USING EFFORT CONTROL MEASURES TO IMPLEMENT CATCH CAPACITY LIMITS IN ICCAT PS FISHERIES: AN UPDATE

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SUMMARY

Total Allowable Catches (TAC's) have been implemented for numerous stocks by ICCAT. However, in the case of tropical tunas (yellowfin tuna [Thunnus albacares] and bigeye tuna [Thunnus obesus]), catch controls, while intended to ensure that overall fishing mortalities are not exceeded, have failed to maintain catches at the desired level because some ICCAT CPCs have exceed targets on a regular basis or were not sufficiently covered by the measures. The document explores how full seasonal closures (over an estimated timeframe), where vessels remain in port, may better assist surface fisheries in achieving the levels of catch reduction sought by the ICCAT. Some examples of how the control rule may be implemented are provided. A decision support tool is developed based on the data and proposed season closures to implement an overall target catch on bigeye tuna, one of the stocks managed to a TAC by ICCAT. This is an update to document SCRS/2019/107. It addresses a request for the catches of juvenile and adult tunas to be adjusted in the model to the observed data.

KEYWORDS

Catch/effort; Tropical tunas; Season regulations.

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1. Introduction

In recent years, all tuna-Regional Fishery Management Organisations (tRFMO) have adopted a range of management measures to ensure that tropical tuna stocks are maintained 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.* 2016). At present, the Indian Ocean Tuna Commission (IOTC) is the only tRFMO to have formally adopted a Harvest Control Rule (HCR) for a tropical tuna stock, skipjack tuna (SKJ), while other stocks are subject to various interim measures, including TACs, 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 (partial in the case of ICCAT). However, these measures have not been effective at maintaining the catches of the target stocks at the agreed levels, e.g. yellowfin tuna (YFT) in IOTC and the former and bigeye tuna (BET) in ICCAT.

In the Atlantic Ocean, the ICCAT adopted Total Allowable Catches (TACs) for yellowfin tuna and bigeye tuna: since 2001 (Recommendation 00-1) for longline fleets and since 2005 (Recommendation 04-1) for the rest of the fleets in a multiannual management plan (ICCAT 2019. Recommendations 16-1 & 18-1). However, both those TACs have been consistently breached, with recent catches well above the TAC (ICCAT SCRS 2018). FAD closures have also been evaluated as ineffective, mainly due to relocation 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 (ICCAT SCRS 2017). 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 2018). Discards of tropical tunas may also be important in some industrial fisheries. These include small specimens of tropical tunas in purse seine fisheries that are part of the *faux poisson*, component that is not properly monitored by all flag states; and specimens of yellowfin tuna and bigeye tuna of less than 1 meter fork length in longliners, unwanted by the sashimi markets (Nobrega *et al.* 2014) and seldom reported to tRFMOs (Hoyle *et al.* 2019).

In the eastern Pacific Ocean, the Inter-American Tropical Tuna Commission (IATTC) adopted a control rule that contemplates two closures of the purse seine fishery (IATTC 2019; IATTC RES C-17-02), with the length of those closures adjusted using a formula 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 must 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 adopted an action plan that includes actions to improve stock status and compliance in all oceans, the former through assistance to the implementation of HCR and the latter through support to improvements in compliance. Considering that the performance reviews of ICCAT (ICCAT , 2016) and IOTC (IOTC, 2016) have recommended that both organisations improve their management framework for tropical tunas, we would like to explore the effectiveness of alternative management measures, along the lines of those adopted by the IATTC, in improving the management framework of those RFMO.

As for the ICCAT 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 TACs, 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 TACs were ineffective, deciding to revert back to fishery closures (IATTC RES C-17-01 amended by C-17-02).

This analysis represents an update to previous work (Sharma and Herrera 2019). This is an update to document SCRS/2019/107. It addresses a request from the 2019 Yellowfin Tuna Stock Assessment Meeting (ICCAT 2019c), where document SCRS/2019/107 was presented, for the catches of juvenile and adult tunas to be adjusted in the model to the observed data. It uses the most recent catch, effort, and catch-at-size data available at the ICCAT, including data up to December 2017. The main objective of the analysis is to explore to which extent the approach taken by the IATTC can be successfully used to manage tropical tunas at the ICCAT (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 bigeye tuna TAC 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 bigeye tuna stock but also potential impacts of the measure on other target stocks (yellowfin tuna and skipjack tuna). In addition, the report recommends actions that ICCAT would need to undertake to make implementation of the new system possible.

2. Methods

2.1 Approach

Effort is assumed to be proportional to fishing mortality. Hence, effort closures temporally would have the same net effect as allowable TAC. 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 ICCAT).

If we have a standardized unit of effort for all fleets, then we could estimate an optimal effort, *Eopt* capacity for the fleet, as a function of optimal fishing mortality, *Fopt* 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 (**Figure 0**), as discussed in Squires et. al. (2016)

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 SCRS report for bigeye tuna and yellowfin tuna (ICCAT SCRS 2017).

We stratified effort data by time and area, and assess its relationship to catch assuming a 1-1 relationship with bigeye tuna catch by year and area (GLM model developed eq. 3). Essentially, if we can limit effort for a portion of days based on the ICCAT 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

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

Where *BETPSCatch* is a function of the *PSEffort*. 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 purse seine well capacity and number of trips (fishing hours by month and if needed by area) which could be estimated and controlled for.

2.2 Data sources and preparation

The ICCAT Secretariat provided all datafiles needed for the analysis. The files provided included exclusively data for the purse seine tropical tuna fishery, for all flags involved, over the period 1990-2017. The following datasets were used to build the file for the analysis:

- **t1ncETRO91-17.xlsx**: Refers to ICCAT's Task I Data (nominal catch), in MS Excel format, which contains nominal catches of Atlantic tunas and tuna-like fish, by year (1990-2017), gear, region, species and flag [MS Excel; version 15/04/2019];
- **t2ceETRO_9117.csv**: Refers to ICCAT's Task II Catch & Effort in text format (1991-2017). It includes catch and effort data by flag country, year, month, one degree square grid, fishing mode and species [csv file; version 15/04/2019];

- **t2szBET_etro9117.csv & t2szYFT_etro9117.csv & t2szSKJ_etro9117.csv**: Refers to ICCAT Task II length frequency samples, which includes the available samples of tropical tunas over the period 1990-2017. It includes the numbers of specimens measured by length class bin, species (one file for each tropical tuna species), flag country, year, month, fishing mode, and five degrees square grid (csv file; version 15/04/2019);
- **t2csBET_etro9117.csv & t2csYFT_etro9117.csv & t2csSKJ_etro9117.csv**: Refers to ICCAT's Task II Catch-at-Size file for the yellowfin tuna (YFT), bigeye tuna (BET) and skipjack tuna (SKJ), in text format (1990-2017). It includes the numbers of specimens caught (numbers measured raised to represent the total catch) by length class bin, species (one file for each tropical tuna species), flag country, year, month, fishing mode, and five degrees square grid (csv file; version 15/04/2019) [csv file; version 15/04/2019].

The above data were used to produce a file that contained catch and effort of tropical tunas in the Atlantic Ocean, in weight, for the period 1990-2017. Thus, the above purse seine data were extracted and managed to produce the following file:

- **VBA_OUTPUTKG.csv**: file containing catches in weight, effort, and the weight of fish measured according to their maturity stage (immature/mature) and by length class bin, in kilograms, by species, fishing mode (associated school/free-swimming school), 5 degree square grid, year (1991-2015) and month. The structure of the table is presented in **Table 0**:

The number of fish recorded under each length class bin was converted to weight using ICCAT's length-weight equations, as per the ICCAT Manual (ICCAT 2019b):

- Yellowfin tuna[3]: $W = 2.153*10^{-5}*FL^{2.976}$ Caverivière (1976)
- Bigeye tuna[4]: $W = 2.396*10^{-5}*FL^{2.9774}$ Parks et al. (1981)
- Skipjack tuna[5]: $W = 7.480*10^{-6}*FL^{3.253}$ Cayré & Laloë (1986)

The amount of fish immature and mature was assigned using ICCAT's length-at-first-maturity for each of ICCAT's tropical tuna stocks, as recorded in the ICCAT Manual:

- Yellowfin tuna[6]: 50% of mature females measuring 108.6 cm (Albaret (1977), Eastern Atlantic);
- Bigeye tuna[7]: 53% mature females measuring 100 cm (Matsumoto and Miyabe (2002), Abidjan). The same authors estimated that 50% mature females measuring 110 cm from samples taken in Dakar. However, data from Abidjan was used as this is the main port of landing of purse seiners in the Atlantic Ocean;
- Skipjack tuna[8]: 50% mature females measuring 45 cm (Hazin et al. (2001), Atlantic). Hazin et al. were chosen among the 4 values available for female maturity, with lengths at first maturity ranging from 42 cm to 51 cm, the one chosen being the most recent study.

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

- PS-EU: Purse seine fleets operating under EU flags (France & Spain) or other flags that operate as EU purse seiners (e.g. Curaçao, Guatemala, El Salvador, etc.);
- PS-Ghana: Purse seine vessels flagged in Ghana and vessels flying other flags that operate as the former;
- PS-Other: Purse seine vessels flagged to other countries and that do not usually operate in the core area of the purse seine fishery (e.g. Western Central or South Atlantic, Mediterranean Sea, etc.).

Although the final file contained information for 1990-2017, only data from the EU-PS fleet, for the period 2003-2017 were used for the analysis. The catches of tropical tunas of the EU group have represented between 77%

[3] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_1_YFT_ENG.pdf; Table 2, Page 9
[4] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_2_BET_ENG.pdf; Table 2, Page 35
[5] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_3_SKJ_ENG.pdf; Table 2, Page 59
[6] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_1_YFT_ENG.pdf; Table 3, Page 9
[7] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_2_BET_ENG.pdf; Table 3, Page 35
[8] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_3_SKJ_ENG.pdf; Table 3, Page 60

and 94% (mean 86%) of the total catches of the purse seine component in the Atlantic Ocean. For developing scenarios estimates of current effort and scaling relative to efforts observed in 2016 were used. This is because the EU-PS fleet reports the highest catches (86%) and it is the only fleet for which catch, effort, and size data are fully available. The selection of 2003-17 as time-period was made in order to consider recent years of activity of purse seiners and for the recordset to be complete for all three stocks, considering that the last year in which catch-at-size data is available is 2017.

The final file used for the analysis contained total catches of tropical tunas in kilograms taken by EU and assimilated purse seiners, total effort in fishing hours, total catches of immature bigeye tuna in kilograms, total catches of mature bigeye tuna in kilograms, total catches of immature and mature yellowfin tuna in kilograms, total catches of mature yellowfin tuna in kilograms, and total catches of immature skipjack tuna in kilograms and total catches of mature skipjack tuna in kilograms, by year, month, and 5 degree square grid. Data by Log School or Free School are also used in this analysis.

2.3 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:

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

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

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 **Figure 15**, 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 relocation 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 core area of the fishery (eastern and central tropical [and subtropical] fishery).

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

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.

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

3. Results

3.1 Exploratory data analysis

Since we are interested in overall patterns in the fishery over time, we compiled some simple plots looking at overall effort for bigeye tuna between 2003-2017 (aggregated, **Figure 1**) and monthly variation in effort between 2003-2017, by area (**Figure 2**). **Figures 3-6** indicate that skipjack tuna is the primary catch and monthly closures within the 2^{nd} and 4^{th} quarters would benefit catch reductions in bigeye tuna with marginal effects on catch rates on yellowfin tuna and skipjack tuna, a concern for the operators.

3.2 Results from Generalized linear models examined

The data were conditioned first on bigeye tuna and then applied to yellowfin tuna using large fish as the dependent variable. The aim was to assess loss in catch of large yellowfin tuna, and of skipjack tuna, 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 models described above.

Diagnostic fits to models 1-4 for bigeye tuna are shown in **Figures 7-10** for different components of the fishery, by size. The ANOVA (**Table 1)** shows this across all species, and for sake of succinctness, we only show diagnostics of models for bigeye tuna. Other diagnostics are similar for both bigeye tuna and skipjack tuna, though not displayed in **Table 1**. In addition, Biomass is used in all models from purely biological reasons to the fact that some models have biomass as significant contributor and others do not.

3.3 Model developed

Based on the data shown on parameters of models derived in **Table 1**, a general model was developed based on the effort observed in 2016 and scaling results relative to this. The models predictive capability of catches for all PS fleets (using EUPS as a proxy for the effort catch relationship) fleet is shown in **Figure 11**. The predictive capability of the model with CV's on overall targets is shown in **Table 2** with consequences to catches of other species, yellowfin tuna and skipjack tuna shown in **Tables 3-4**. For illustrative purposes, two other models are developed with differential closure patterns (all at once) or two (multiple closures over the year). Effects of these closures are shown in **Figures 12-13** and **Tables 5-6** for bigeye tuna. The overall effect on effort is displayed in **Figure 14** for the three scenarios. It is obvious something needs to be done for this species as it was noted to be overfished in the last assessment (see Base run on **Figure 15**), and consequentially some difficult decisions need to be taken on the part of the industrial fleet, and this is the proposed solution.

For example, if we wanted to reduce catches of bigeye tuna to a target of 10000 tons through the implementation of one seasonal closure or two, this could be achieved as shown in **Table 5** (two closures) or **Table 6** (one closure), resulting in the catch distribution patterns shown in **Figures 12-13**.

4. 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 and therefore it is assumed that the use of fishing hours/days in the context of ICCAT would equally work.

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, olympic 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 effected 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 purse seiners). However, if we update our analysis with the latest information the relationship would be valid for the latest technology and could be updated regularly (e.g. 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). In addition, in recent years all tRFMO have adopted measures intended to restrain further increases in fishing efficiency. Those include FAD limits, capacity limits, including fishing and support vessels, and other measures, such as time-area closures. Among those, ICCAT implemented capacity limits for some CPC, limits on the number of active FADs and a time-area closure through the adoption of its Multi-annual Conservation and Management Programme for Tropical Tunas (ICCAT 2019; Recommendation 16-01[9]). Those measures are likely to reduce considerably the potential for purse seine fisheries to further increase their efficiency, limiting effort creep in this component

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 ICCAT CPC are very uncertain (e.g. Ghana, 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 & Baez 2018); the adoption of TACs has led to gross underreporting of catches by some fleets (e.g. Chinese Taipei longline fleet, ICCAT 2015; non-marketable tropical tuna species from most industrial fleets, including those known as *faux-poisson* by purse seiners and those not eligible for the sashimi market in longliners); the ICCAT has not set any mechanism to independently monitor CPC compliance with the TACs of tropical tunas; the costs of such a mechanism will be extremely high.

4.1 Implementation of closures in the context of the ICCAT

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 Total Allowable bigeye tuna Catches recommended by the ICCAT for the industrial tuna purse seine component. Other than the recommended TAC, 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 ICCAT 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 national report presented 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 ICCAT's data requirements (Task 2);

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 bigeye tuna stock (i.e. effort creep);

3. Any other management measure ICCAT has implemented in complement to the fishery closure that could contribute to a decrease in effective fishing effort directed at the bigeye tuna stock (e.g. time-area closure on fishing with FADs).

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

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

4.2 Conclusion

This study shows the potential benefits for ICCAT's management to consider replacing the existing TACs of tropical tunas with fishery closures for its purse seine component, and the capacity of this approach to be used for other fisheries in the future (e.g. pole-and-line).

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[9] https://www.iccat.int/Documents/Recs/compendiopdf-e/2016-01-e.pdf

There are many possible scenarios of developing solutions to achieve a certain bigeye tuna target with certain monthly closures. However, we may have conflicting objectives as seen that don't allow the catch to exceed 40K tonnes of large yellowfin tuna while keeping bigeye tuna targets low. For instance, if we wanted 45K t of large yellowfin tuna, this would not have been possible using scenario 2. Therefore, optimizing to one target may not allow maximizing for a second species, as seen above, although selection of the nearest scenario would still be possible. However, considering the multi-species nature of surface fisheries at the ICCAT and the fact that catch limits exist for both bigeye tuna and yellowfin tuna, it would only be reasonable that the closure adopted seeks a reduction in the catches of both stocks. In addition, the TAC 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 yellowfin tuna on free-schools towards fishing on FADs, where yellowfin tuna, mostly juvenile, only represents a fraction of the total catch. In the ICCAT, any catch limits on bigeye tuna could lead to increased fishing of yellowfin tuna by purse seiners (free-swimming schools) and longliners (change of targeting from bigeye tuna to yellowfin tuna), further compromising the status of this stock, which is indeed subject to an unallocated TAC.

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 (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 (large yellowfin tuna) are lower and closures in those months would benefit bigeye tuna reductions while not compromising the catches of large yellowfin tuna.

Given the large uncertainties in achieving TACs 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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Table 0. Structure of the Table including the ICCAT catch, effort and size data used for the analysis

ID	Unique identifier for row
Flag	Flag country: Includes EU (EUPS; ESP, FRA, CUW, GTM, PAN, BLZ, SLV and other FIS fleets assimilated to EU), Ghana (Ghana: Ghana and Senegal), and all other fleets combined (Other: mostly other fleets operating in the Western Atlantic Ocean)
Gear	Gear type: Purse seine in all cases (PS)
Year	Year (from 1991 to 2017)
Quarter	Quarter
MonthStart	Month
Grid	5 degrees square grid as per ICCAT's standards
Lat	Latitude in degrees (centroid)
Lon	Longitude in degrees (centroid)
FhoursE	Number of hours fishing
TCTropsps	Total catch (kg) of tropical tunas recorded in the Catch-and-Effort Table (raised to nominal catch)
BET_FS_Immature	Amount (kg) of Immature bigeye tuna (BET) caught on Free-Schools
BET_FS_Mature	Amount (kg) of Mature bigeye tuna (BET) caught on Free-Schools
BET_LS_Immature	Amount (kg) of Immature bigeye tuna (BET) caught on Associated-Schools
BET_LS_Mature	Amount (kg) of Mature bigeye tuna (BET) caught on Associated-Schools
BET_UNCL_Immature	Amount (kg) of Immature bigeye tuna (BET) caught (School type unknown)
BET_UNCL_Mature	Amount (kg) of Mature bigeye tuna (BET) caught (School type unknown)
SKJ_FS_Immature	Amount (kg) of Immature skipjack tuna (SKJ) caught on Free-Schools
SKJ_FS_Mature	Amount (kg) of Mature skipjack tuna (SKJ) caught on Free-Schools
SKJ_LS_Immature	Amount (kg) of Immature skipjack tuna (SKJ) caught on Associated-Schools
SKJ_LS_Mature	Amount (kg) of Mature skipjack tuna (SKJ) caught on Associated-Schools
SKJ_UNCL_Immature	Amount (kg) of Immature skipjack tuna (SKJ) caught (School type unknown)
SKJ_UNCL_Mature	Amount (kg) of Mature skipjack tuna (SKJ) caught (School type unknown)
YFT_FS_Immature	Amount (kg) of Immature yellowfin tuna (YFT) caught on Free-Schools
YFT_FS_Mature	Amount (kg) of Mature yellowfin tuna (YFT) caught on Free-Schools
YFT_LS_Immature	Amount (kg) of Immature yellowfin tuna (YFT) caught on Associated-Schools
YFT_LS_Mature	Amount (kg) of Mature yellowfin tuna (YFT) caught on Associated-Schools
YFT_UNCL_Immature	Amount (kg) of Immature yellowfin tuna (YFT) caught (School type unknown)
YFT_UNCL_Mature	Amount (kg) of Mature yellowfin tuna (YFT) caught (School type unknown)
BET_UNCL	Amount (kg) of bigeye tuna (BET) caught (Maturity & School type unknown)
SKJ_UNCL	Amount (kg) of skipjack tuna (SKJ) caught (Maturity & School type unknown)
YFT_UNCL	Amount (kg) of yellowfin tuna (YFT) caught (Maturity & School type unknown)
TIMESTAMP	The date & time the file was created

Table 1. ANOVAs on Models examined

Free-swimming school:
Immature Yellowfin tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	2.89E+13					
Biomass	1	1.28E+09	4428	2.89E+13	0.3474	0.5556	
factor(MonthStart)	11	4.34E+11	4417	2.84E+13	10.6768	<2e-16	
FhoursE	1	5.57E+12	4416	2.29E+13	1505.4815	<2e-16	0.001
factor(MonthStart):FhoursE	11	6.57E+12	4405	1.63E+13	161.443	<2e-16	0.001

Free-swimming school:
Mature Yellowfin tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.19E+15					
Biomass	1	8.33E+10	4428	1.19E+15	0.8598	0.3538	
factor(MonthStart)	11	1.38E+13	4417	1.18E+15	12.9583	<2e-16	0.001
FhoursE	1	6.49E+14	4416	5.27E+14	6700.0719	<2e-16	0.001
factor(MonthStart):FhoursE	11	1.01E+14	4405	4.27E+14	94.3612	<2e-16	0.001

Associated school: Immature
Yellowfin tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	2.74E+13					
Biomass	1	9.55E+08	4428	2.74E+13	0.2939	0.5878	
factor(MonthStart)	11	2.05E+11	4417	2.72E+13	5.737	2.88E-09	0.001
FhoursE	1	1.11E+13	4416	1.61E+13	3404.1739	<2e-16	0.001
factor(MonthStart):FhoursE	11	1.83E+12	4405	1.43E+13	51.1219	<2e-16	0.001

Associated school:
Mature Yellowfin tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	5.67E+12					
Biomass	1	2.08E+09	4428	5.67E+12	2.9425	8.64E-02	
factor(MonthStart)	11	1.35E+11	4417	5.53E+12	17.3365	<2e-16	0.001
FhoursE	1	1.86E+12	4416	3.67E+12	2630.3148	<2e-16	0.001
factor(MonthStart):FhoursE	11	5.53E+11	4405	3.12E+12	70.9839	<2e-16	0.001

Table 1 (cont.). ANOVAs on Models examined

Free-swimming school:
Immature Bigeye tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	6.36E+11					
Biomass	1	1.88E+09	4428	6.34E+11	19.5573	1.00E-05	
factor(MonthStart)	11	8.90E+09	4417	6.25E+11	8.4315	7.14E-15	0.001
FhoursE	1	1.43E+11	4416	4.82E+11	1491.1559	< 2e-16	0.001
factor(MonthStart):FhoursE	11	5.97E+10	4405	4.23E+11	56.6026	< 2e-16	0.001

Free-swimming school:
Mature Bigeye tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.59E+13					
Biomass	1	1.31E+10	4428	1.59E+13	5.5174	0.01887	
factor(MonthStart)	11	2.07E+11	4417	1.57E+13	7.9521	7.35E-14	0.001
FhoursE	1	3.59E+12	4416	1.21E+13	1515.8374	<2e-16	0.001
factor(MonthStart):FhoursE	11	1.68E+12	4405	1.04E+13	64.497	<2e-16	0.001

Associated school: Immature
Bigeye tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.53E+13					
Biomass	1	2.52E+10	4428	1.53E+13	10.727	0.001064	
factor(MonthStart)	11	2.00E+11	4417	1.51E+13	7.7544	1.92E-13	0.001
FhoursE	1	4.39E+12	4416	1.07E+13	1868.3562	<2e-16	0.001
factor(MonthStart):FhoursE	11	3.47E+11	4405	1.03E+13	13.4527	<2e-16	0.001

Associated school:
Mature Bigeye tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.08E+12					
Biomass	1	3.20E+09	4428	1.07E+12	15.9703	6.54E-05	0.01
factor(MonthStart)	11	2.03E+10	4417	1.05E+12	9.2004	<2e-16	0.001
FhoursE	1	1.19E+11	4416	9.33E+11	594.0814	<2e-16	0.001
factor(MonthStart):FhoursE	11	5.10E+10	4405	8.82E+11	23.1379	<2e-16	0.001

Table 1 (cont.). ANOVAs on Models examined

Free-swimming school:
Immature Skipjack tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	9.02E+12					
Biomass	1	1.43E+11	4428	8.88E+12	87.2662	<2e-16	0.001
factor(MonthStart)	11	7.75E+10	4417	8.80E+12	4.2957	2.11E-06	0.001
FhoursE	1	1.09E+12	4416	7.71E+12	665.9882	<2e-16	0.001
factor(MonthStart):FhoursE	11	4.82E+11	4405	7.23E+12	26.7101	<2e-16	0.001

Free-swimming school:
Mature Skipjack tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.49E+14					
Biomass	1	9.15E+11	4428	1.48E+14	50.817	1.18E-12	0.001
factor(MonthStart)	11	2.93E+12	4417	1.45E+14	14.769	< 2.2e-16	0.001
FhoursE	1	3.31E+13	4416	1.12E+14	1839.59	< 2.2e-16	0.001
factor(MonthStart):FhoursE	11	3.25E+13	4405	7.94E+13	163.814	< 2.2e-16	0.001

Associated school: Immature
Skipjack tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	2.24E+14					
Biomass	1	3.19E+11	4428	2.24E+14	10.1401	0.001461	0.001
factor(MonthStart)	11	2.81E+12	4417	2.21E+14	8.1419	2.93E-14	0.001
FhoursE	1	6.71E+13	4416	1.54E+14	2134.262	< 2.2e-16	0.001
factor(MonthStart):FhoursE	11	1.57E+13	4405	1.38E+14	45.393	< 2.2e-16	0.001

Associated school:
Mature Skipjack tuna

Variables	Df	Deviance	Resid. DF	Resid Dev	F	Pr(>F)	Sign.
NULL	4429	1.11E+15					
Biomass	1	7.36E+11	4428	1.11E+15	5.0299	2.50E-02	0.05
factor(MonthStart)	11	1.26E+13	4417	1.10E+15	7.8033	1.51E-13	0.001
FhoursE	1	3.57E+14	4416	7.41E+14	2439.4333	< 2.2e-16	0.001
factor(MonthStart):FhoursE	11	9.64E+13	4405	6.45E+14	59.8339	< 2.2e-16	0.001

Table 2. Bigeye tuna: Catch Estimated with uncertainty based on average effort distribution (catches in kgs).

Month	Avg Eff	Fishing (on=1)	2017 Biomass (BET)	Estimated Immature FS_BET	Estimated Mature FS_BET	Estimated Immature LS_BET	Estimated Mature_LS_BET	SE (Immature FS_BET)	SE (Estimated Mature FS_BET)	SE Estimated Immature LS_BET	SE Estimated Mature_LS_BET
1	9517	1	254037	3294	38107	1019802	92662	11979	59553	59256	17310
2	9555	1	254037	925	32804	1062487	87250	36926	137512	136832	39971
3	10279	1	254037	9528	15851	1737840	34681	99727	117362	116785	34110
4	11931	1	254037	18	121951	1012662	35529	72727	125720	125102	36542
5	10937	1	254037	17667	199943	500757	42327	37354	119018	118430	34594
6	11058	1	254037	220509	1912698	684010	58199	44688	121547	120946	35325
7	11742	1	254037	195810	814219	699360	187171	28935	136776	136104	39760
8	12432	1	254037	8360	64176	1357114	198107	37061	145998	145269	42437
9	10749	1	254037	28867	30840	1774773	131770	55529	124439	123818	36167
10	11645	1	254037	21087	7844	2332020	170582	54567	143896	143184	41826
11	11254	1	254037	285	46792	2040457	95643	54948	130389	129741	37901
12	12382	1	254037	114065	73936	2437343	42152	144425	137096	136422	39848
			TOTAL CATCH (T)	620416	3359163	16658626	1176073				
			cv	1.09	0.45	0.09	0.37				

Table 3: Yellowfin tuna: Catch Estimated with uncertainty based on average effort distribution (catches in kgs).

Month	Avg Eff	Fishing (on=1)	2017 Biomass (BET)	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	9517	1	254037	3425	6888819	843173	89169	74359	380639	69722	32535
2	9555	1	254037	1447	5741274	851585	111637	171679	878878	160962	75121
3	10279	1	254037	71	1986567	1324965	121178	146544	750140	137408	64116
4	11931	1	254037	82646	5204769	2919761	947585	156983	803589	147197	68682
5	10937	1	254037	389883	4186558	2048518	784192	148616	760749	139348	65023
6	11058	1	254037	3143833	4151387	1143538	317269	151770	776845	142310	66402
7	11742	1	254037	1767296	3191854	1423403	767148	170783	874207	160137	74727
8	12432	1	254037	104699	5800859	1275829	676879	182299	933155	170930	79756
9	10749	1	254037	93981	3136079	2018939	921850	155375	795348	145694	67981
10	11645	1	254037	113691	1443355	2668397	1225058	179659	919721	168448	78618
11	11254	1	254037	1917	1818495	1630023	809198	162827	833421	152655	71232
12	12382	1	254037	15905	2884664	1727213	870040	171188	876273	160509	74896
			TOTAL CATCH (T)	5718795	46434681	19875343	7641202				
			cv	0.33	0.21	0.09	0.11				

Table 4: Skipjack tuna: Catch Estimated with uncertainty based on average effort distribution (catches in kgs).

Month	Avg Eff	Fishing (on=1)	2017 Biomass (BET)	Estimated Immature FS_SKJ	Estimated Mature FS_SKJ	Estimated Immature LS_SKJ	Estimated Mature_LS_SKJ	SE (Immature FS_SKJ)	SE (Estimated Mature FS_SKJ)	SE Estimated Immature LS_SKJ	SE Estimated Mature_LS_SKJ
1	9517	1	254037	252451	103282	4607881	3592891	49540	164166	216792	467965
2	9555	1	254037	68757	29507	5852112	4186311	114395	379055	500582	1080551
3	10279	1	254037	27760	14168	5476831	4375456	97633	323545	427248	922215
4	11931	1	254037	235003	385751	2442220	8105416	104589	346511	457621	987920
5	10937	1	254037	207122	899919	1630573	6486632	99007	328097	433239	935209
6	11058	1	254037	454850	5463238	3215796	8098598	101110	335030	442426	955053
7	11742	1	254037	637766	2777848	5028612	8684302	113785	377014	497887	1074794
8	12432	1	254037	136107	419737	5519322	8977244	121453	402450	531440	1147207
9	10749	1	254037	119687	212997	3733901	5108690	103519	343024	452984	977774
10	11645	1	254037	66997	888660	7447423	7159031	119707	396649	523777	1130752
11	11254	1	254037	2365	18998	6918775	4684756	108469	359405	474603	1024527
12	12382	1	254037	78678	51964	7432821	5248755	114043	377863	499070	1077264
			TOTAL CATCH (T)	2287541	11266069	59306266	74708081				
			cv	0.55	0.37	0.09	0.16				

Table 5. Bigeye tuna: Catch Estimated with uncertainty based on two closures, target catch of BET set at 10000 metric tons, and minimal loss to YFT and SKJ (Sc 2).

Month	Avg Eff	Fishing (on=1)	2017 Biomass (BET)	Estimated Immature FS_BET	Estimated Mature FS_BET	Estimated Immature LS_BET	Estimated Mature_LS_BET	SE (Immature FS_BET)	SE (Estimated Mature FS_BET)	SE Estimated Immature LS_BET	SE Estimated Mature_LS_BET
1	4500	1	254037	2032	23304	666608	62072	9139	45433	45205	13205
2	4500	1	254037	538	18616	628678	51270	24243	90279	89831	26241
3	4500	1	254037	5584	9285	1073377	22062	68277	80352	79955	23353
4	4500	1	254037	9	64162	556812	19461	45908	79361	78969	23067
5	4500	1	254037	10345	115478	293379	24929	25168	80192	79794	23308
6	0	0	254037	0	0	0	0	0	0	0	0
7	0	0	254037	0	0	0	0	0	0	0	0
8	4500	1	254037	3784	28632	626737	89881	20331	80093	79691	23280
9	6365	1	254037	23885	25411	1480473	109831	47945	107444	106907	31228
10	0	0	254037	0	0	0	0	0	0	0	0
11	10	0	254037	0	0	0	0	0	0	0	0
12	13500	1	254037	169524	111900	3620786	61154	202996	192696	191751	56009
			TOTAL CATCH (T)	215702	396789	8946851	440659				
			cv	2.06	1.90	0.08	0.50				

Table 6. Bigeye tuna: Catch Estimated with uncertainty based on one closure, target catch of BET set at 10000 metric tons, and minimal loss to YFT and SKJ (Sc 3).

Month	Avg Eff	Fishing (on=1)	2017 Biomass (BET)	Estimated Immature FS_BET	Estimated Mature FS_BET	Estimated Immature LS_BET	Estimated Mature_LS_BET	SE (Immature FS_BET)	SE (Estimated Mature FS_BET)	SE Estimated Immature LS_BET	SE Estimated Mature_LS_BET
1	4500	1	254037	2032	23304	666608	62072	9139	45433	45205	13205
2	4500	1	254037	538	18616	628678	51270	24243	90279	89831	26241
3	4500	1	254037	5584	9285	1073377	22062	68277	80352	79955	23353
4	4500	1	254037	9	64162	556812	19461	45908	79361	78969	23067
5	5000	0	254037	0	0	0	0	0	0	0	0
6	11058	0	254037	0	0	0	0	0	0	0	0
7	11742	0	254037	0	0	0	0	0	0	0	0
8	4500	1	254037	3784	28632	626737	89881	20331	80093	79691	23280
9	4500	1	254037	16942	17846	1070400	79262	37377	83763	83343	24345
10	7192	1	254037	18231	6749	2021430	147593	48460	127789	127157	37145
11	4500	1	254037	168	26882	1202551	57038	36560	86755	86322	25217
12	4500	1	254037	59050	36277	1263377	23301	86324	81942	81537	23816
			TOTAL CATCH (T)	106338	231754	9109970	551938				
			cv	3.54	3.26	0.08	0.40				

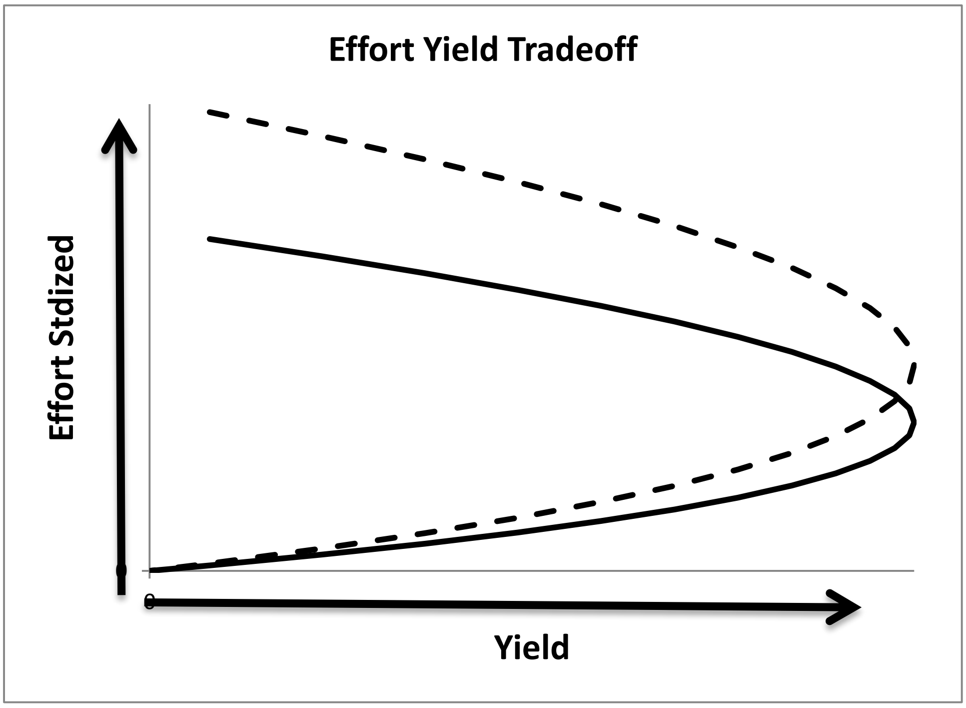

Figure 0. Optimal effort related to yield with different q's.

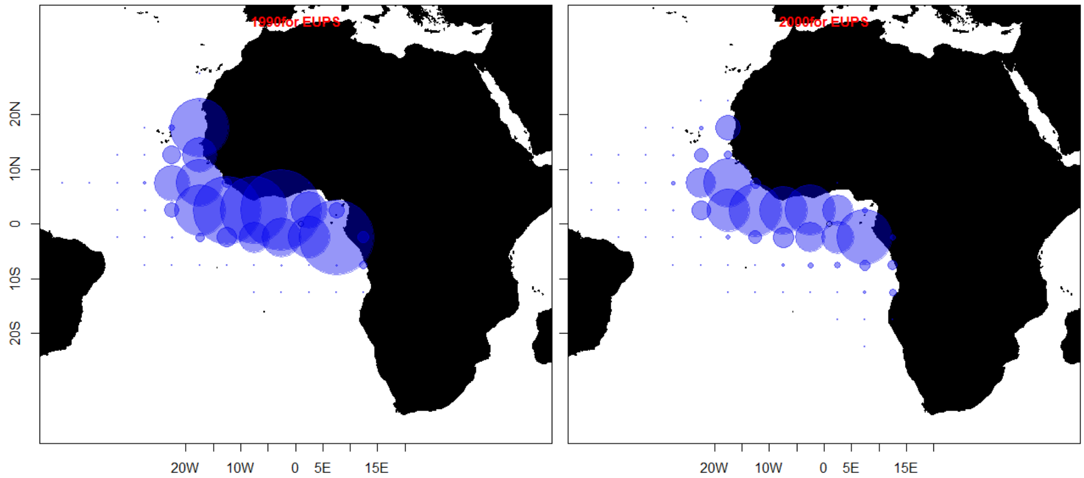

Figure 1. Effort distribution for the PS fleet in the Atlantic by the 1990's and 2000's. Magnitude and spatial extent of the PS fishery has remained the same.

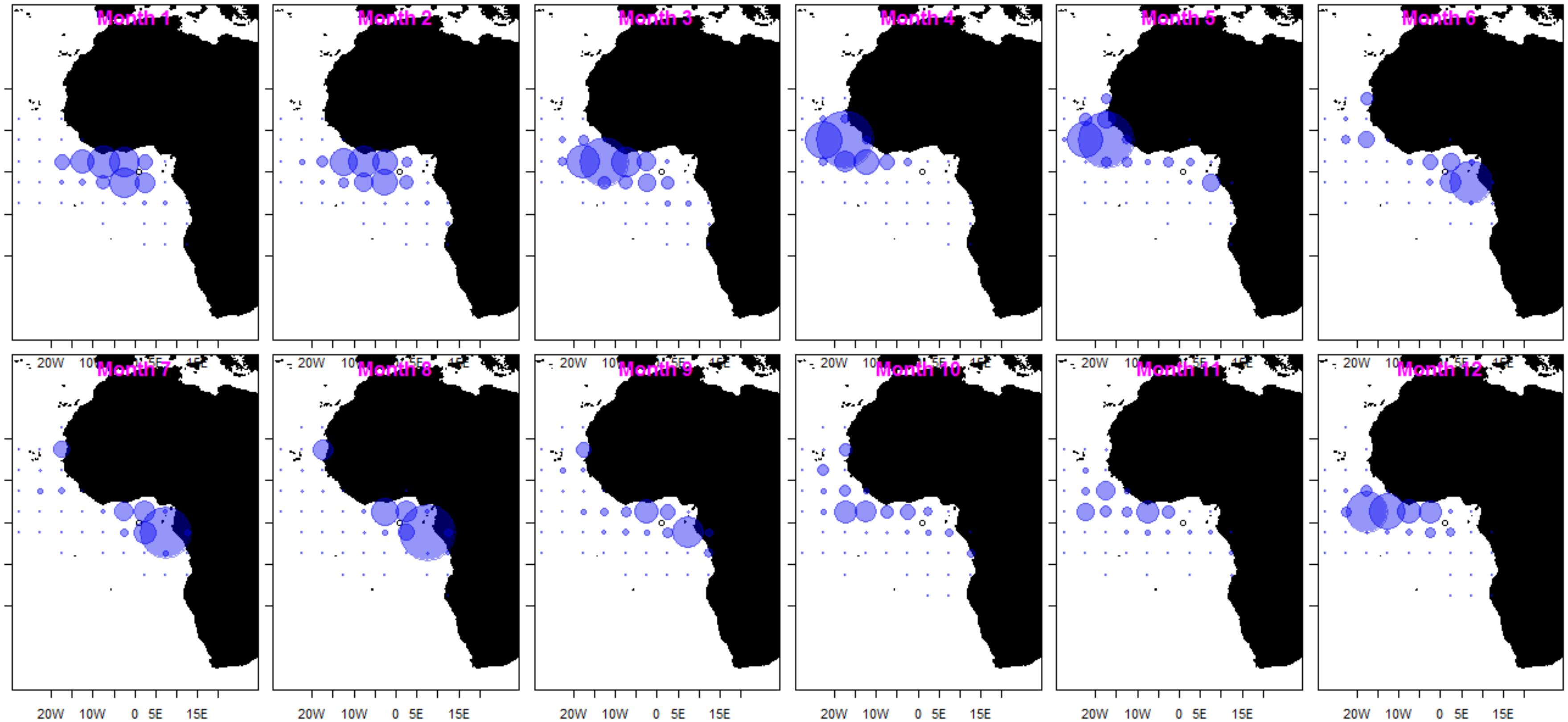

Figure 2: Temporal distribution of effort by month for PS fishery (Month 1=January, Month 12=December on aggregated data over the period 2003-2017)

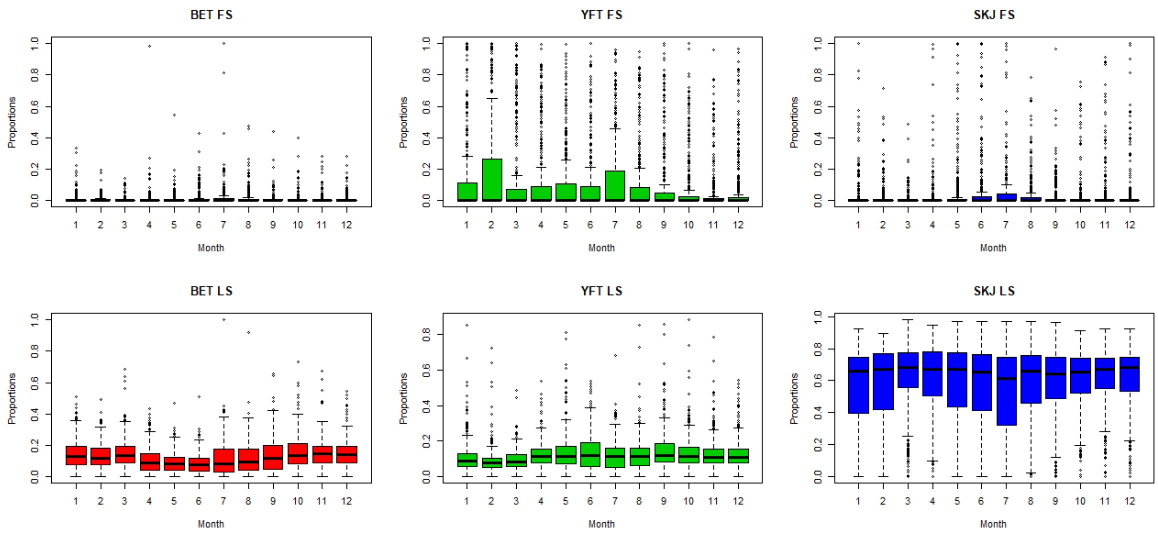

Figure 3: Box plots showing catches by month, by species and fishing mode for the period 2003-2017

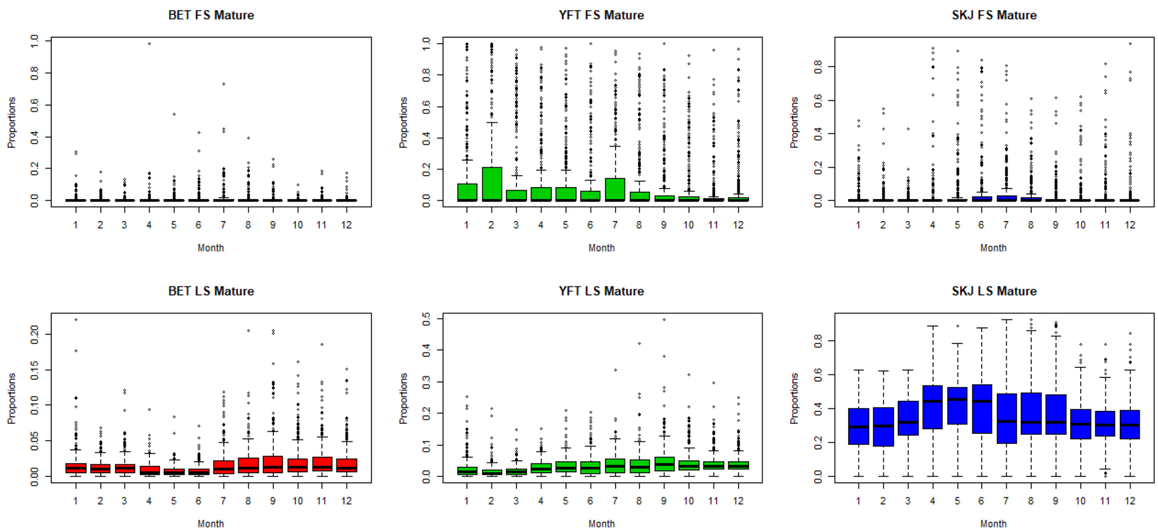

Figure 4: Mature Fish: Box plots showing catches by month, by species and fishing mode for the period 2003-2017.

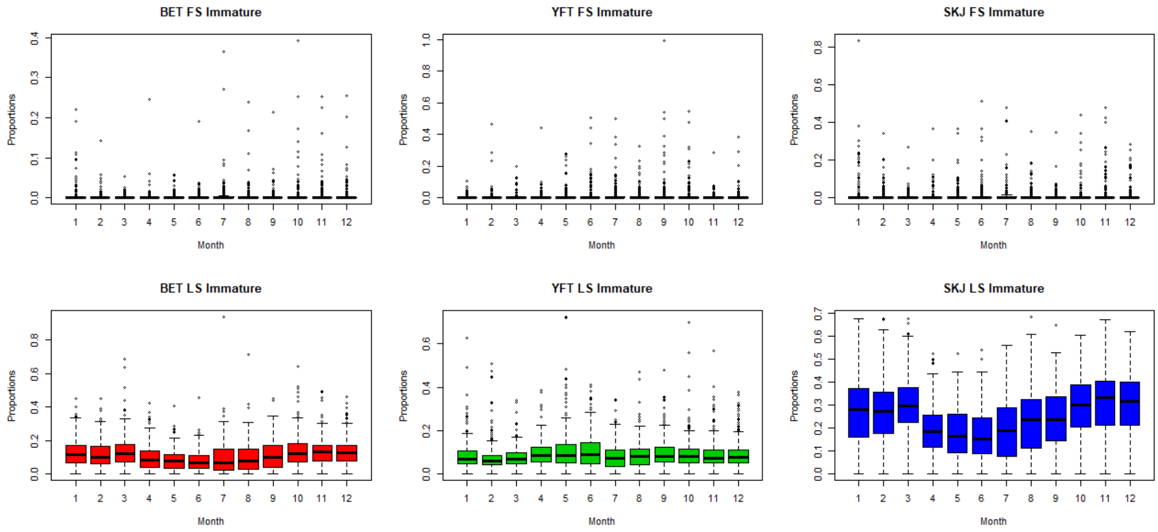

Figure 5: Immature Fish: Box plots showing catches by month, by species and fishing mode for the period 2003-2017.

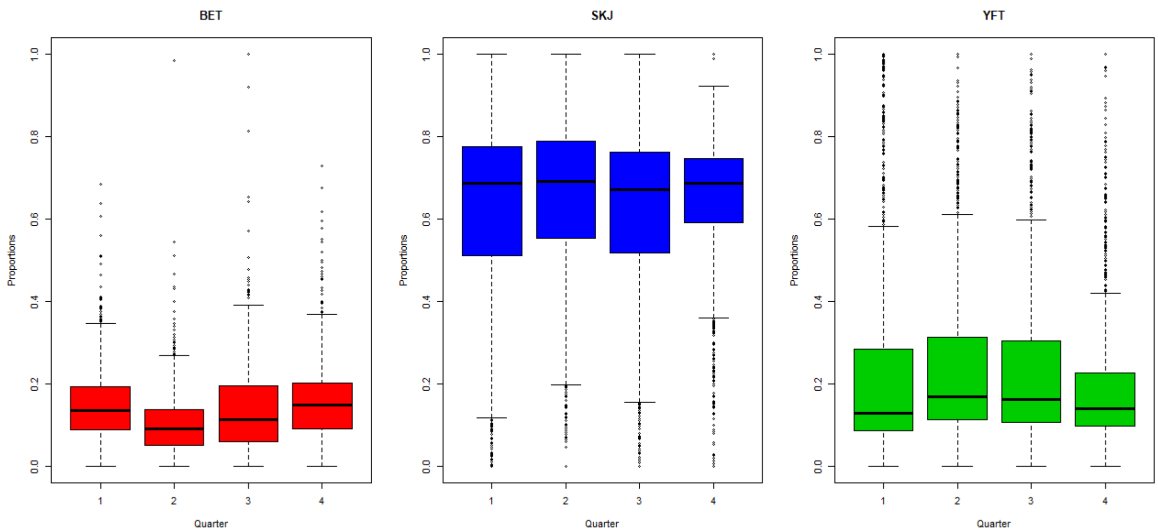

Figure 6: Box plots showing catches by quarter and species for the period 2003-2017.

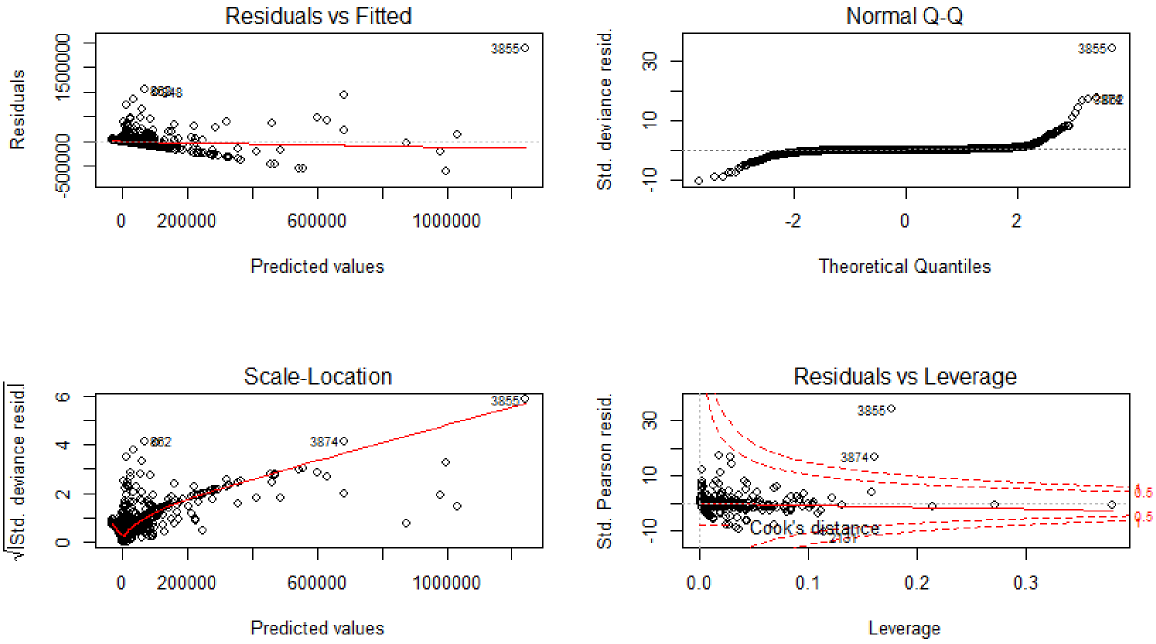

Figure 7: Residual diagnostics for model 1 (Immature bigeye tuna free-swimming school)

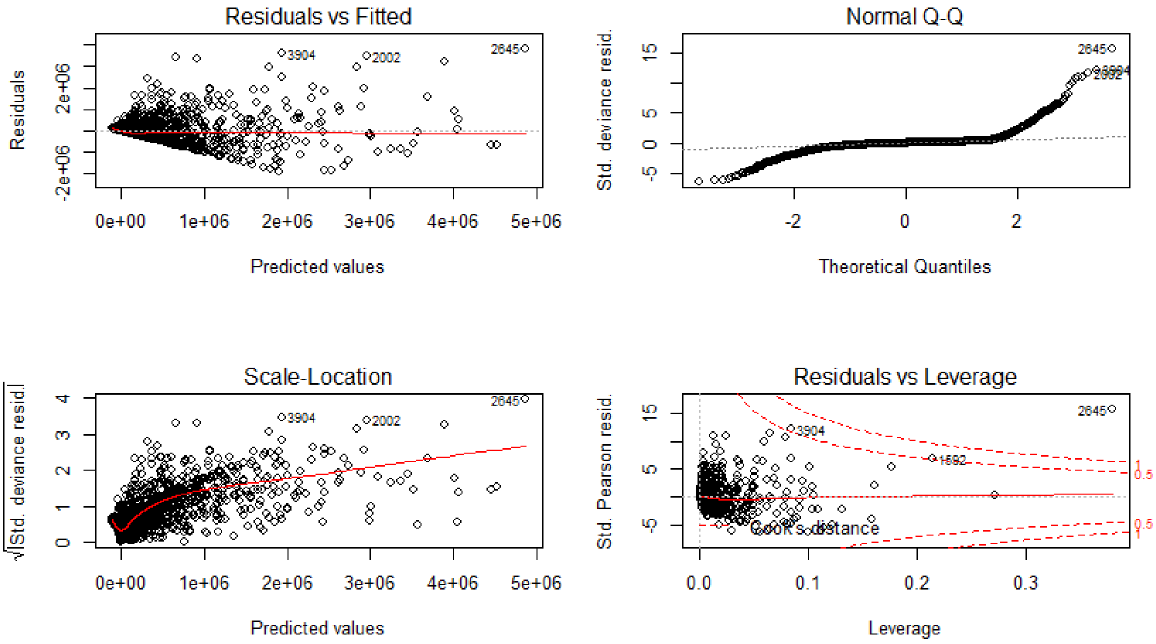

Figure 8: Residual diagnostic for model 2 (Mature bigeye tuna free-swimming school)

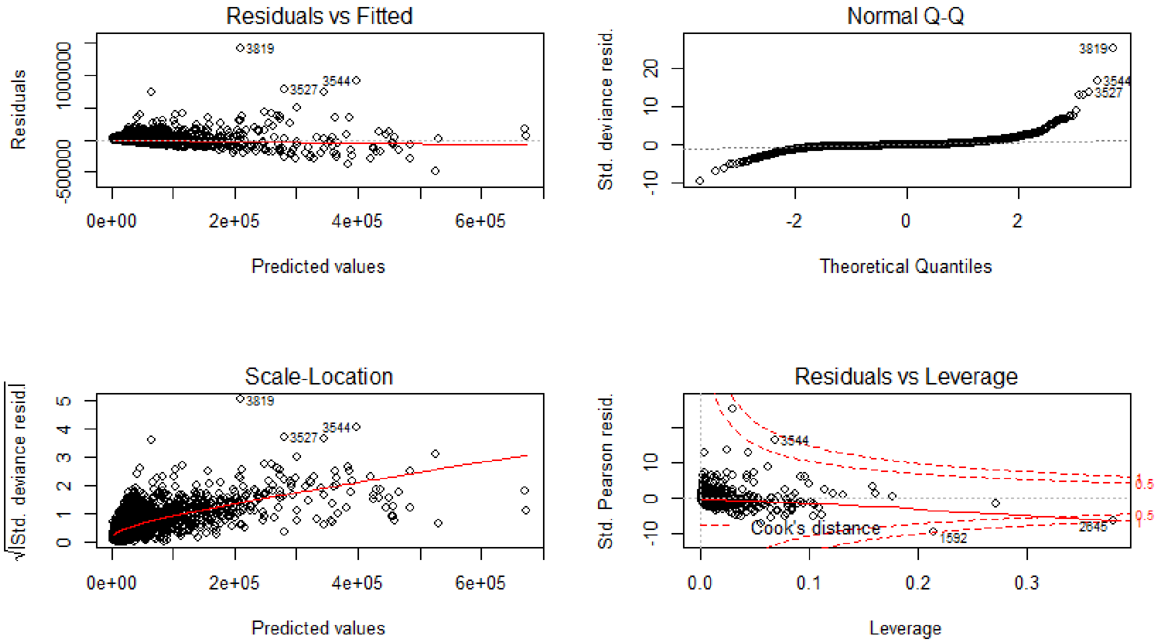

Figure 9: Residual diagnostics for model 3 (Immature bigeye tuna associated school)

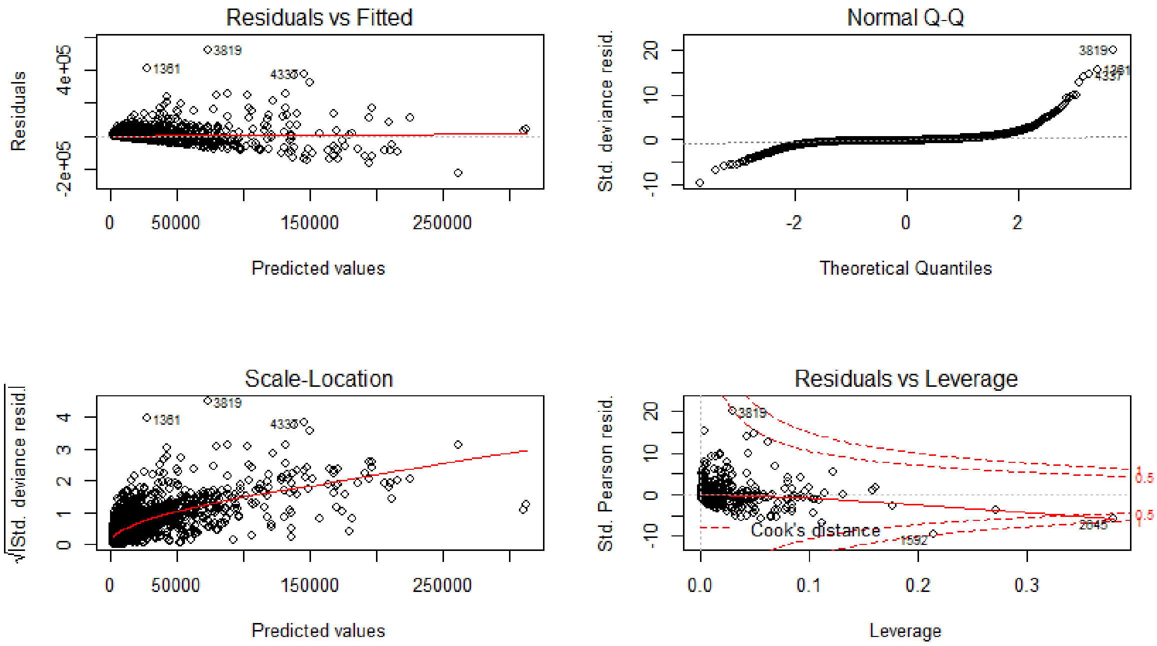

Figure 10: Residual diagnostics for model 4 (Mature bigeye tuna associated school)

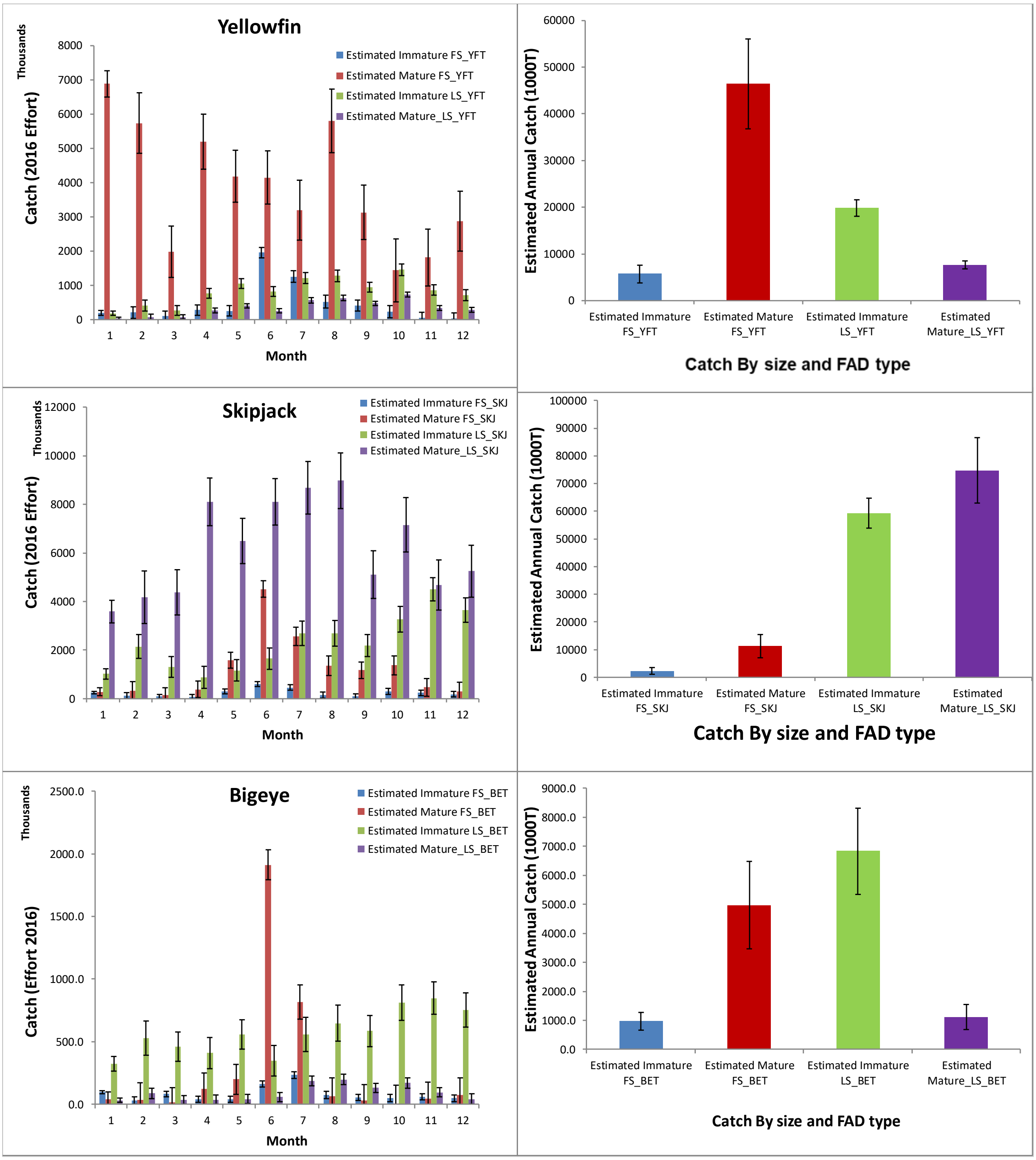

Figure 11: BET, YFT and SKJ caught in different schools using 2016 Effort Distribution (all PS fleets).

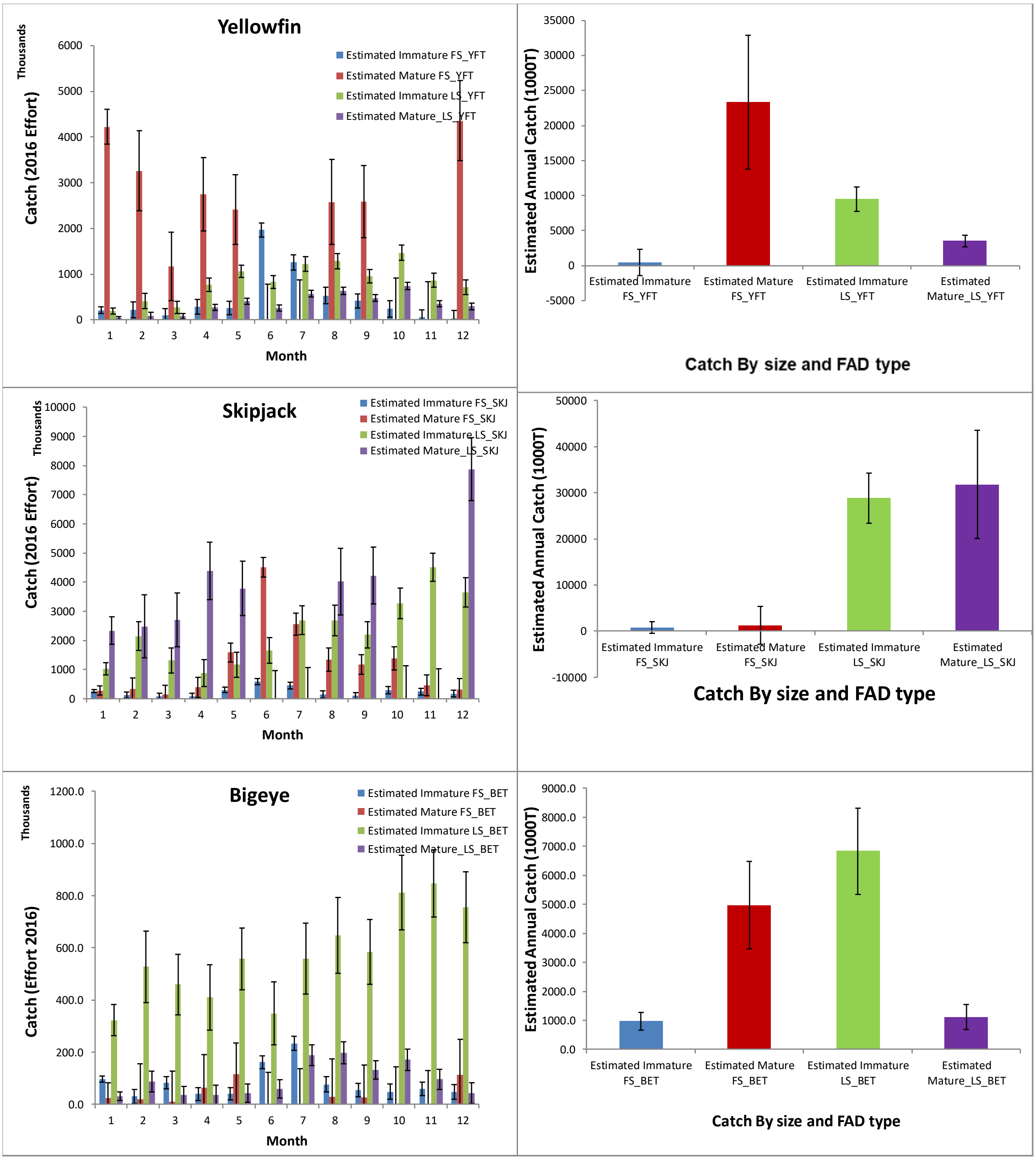

Figure 12. Reduction in effort required to achieve a target catch of bigeye tuna of 10,000 metric tons, implemented through a couple of two-month closures: October-November and June-July.

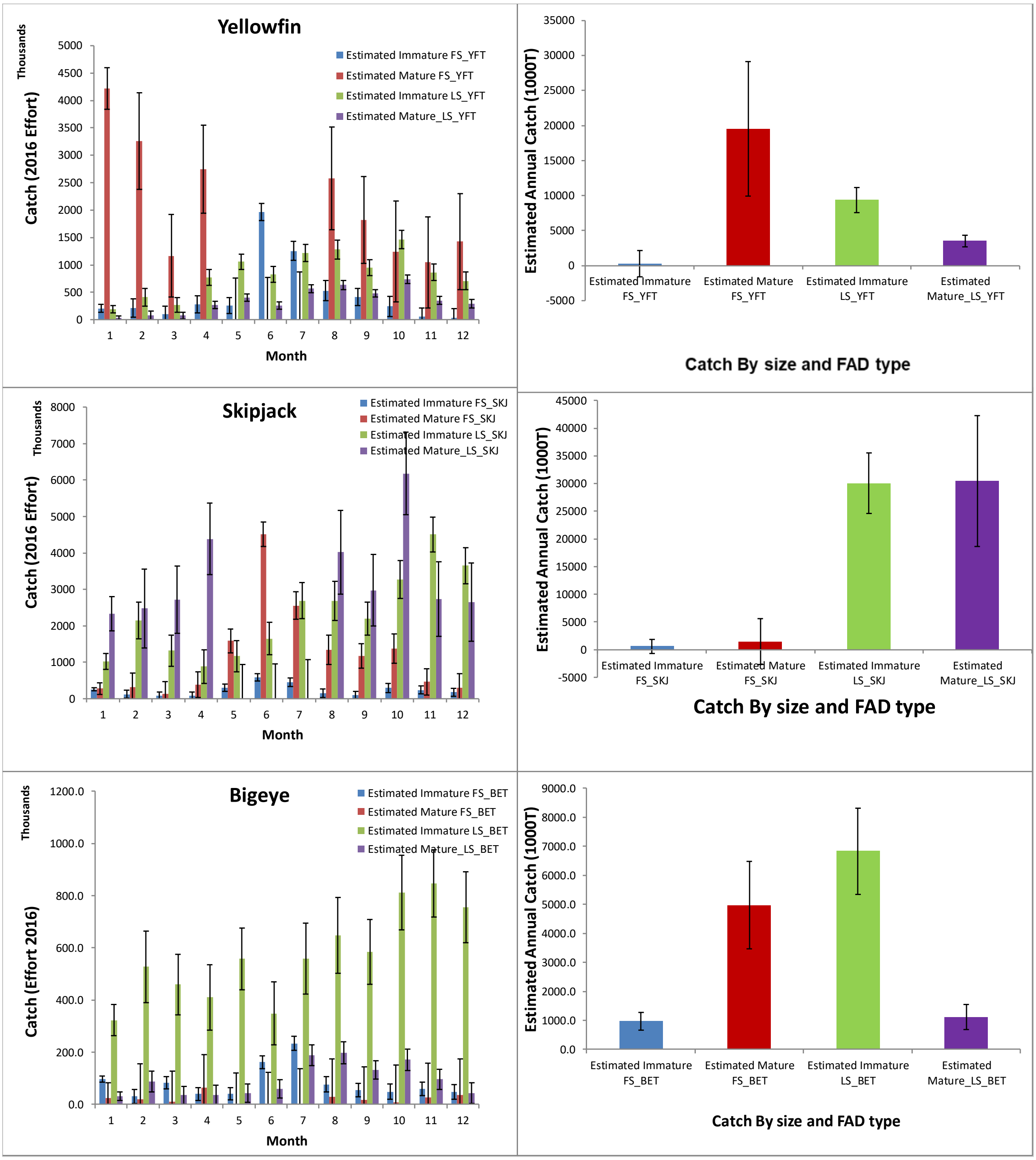

Figure 13: Reduction in effort required to achieve a target catch of bigeye tuna of 10,000 metric tons with a minimum loss in catches of yellowfin tuna and skipjack tuna, implemented through a unique three-month closure: May-July.

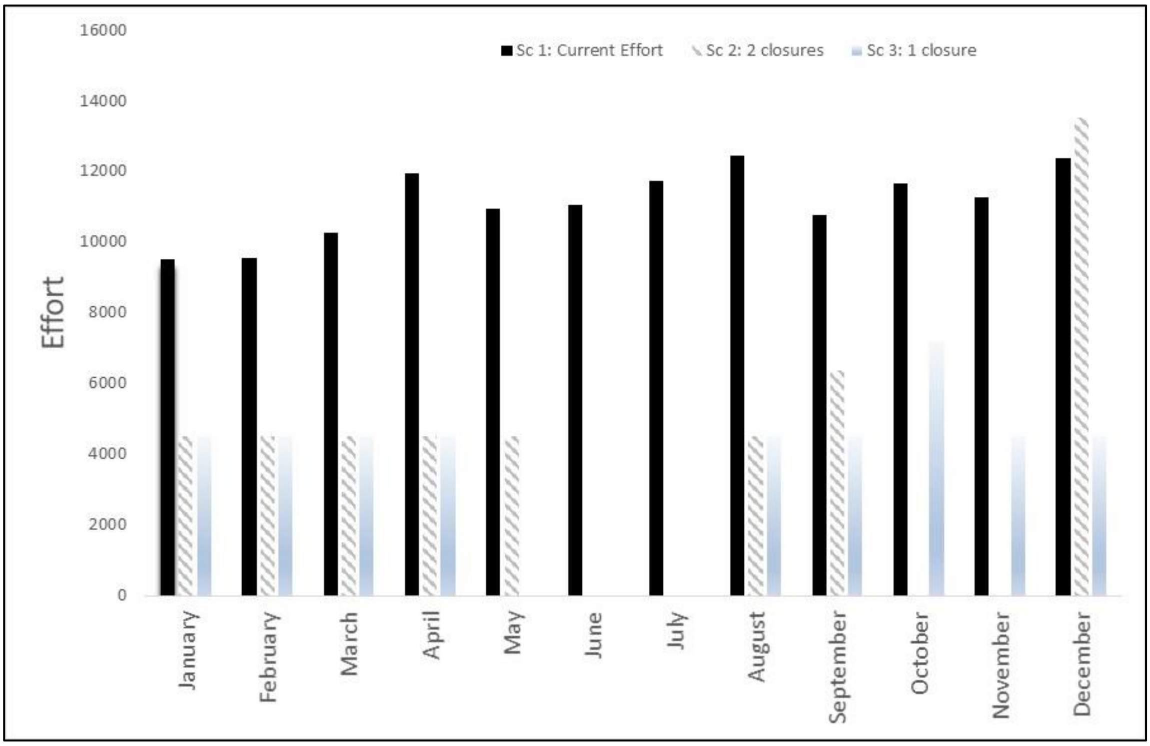

Figure 14: Effort Distributions by the 3 scenarios.

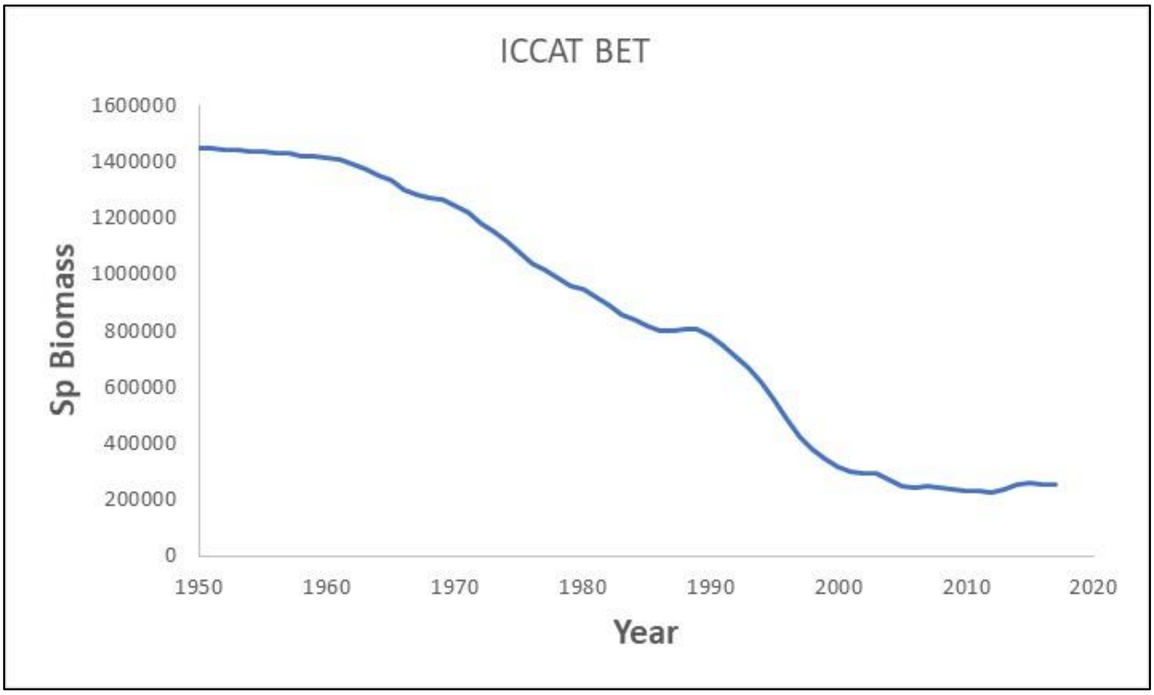

Figure 15: Bigeye Tuna Abundance from 2018 Assessment.