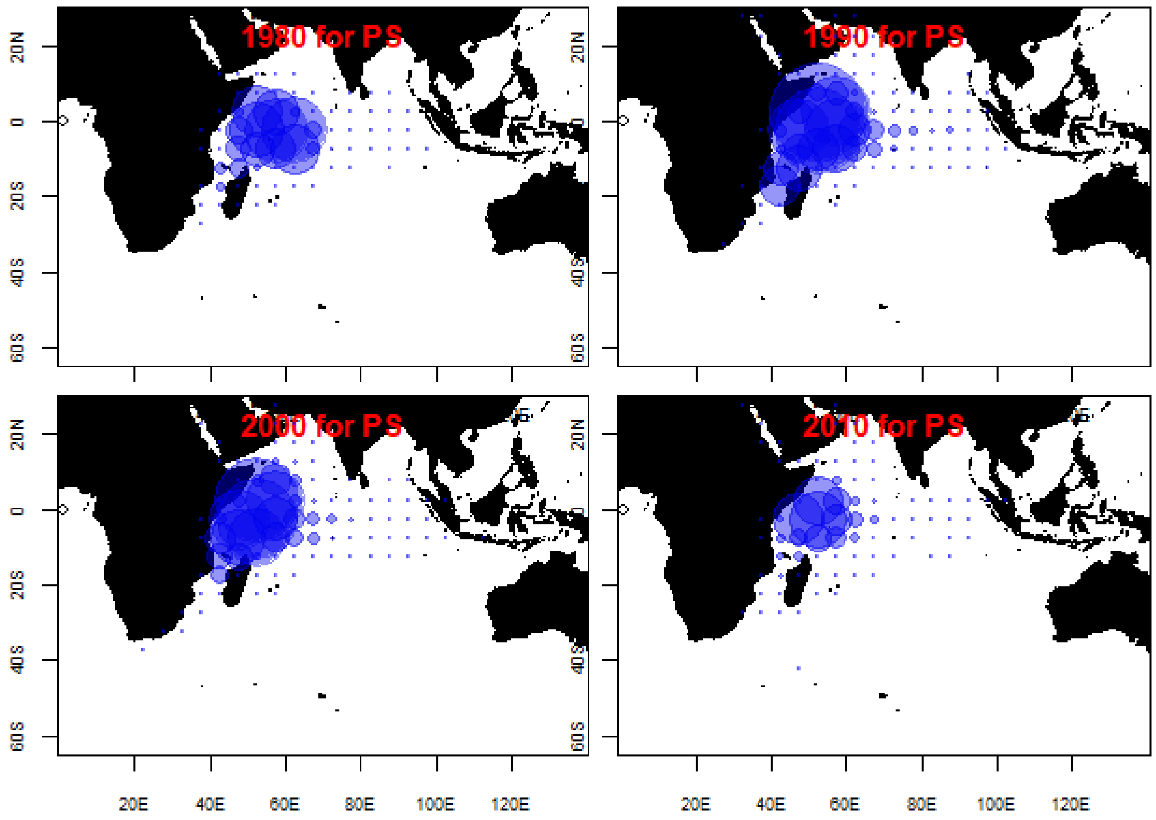


Figure 3: Effort distribution for the PS fleet in the Indian Ocean by the 1980's to 2010's. Magnitude and spatial extent of the PS fishery has remained the same

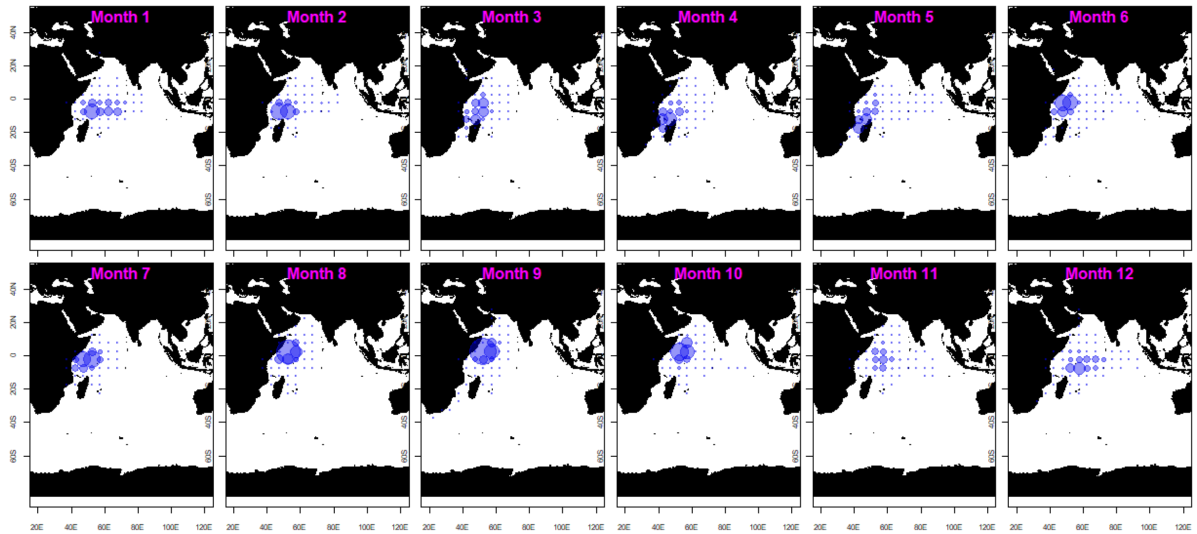


Figure 4: Temporal distribution by month for PS fishery (Month 1=January, Month 12=December on aggregated data over the period 2002-2017)

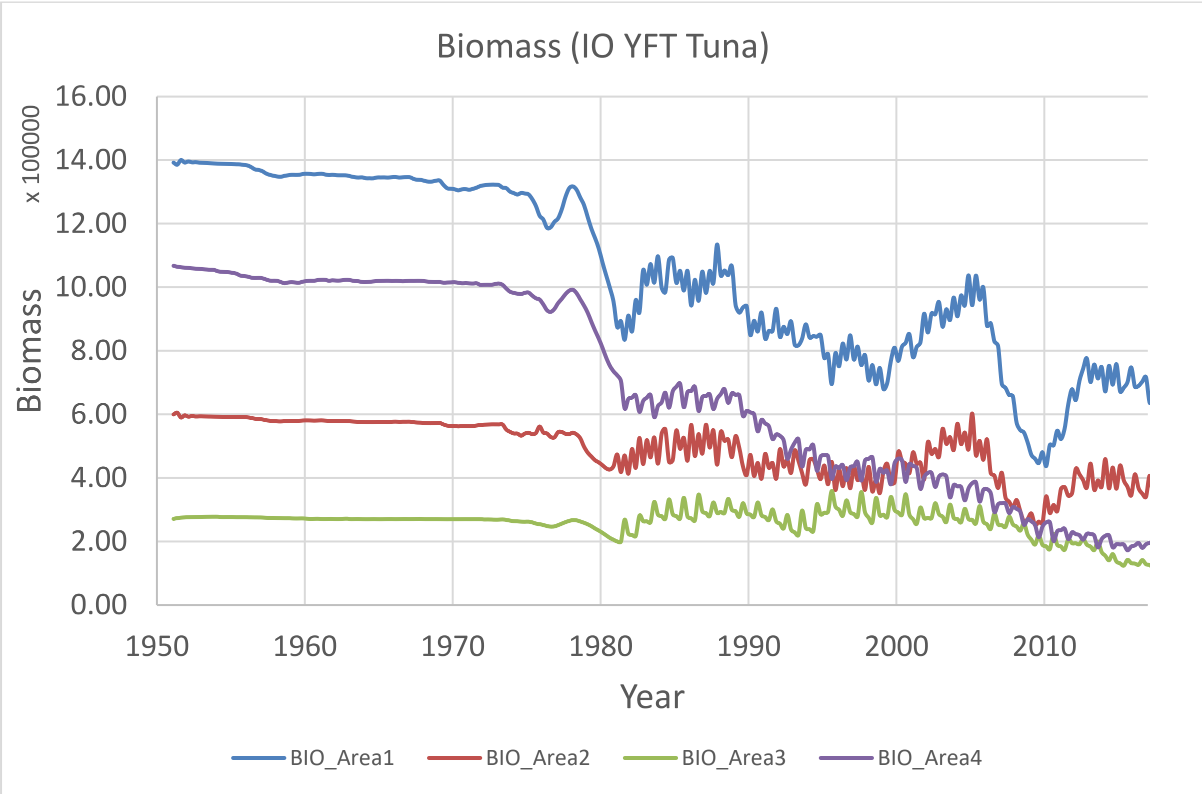
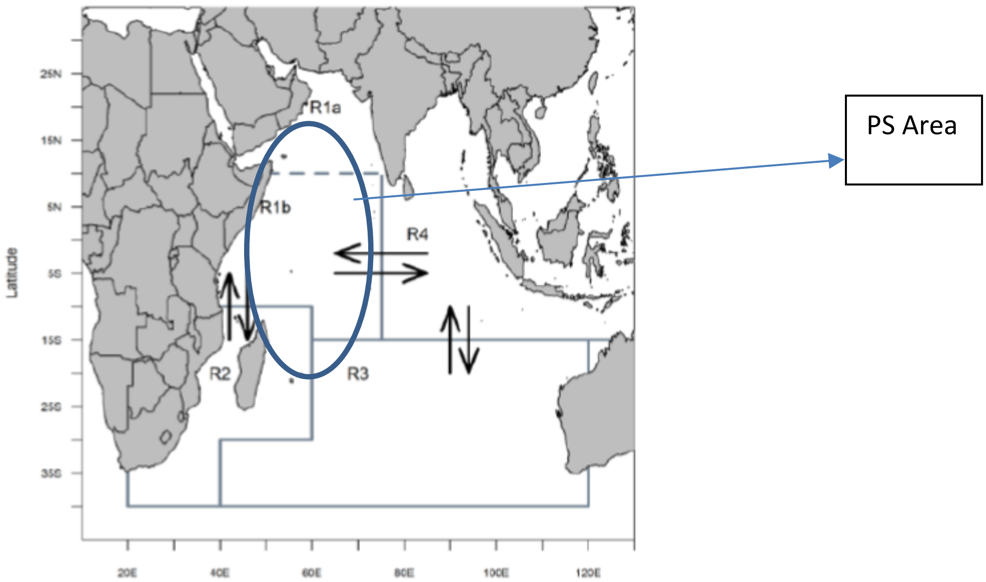
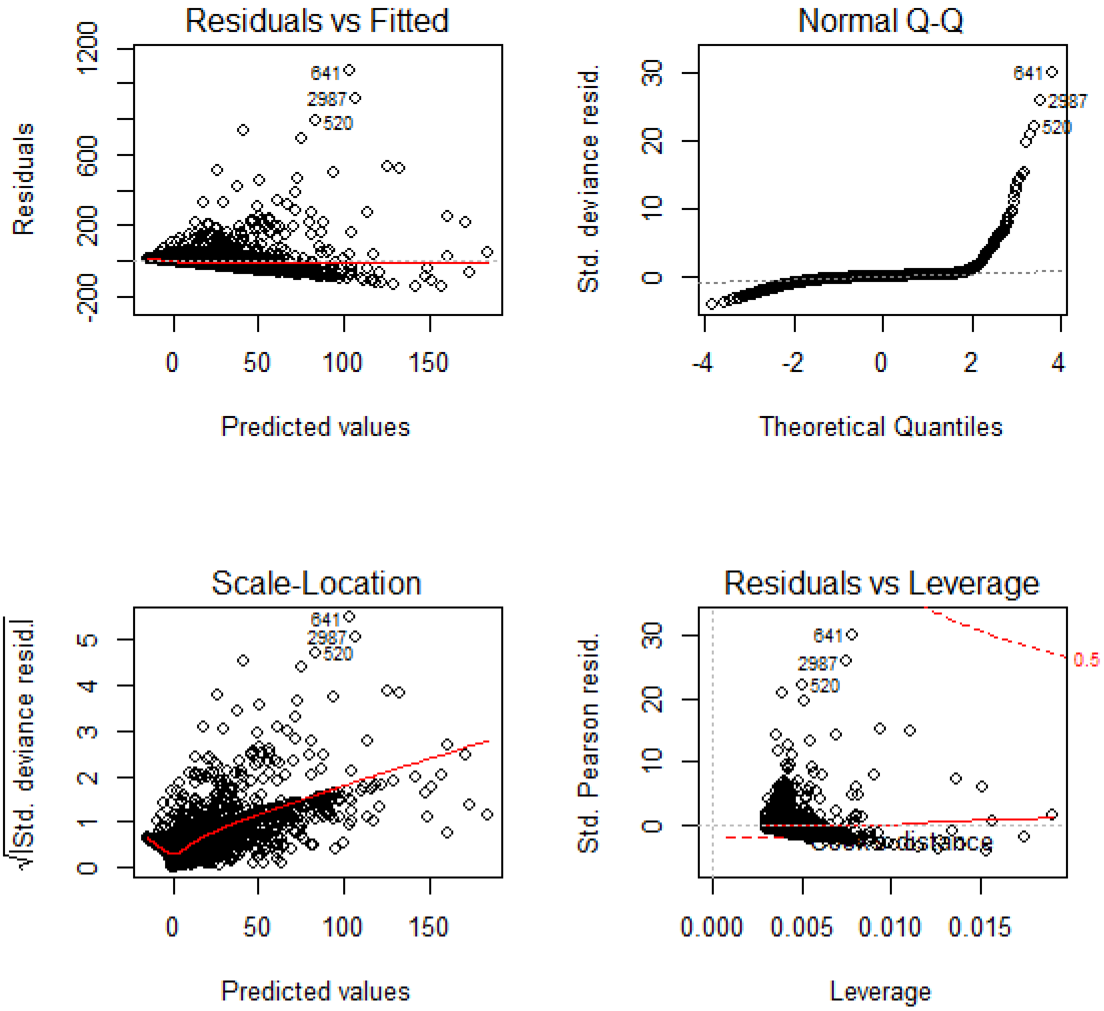


Figure 5: YFT abundance trends from last assessment (base run) using a quarterly time step.





Model 6: YFT Immatue with Year effect

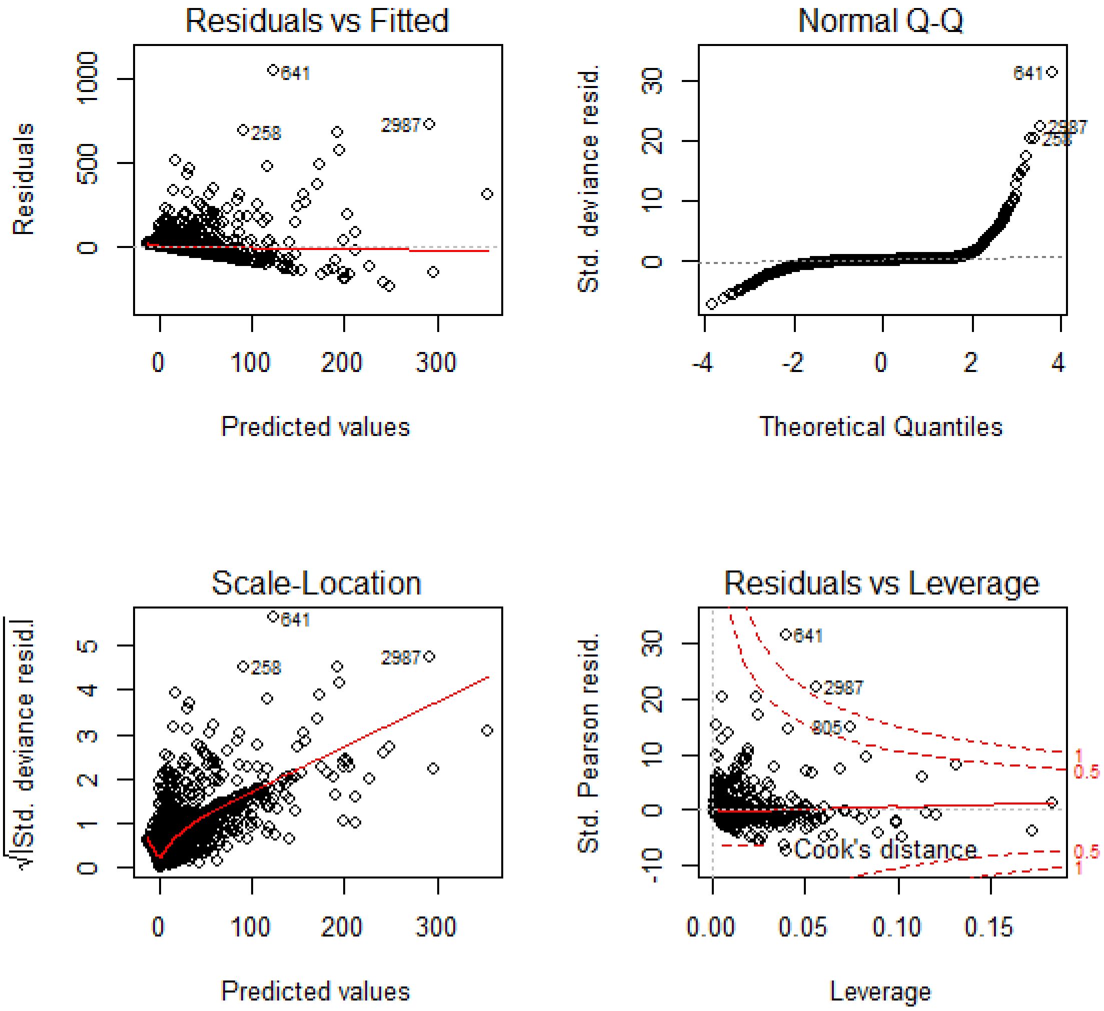


Figure 7: Model 2: YFT Immature no year effect but Month:Effort interaction (FINAL MODEL CHOSEN FOR ALL STOCKS). Biomass accounts for Year effect.

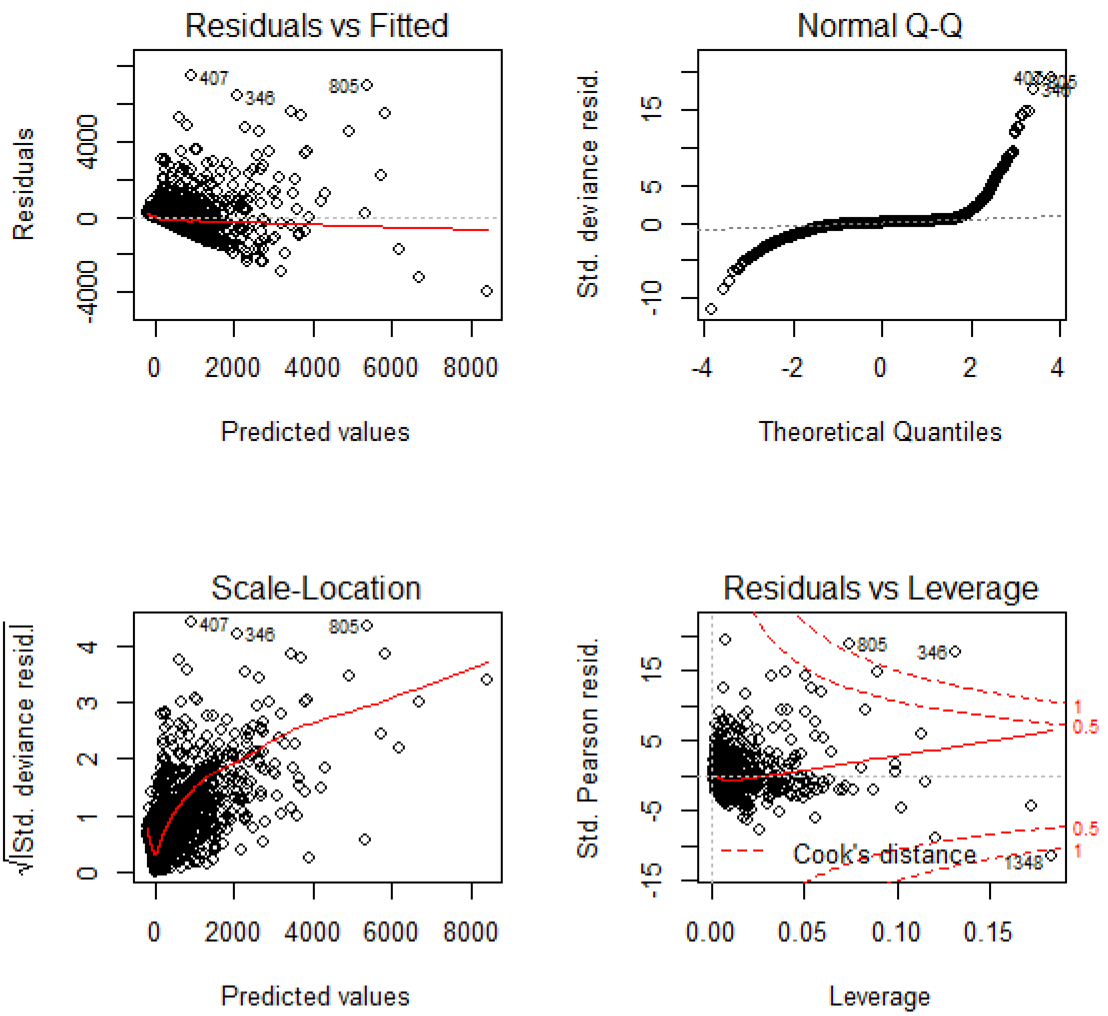


Figure 8: Model 3; YFT Mature_FS with month effort interaction

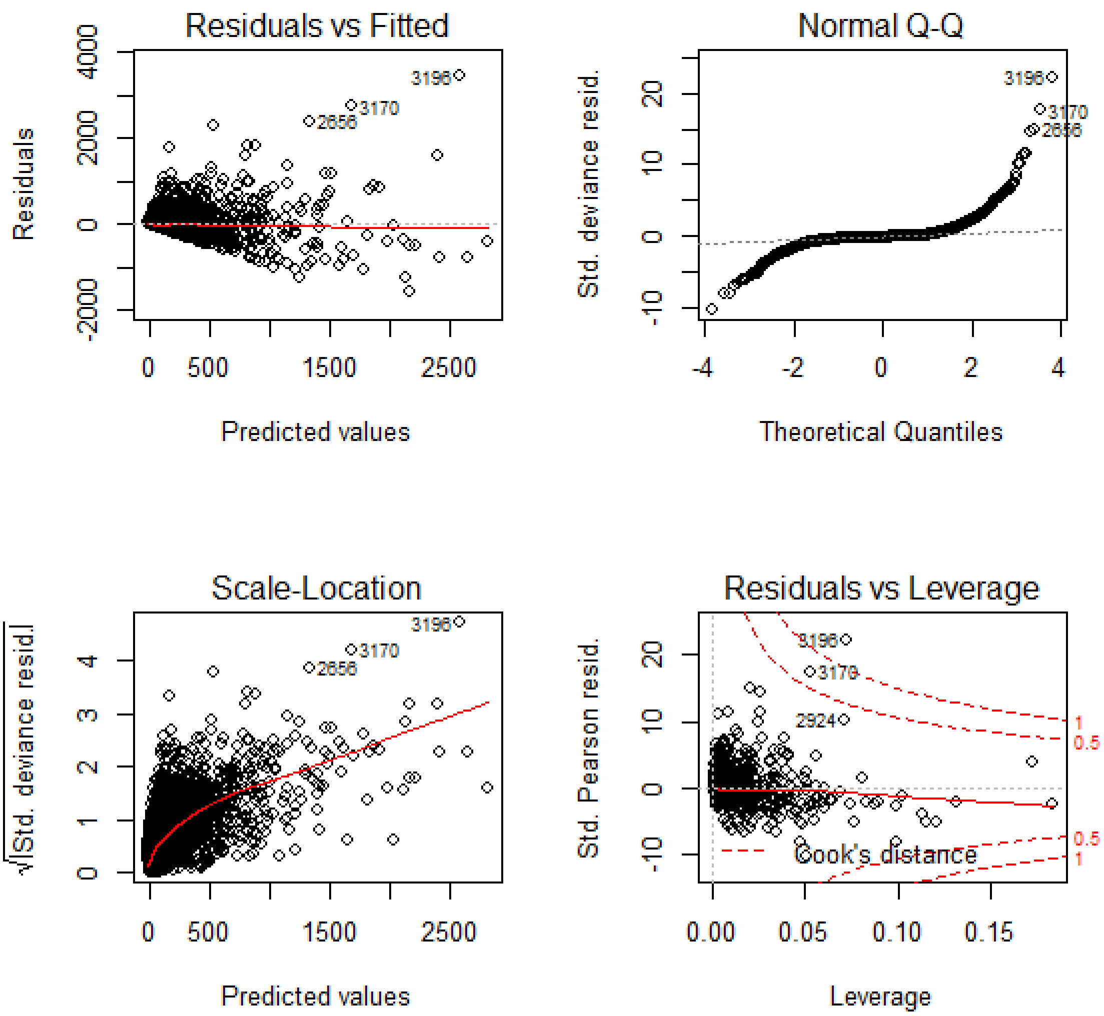


Figure 9: Model 4-YFT Immature_LS with month effort interaction

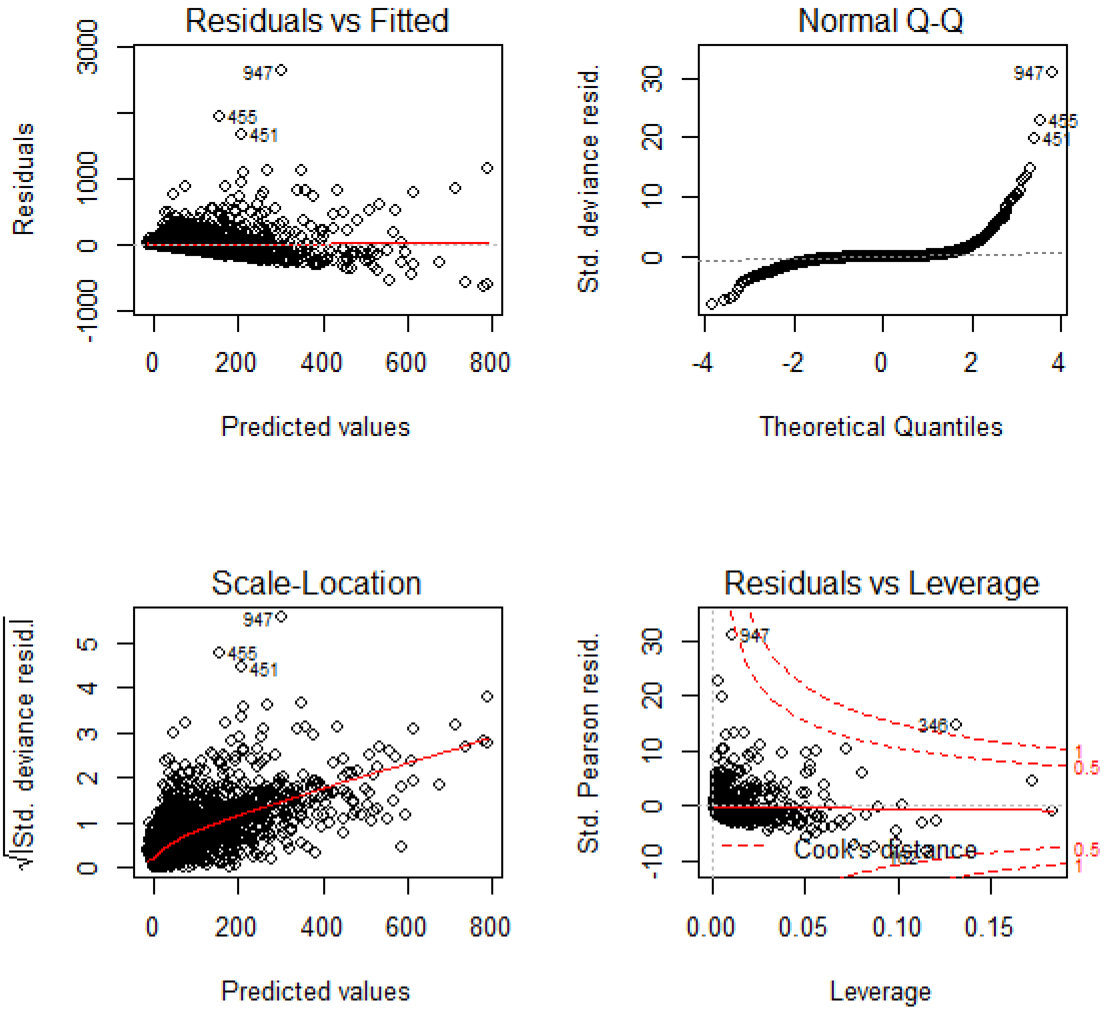


Figure 10: Model 5- YFT Mature_LS with month effort interaction

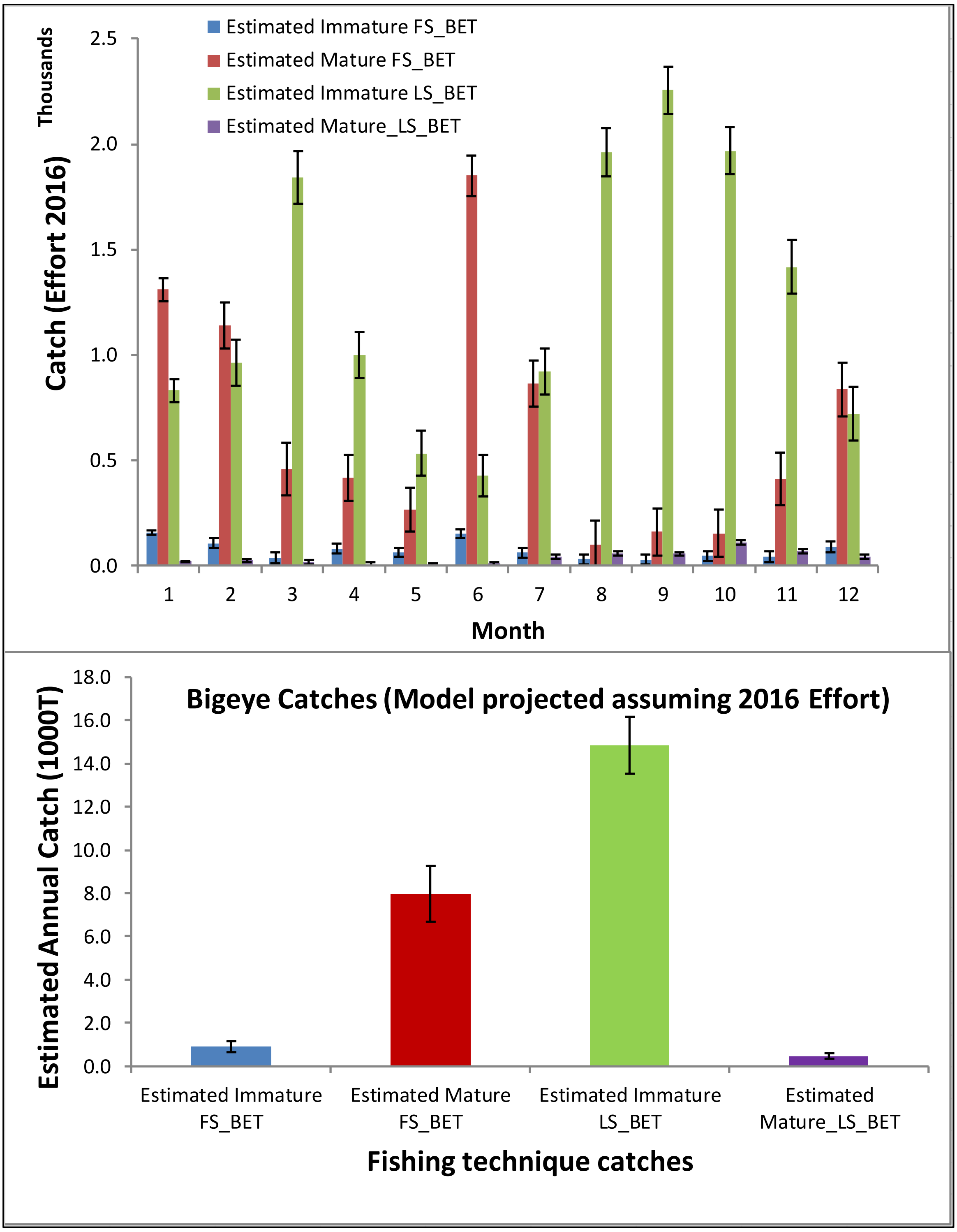


Figure 11: Base Distribution BET (2016 Effort)

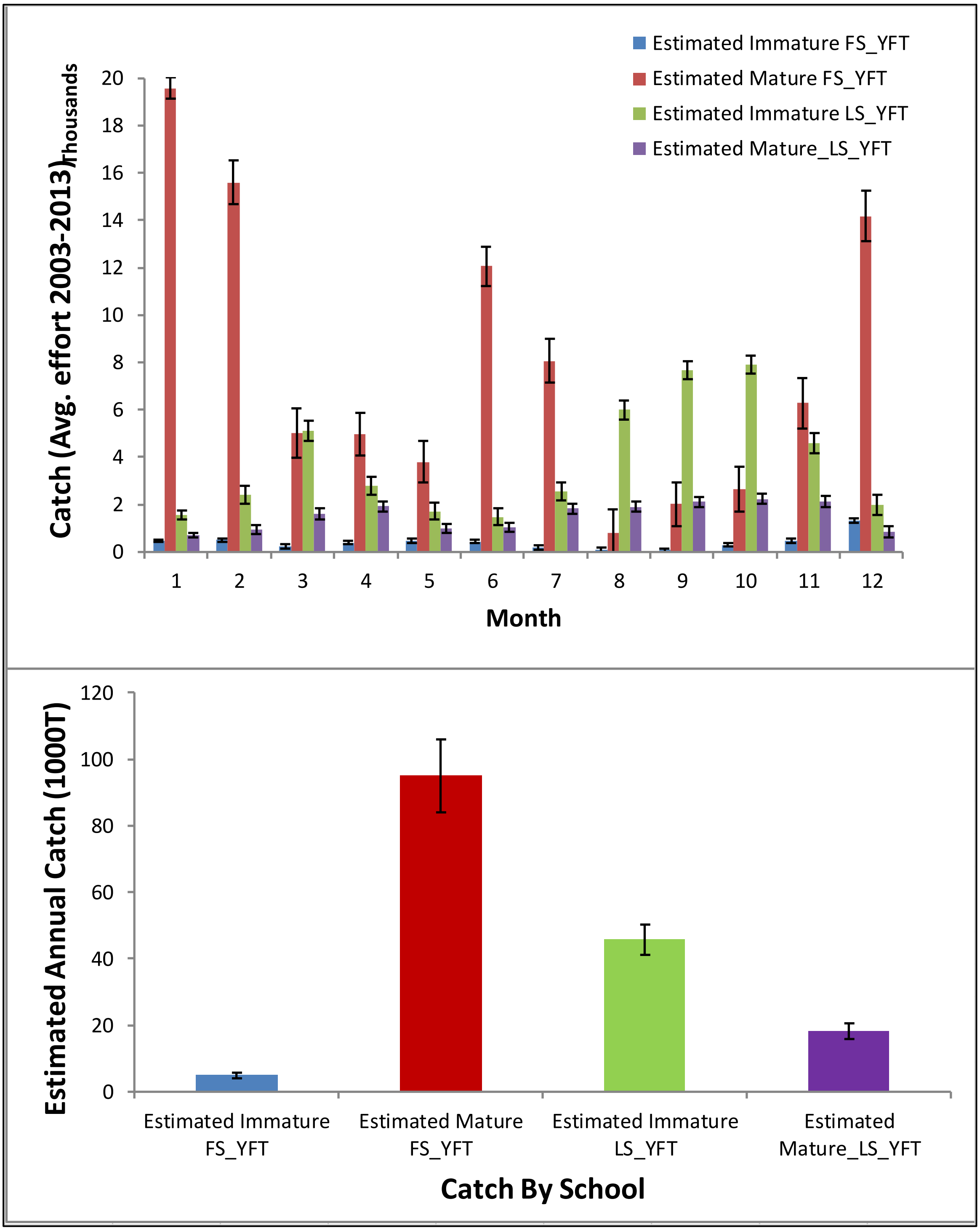


Figure 12: Base Distribution YFT (2016 Effort)

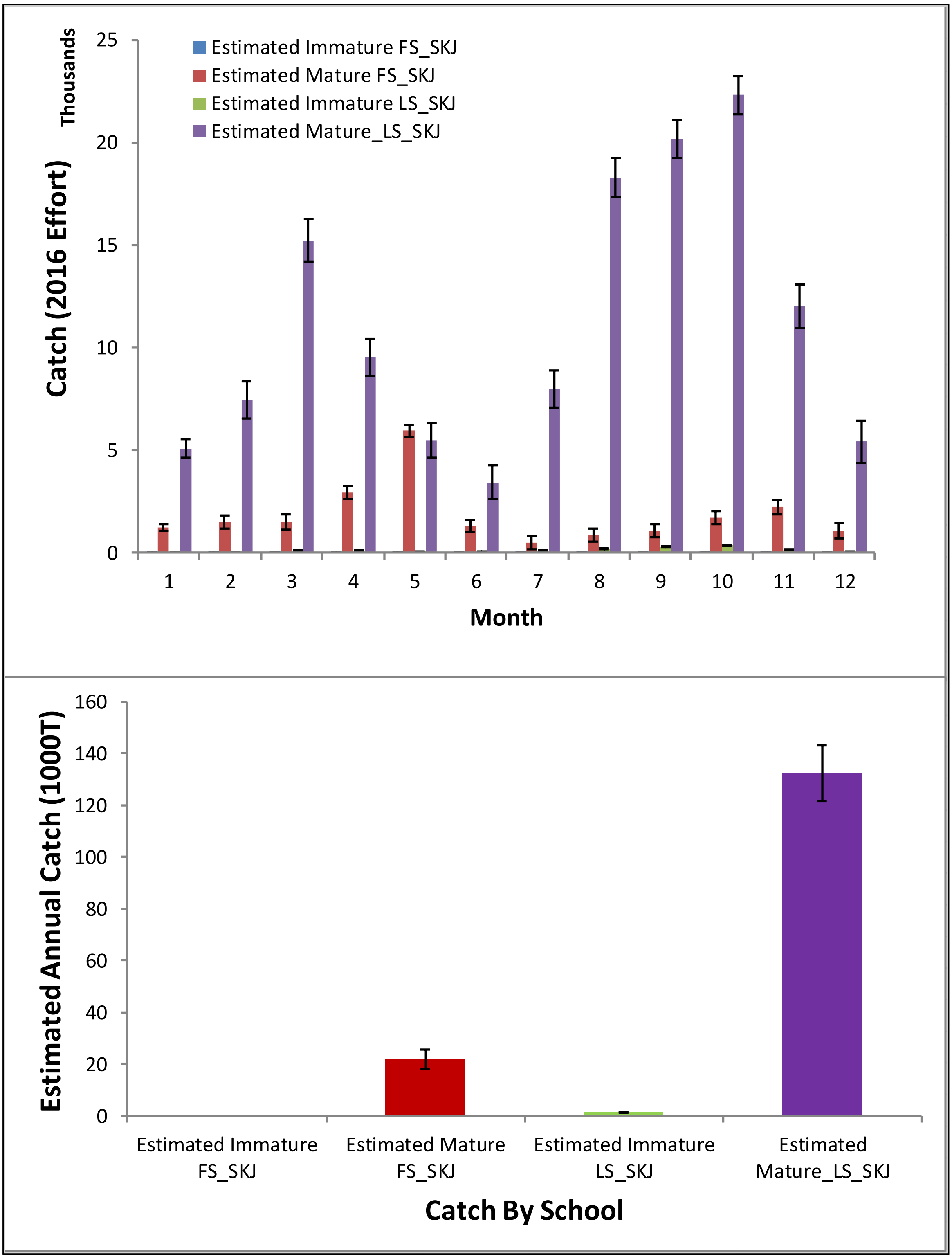


Figure 13: Base Distribution SKJ (2016 Effort)

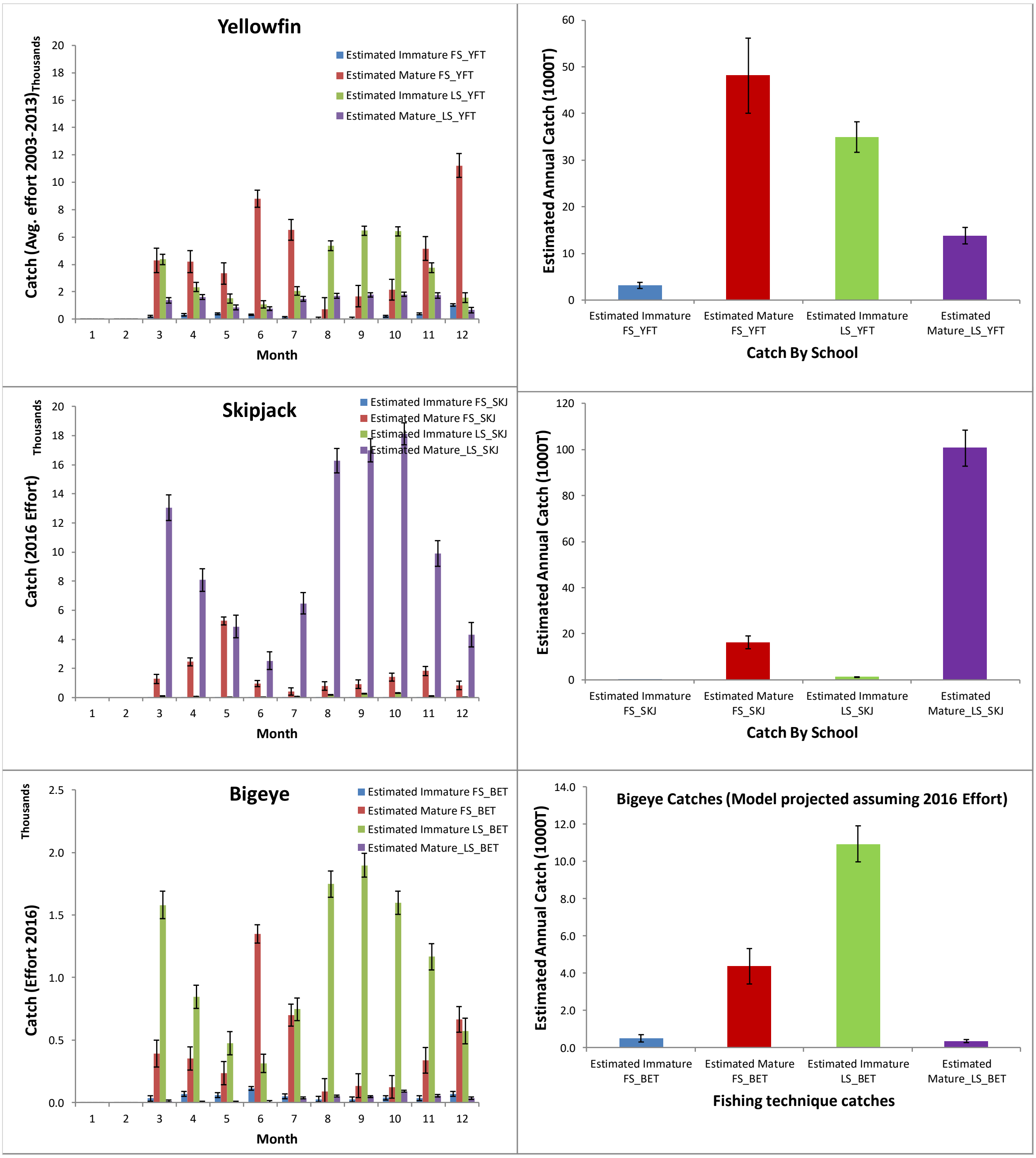


Figure 14: Model 1: Effort closure to minimize YFT catch but keep Skipjack Fishing at decent potential (2 month closure in January & February)

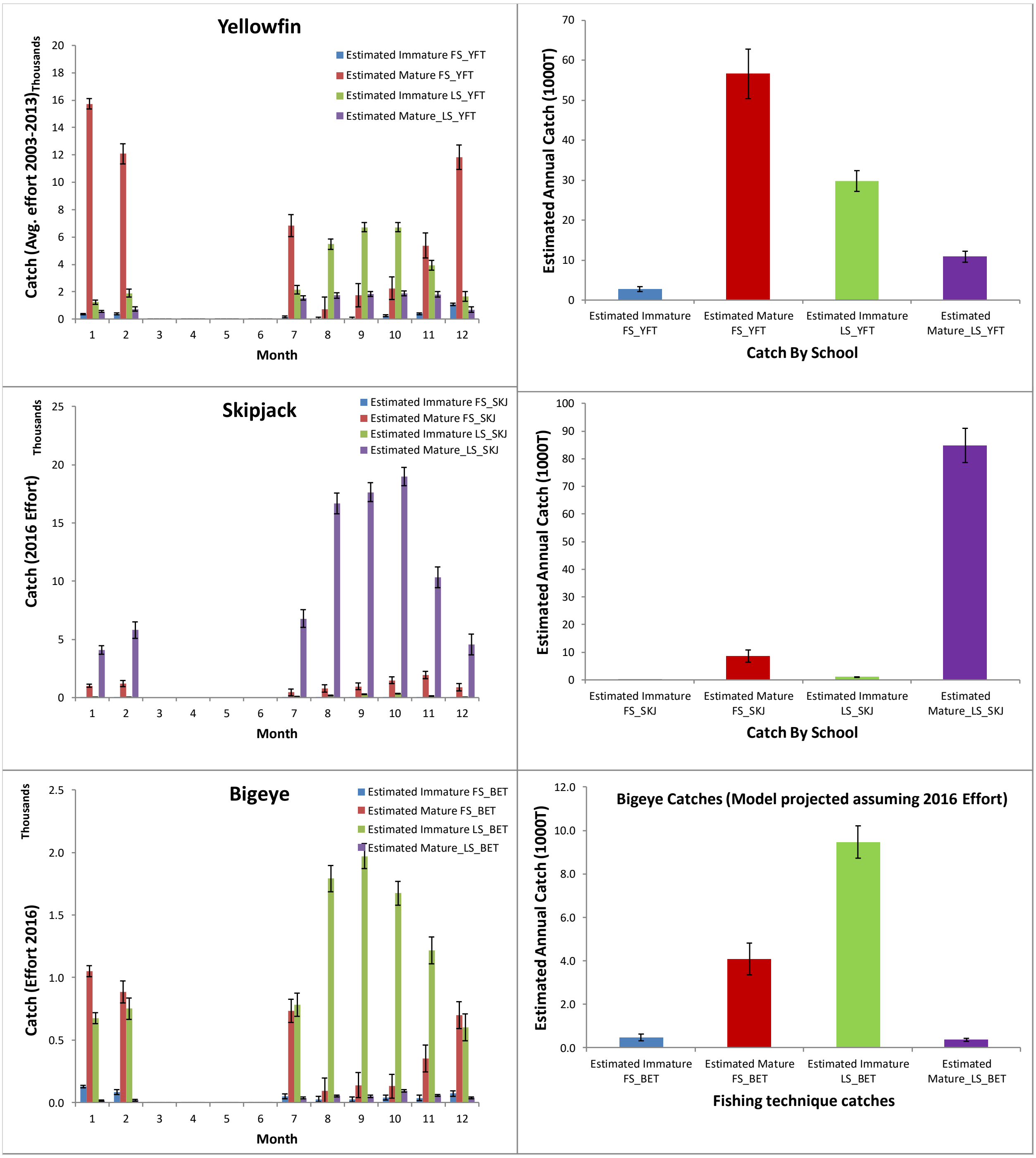


Figure 15: Model 2: Effort closure to minimize loss in Northern summer (close 3-6)

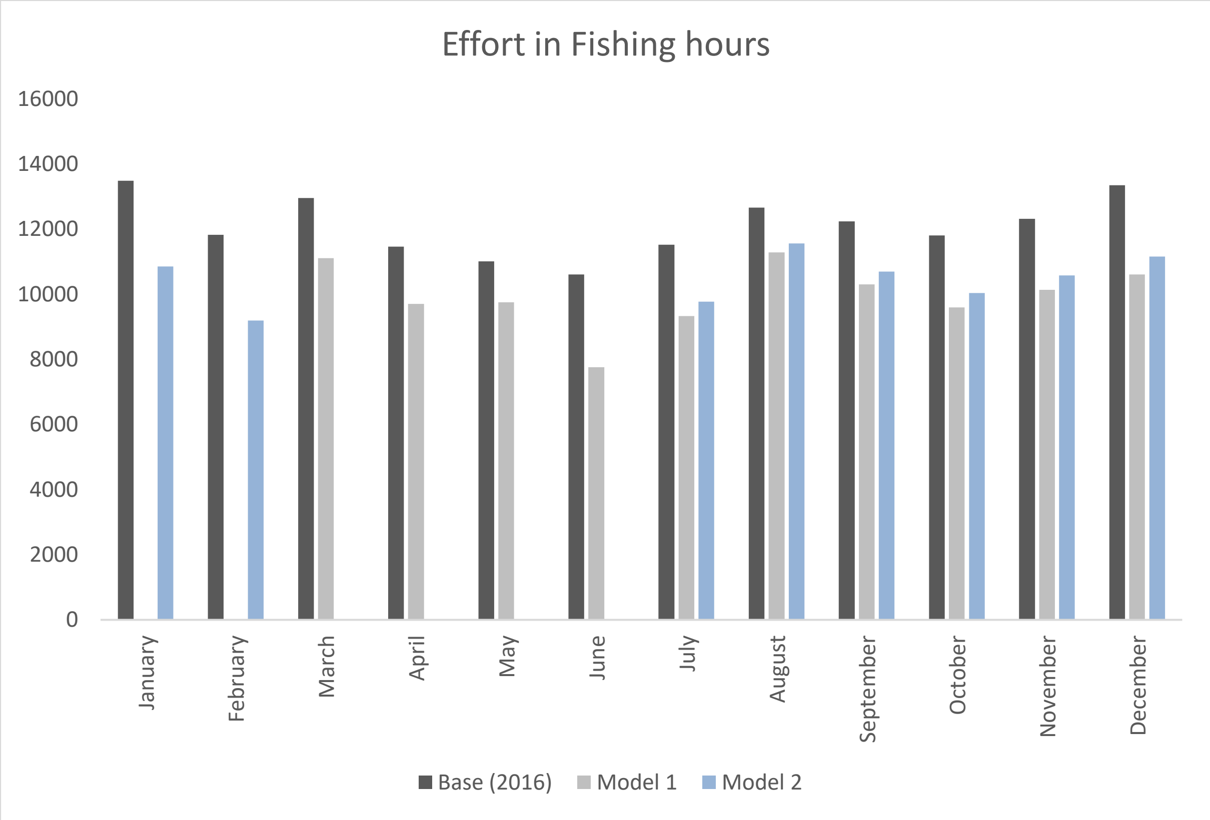


Figure 16: Effort comparisons for Base (observed effort in 2016) and Model 1 and Model 2. Both meet the goal of restricting YFT catches in PS to 100,000T. Note that in Model 1, there is no effort in January and February and Model 2 March through June. The effort in all other months has to reduce as well to meet the target of achieving 100,000T