Assessing the response of Indian Ocean yellowfin tuna (*Thunnus albacares*) stock to variations in DFAD fishing effort

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Abstract

The *Indian Ocean Tuna Commission* (IOTC) and the regional Indian Ocean stakeholders have noted concern over the extensive use of DFAD fishing (drifting Fishing Aggregation Devices) by the industrial purse seine fleets. One of the major concerns is the increased fishing mortality of juvenile yellowfin tuna (*Thunnus albacares*) due to DFAD fishing. In 2020, sustainable biomass levels were exceeded by ~27-32%, propelling long-term declines in the stock. Furthermore, with the current stock status subject to overfishing and overfished there is potentially a threat to the global supply chains and employment. In this paper, we perform medium-term deterministic projections for the yellowfin tuna stock in the Indian Ocean considering four scenarios for the industrial purse seine fishing effort compared to the reference or base case relating to 2020 effort levels (scenario 1): a 50% reduction of DFAD sets without re-allocation of effort on free school sets (scenario 2a), a 50% reduction of instrumented buoys deployed in the water (scenario 2b), a seasonal closure of DFAD fishing during the third quarter of the year (scenario 3), and finally an extreme case called DFAD-free, i.e. zero DFAD sets all year (scenario 4). We indicate the potential impacts and benefits of fishing at the same level as that in 2020, projected over 10 years. We show that the *3rd quarter temporal DFAD closure* (e.g., IOTC Resolution 23/02 - zero sets on FADs in Q3) is the most beneficial of the scenarios (excluding the full cessation of DFADs all year round). The *3rd quarter temporal DFAD closure* performance projected future increases in spawning stock biomass (SSB) of between ~12-14%, catch increases of ~5-7%, and recruitment increases of ~2-4% relative to fishing at the same level as that in 2020. In contrast, the scenarios 2a resulted in ~6-7% loss of SSB, and between ~1-2% loss in recruitment numbers. Further research in the area of input-based measures is necessary given the ever-increasing levels of purse seine efficiency to the stocks biomass targets. A Management Strategy Evaluation

(MSE) framework for testing alternative candidate harvest control rules (HCR) would possibly be the best approach to develop harvesting strategies given the uncertainties associated with DFAD year on year fishing efficiency increases, and reaching future desired biomass targets for sustainable Indian Ocean yellowfin stocks.

Therefore, we invite the IOTC to:

- Note the importance and implications of this research to reach or maintain stocks relative to biomass targets.
- Note the importance of gaining a better understanding of DFAD instrumented buoy deployments versus the number of DFAD sets and thus catch rates by acquiring more detailed data on the number of instrumented buoy deployments by all PS fleets.

1. Introduction

Over the last two decades, global purse seine fishing effort for tropical tunas has increased dramatically and currently accounts for over 60% of the catches in the Indian Ocean (IO) (Lecomte *et al.,* 2017). The largest catches in the IO are from yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) tuna. These two tuna species are caught associated with floating objects (FOBs) and/or in free schools (FSC). FOBs have been used for many centuries to enhance the fishers' ability to catch fish (Lopez *et al.,* 2014a). FOBs can be natural (e.g. logs) or artificial Fish Aggregation Devices (FADs). On the other hand, FSC involves setting on free-school swimming tuna on the subsurface of the ocean, detected by the use of bird radars (Gaertner and Pallarés, 2002), and/or by the crew visually via the use of high-powered binoculars (NRC, 1992). In recent years however industrial tuna fishing has seen dramatic technological developments that have improved the skippers’ ability to detect deployed FADs and those that have the largest biomasses beneath them (Torres-Irineo *et al.,* 2014; Tidd *et al.,* 2016). The information of the potential catches via instrumented echo-sounder buoys is relayed via satellite transmission, even before leaving port, thus reducing searching time (Lopez *et al.,* 2014b). However, over the last decade there have been increasing concerns amongst stakeholders regarding the surge in activities and efficiency of purse seine fishing fleets’ usage of drifting fish aggregation devices

(DFADs) (Maufroy *et al.*, 2017, Baske *et al.*, 2012; IOTC-2021-SS4-PropD accessed 6/6/2023).

This rise in efficiency has led to increased catchability of tropical tunas even when stocks are in decline (Tidd *et al.*, 2016). Catchability is a key parameter in fisheries stock assessments and is defined as the average proportion of a stock that is taken by each unit of fishing effort (Gulland, 1983). The general assumption within fisheries science is that catch per unit effort (CPUE) is proportional to stock size and varies over time. However for DFAD tuna fishing this proportionality is affected by the advancement of the aforementioned technologies. Especially vulnerable to DFAD fishing are the juvenile yellowfin tuna cohort of the population (Fonteneau *et al.*, 2013). Hence, prolonged use of this type of fishing activity could be detrimental both in the short and long term to the structure of the fish stock population. For example, increasing the number of fishing operations (fishing effort) in terms of the number of DFAD sets in the short term can increase catch yields, and therefore increase the catch number of juveniles. As a consequence, fewer fish remain in the fishery to grow to increase the spawning stock biomass (SSB) to be caught at a larger size by other fishing gears (e.g., longline). Therefore, in the long term, less recruitment can be expected, along with a decrease in potential yields and revenues will be greatly reduced with the likelihood of a depleted stock. This could also threaten global food-insecure populations and employment as well as the Indian Ocean ecosystem (Hicks, 2019; Sasidharad *et al.*, 2023). Furthermore, the increase in DFAD deployments has contributed to environmental issues due to the discarding/monitoring of unused DFADs contributing to marine litter (Davies *et al.*, 2017; Imzilen *et al.*, 2022). This raises also the legal responsibility of these unused objects during their drifting stage (Hanich *et al.*, 2019).

This paper aims at estimating the effects of various effort limitation measures may have on the SSB, recruitment and catch yields for yellowfin tuna. To do this, our case study investigates 4 different scenarios of management measures restricting the use of FADs and therefore affecting the industrial purse seine fleet operating in the Indian Ocean. This fleet consists of ~48 vessels (Chassot presentation - IOTC secretariat, October 2022 - FAD indicators), which landed one-quarter of the total catch through a combination of FSC and FAD operations, i.e. ~436,000t in 2020 (IOTC). Of this quantity, over three-quarters were caught on floating objects (~9800 sets) (Chassot presentation - IOTC secretariat, October 2022 - FAD indicators) and a smaller number on free school sets (FSC). Based on econometric methods previously developed (Tidd et al 2023), we determine the utility and the effect of decreasing FAD sets/instrumented buoy deployments in the Indian Ocean. Incorporating this new information into a medium-term forecast using a stock assessment model allows to estimate the effects of different DFAD management measures on the SSB, recruitment and catches in the future with the implementation of seasonal temporal closures (e.g. IOTC Resolution 23/02), the percentage decrease/increase in the number of FAD sets, and the instrumented buoy deployments. It is therefore hoped that this study will further assist fisheries managers when considering implementing new input-based measures associated with DFAD regulations for the sustainability of their fisheries of concern.

2. Methods

2.1 Operating model definition

The biological operating model (OM) used in this study consists of an age-structured population dynamics model of the Indian Ocean yellowfin stock. The dynamics of the stock is governed by the mortality and annual recruitment of juvenile fish. Both fishing mortality and natural mortality cause the stock numbers to decline as each year class grows older.

The stocks dynamics is based on the standard age-structured model:

$$N_{a,t} = \begin{cases} R_t & for\ a = 1 \\ N_{a-1,t-1} \mathrm{e}^{-Z_{a-1,t-1}} & for\ 2 < a < P \\ N_{a-1,t-1} \mathrm{e}^{-Z_{a-1,t-1}} + N_{a,t-1} \mathrm{e}^{-Z_{a,t-1}} & for\ a = P \end{cases} \tag{1}$$

Where $N_{a,t}$ is the number (in thousands) of fish of age a (where P is the plus-group) at time t (in quarters), $Z_{a,t}$ is the total mortality at age a and time t, with $Z_{a,t} = M_a + F_{a,t}$, where M_a is the natural mortality at age a and $F_{a,t,}$ is the fishing mortality at age a, at time t.

At each time step, the Spawning Stock Biomass (SSB) is calculated as follows:

$$\mathrm{SSB}_t = \sum N_{a,t} W_{a,t} O_{\mathrm{a,t}} \tag{2}$$

Where $W_{a,t}$ is the fish weight at age in kilogrammes at time t, and, $O_{a,t}$ is the proportion of mature fish at age a and at time t.

The stock-recruitment relationship is assumed to be of the Beverton and Holt type (Beverton and Holt, 1957), which implies that there is an asymptotic maximum in recruitment:

$$R_t = \frac{(4\mathrm{h}\mathrm{R}_0\mathrm{SSB}_{\mathrm{t}-1})}{(\mathrm{S}_0(1-\mathrm{h})+\mathrm{SSB}_{\mathrm{t}-1}(5\mathrm{h}-1))} \tag{3}$$

where R_0, represent the unfished virgin recruitment numbers at age 0, S_0 the unfished virgin SSB and h is the steepness.

Catch numbers at age $C_{a,t}$ are related to the fishing mortality at age through the Baranov catch equation (Baranov, 1918):

$$\mathrm{C}_{\mathrm{a,t}} = \mathrm{N}_{\mathrm{a,t}} \frac{\mathrm{F}_{\mathrm{a,t}}}{\mathrm{Z}_{\mathrm{a,t}}} (1 - \mathrm{e}^{-\mathrm{Z}_{\mathrm{a,t}}}) \tag{4}$$

And catch yield in tonnes ($Y_{a,t}$) is calculated as follows:

$$Y_{a,t} = \sum C_{a,t} W_{a,t} \tag{5}$$

2.2 Model inputs and parametrization

Single species assessments for yellowfin are carried out routinely by *The Indian Ocean Tuna Commission* (IOTC) https://iotc.org/ using Stock Synthesis (SS3) (Methot and Wetzel, 2013) and provide the basic framework for our study. The basis of the IOTC SS3 stock assessment comprises an age-based (29 age groups, quarterly ages 0-28) model structured along multiple areas, seasonality in the form of a quarterly time step and combined genders.

The parametrization of the OM used in this study relies on the SS3 base model used in the 2020 IOTC assessment for yellowfin tuna (IOTC–2021–WPTT23–12). SS3 input files were provided by the IOTC Secretariat. For each quarter, stock numbers at age

($N_{a,t}$ in Eq.1), as well as catch-numbers-at-age ($C_{a,t}$ in Eq.4), were extracted from the SS3 Report.sso file. Since the OM had no spatial structure, the stock and catch numbers at age were aggregated summing over all regions, for each age group (0-29) and quarter.

Biological parameters, such as natural mortality at age (M_a) and weight-at-age ($W_{a,t}$), were also taken from the SS3 files of the base model. The parameters for the stock-recruitment relationship (Eq. 3) were estimated using the SS3 estimation of the unfished virgin recruitment at age 0 (R_0=116231, in thousands), and the unfished virgin SSB (S_0 =3,323,090 tonnes). We used two alternative values of steepness (h) (0.8 and 0.7) to conduct a sensitivity analysis.

All data were exported from SS3 output files into the *R* software via the ss3om package (https://github.com/flr/ss3om accessed 1/8/23).

3. Estimating the evolution of $F_{a,t}$ according to different DFAD management scenarios

Changes in the yields after increasing/decreasing numbers of DFAD sets were estimated using the results of a recent study (Tidd *et al.*, 2023, currently in review, August 2023). The study used an econometric methodology based on an estimation of fishing capacity and provided an in-depth analysis of factors that may influence capacity utilisation within the French purse seine fleet. The study estimated that a 1% change in the *number of DFAD sets* would give a change of catch yield of 0.29% on yellowfin tuna (referred to as *elasticity*). Similarly, a 1% increase in the number of *buoy deployments* results in a 0.05% decrease in catch.

In order to build model projections accounting for the above-mentioned elasticities, we first removed the catch numbers-at-age associated to DFAD sets from the total catch-at-age estimated for all gears in each quarter of 2020. The catch numbers-at-age associated to DFAD were then converted to yields using Eq. (5). Secondly, we calculated the new DFAD yields using the % change expected for each scenario, considering the elasticity values described above. Thirdly we inferred revised catch numbers at age for DFADs and added them to the rest of the catch numbers at age for the other gears. The new F-at-age for each scenario was then estimated, by performing a non-linear optimisation of (Eq 4). These new *F's* were considered constant for the full forecast period.

2.3 Scenarios

Stock numbers-at-age were projected between 2021 and 2030 considering 5 different scenarios:

- **Scenario 1** (Reference or base case relating to 2020 effort levels). In this scenario, the fishing mortality induced by DFADs was considered to remain the same as in 2020 (averaged over all quarters).
- **Scenario 2a** (50% reduction of DFAD sets). In this scenario, DFAD future effort was considered as half of the 2020 effort levels (in terms of the number of DFAD sets).
- **Scenario 2b** (50% reduction of instrumented buoys deployments). In this scenario, a 50% reduction in instrumented buoy deployments for the DFAD fishery affects changes in the fishing mortality at age due to the DFAD purse-seine fisheries.
- **Scenario 3** (Seasonal closure of DFAD fishing during the third quarter of the year)**.** The fishing mortality at age related to DFAD fishing in the 3rd quarter of every year was set at zero, while in the other quarters DFAD effort was maintained at the 2020 levels.
- **Scenario 4** (DFAD-free fishery, i.e. zero DFAD sets all year long). This is an extreme scenario to explore the consequences of a DFAD ban by the global market. Consequently, the fishing mortality induced by the DFADs was set at zero in all quarters.

In all scenarios, the fishing mortality related to the other fleets (including the FSC by the industrial purse seiners) was considered the same as in 2020 (i.e., effort levels were considered the same for all other fleets, with no reallocation of effort on FSC for purse seiners). The parameters setting the biological variables of the model (weights at age, maturity at age, etc.) used 3-year averages before the year 2020 in the projections. All results were evaluated as a '% change (Δ)' in SSB, catch and recruitment, and a yearly % rate of change was calculated for these variables, relative to the baseline stock

projection (base case) after 10 years (Scenario 1). A target *Fbar* (mean *F*) per quarter time-step relating to each of the scenarios (calculated from estimating a new *F* - Eq (1-5) was used as the control object for future fishing mortality.
All projections were conducted using FLR (www.flr-project.org accessed 2//2/23).

3. Results

In Table 1, the results from the simulations are presented in terms of relative changes (%) to the baseline projection in 2030. Figures 1 and 2 contain all of the scenario projections with two different levels of steepness (0.8 and 0.7, respectively). The population trends resulting from the effort-based projections demonstrate that in the absence of DFADs (Scenario 4), the catch, the SSB and recruitment for yellowfin would be substantially larger than if the fishing effort remain constant from 2020 (Scenario 1) (Figure 1, 2 and Table 1). In contrast to eliminating DFADs (Scenario 4), Scenario 2b shows that with a 50% decrease in the operational instrumented buoys at sea, a decline in SSB by over ~1% relative to the baseline is observed for each value of steepness, while recruitment shows a decrease of less than 0.4%. Thereby any decrease in instrumented buoy deployments would contribute to a higher *F* and a small drop in SSB.

A 50% decline in the number of DFADs sets (Scenario 2a) results in small increases in SSB (~5-7% for the 2 different values of steepness). Catch increases between 1 and 3% as is the recruitment relative to Scenario 1.

To estimate the effects of a 3rd quarter seasonal closure, we show that with a cessation in DFADs in this period, SSB for yellowfin increased by ~14-17% and catch increases over the forecast period between ~4-6% relative to Scenario 1 (for the 2 values of steepness) (Table 1). For the 0.8 value of steepness (a more productive assumption), the values are nonetheless higher than with the lower steepness of 0.7 (Figures 1 and 2), and the difference in catch over the period stands around 40,000 tonnes.

Table 1 10-year projection results relative to the Scenario 1 (base case) in the year 2030 for two different values of steepness (*h*). **Scenario 1,** (Reference or base case relating to 2020 effort levels), **Scenario 2a** (50% reduction of DFAD sets), **Scenario 2b** (50% reduction of instrumented buoys deployed), **Scenario 3** (Seasonal closure of FAD fishing during the third quarter of the year) and **Scenario 4** (DFAD-free, zero DFAD sets all year)**.** Dark red to orange colouration depicts areas of the highest losses, while yellow to darker green, higher % increases.

Table 1. Relative changes in 4 scenarios relatively to 2030 baseline projections

Δ%	**Scenario 2a**	**Scenario 2b**	**Scenario 3**	**Scenario 4**	**Steepness (*h*)**
ssb	5.5	-0.92	9.5	42.9	0.8
rec	1.0	-0.18	1.7	6.1	0.8
catch	1.5	-0.27	2.5	9.4	0.8
ssb	6.2	-1.04	10.8	49.3	0.7
rec	1.9	-0.34	3.3	12.03	0.7
catch	2.3	-0.4	3.7	14.4	0.7

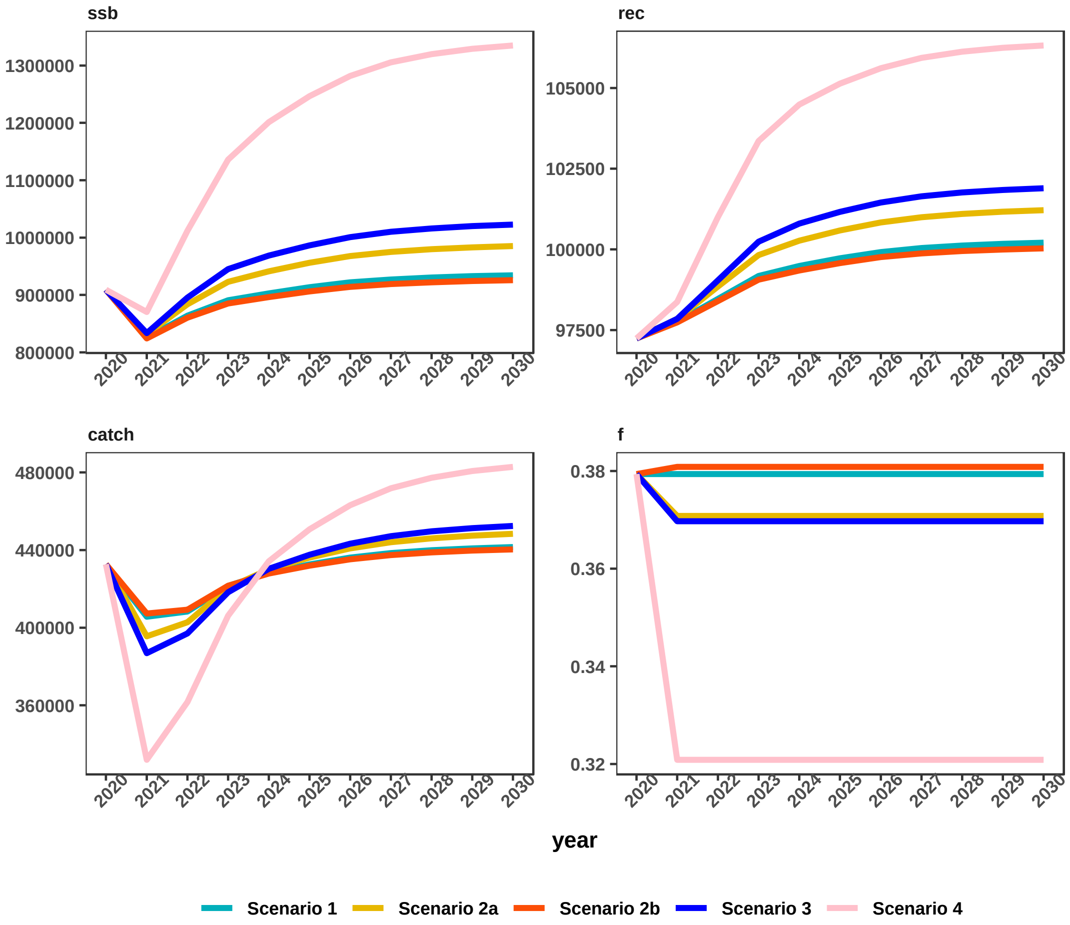

Figure 1 10-year projection results with a steepness of 0.8. **Scenario 1,** (Reference or base case relating to 2020 effort levels), **Scenario 2a** (50% reduction of FAD/FOB sets), **Scenario 2b** (50% reduction of instrumented buoys deployed in the water), **Scenario 3** (Seasonal closure of FAD fishing during the third quarter of the year) and **Scenario 4** (FAD-free, zero FAD sets all year).

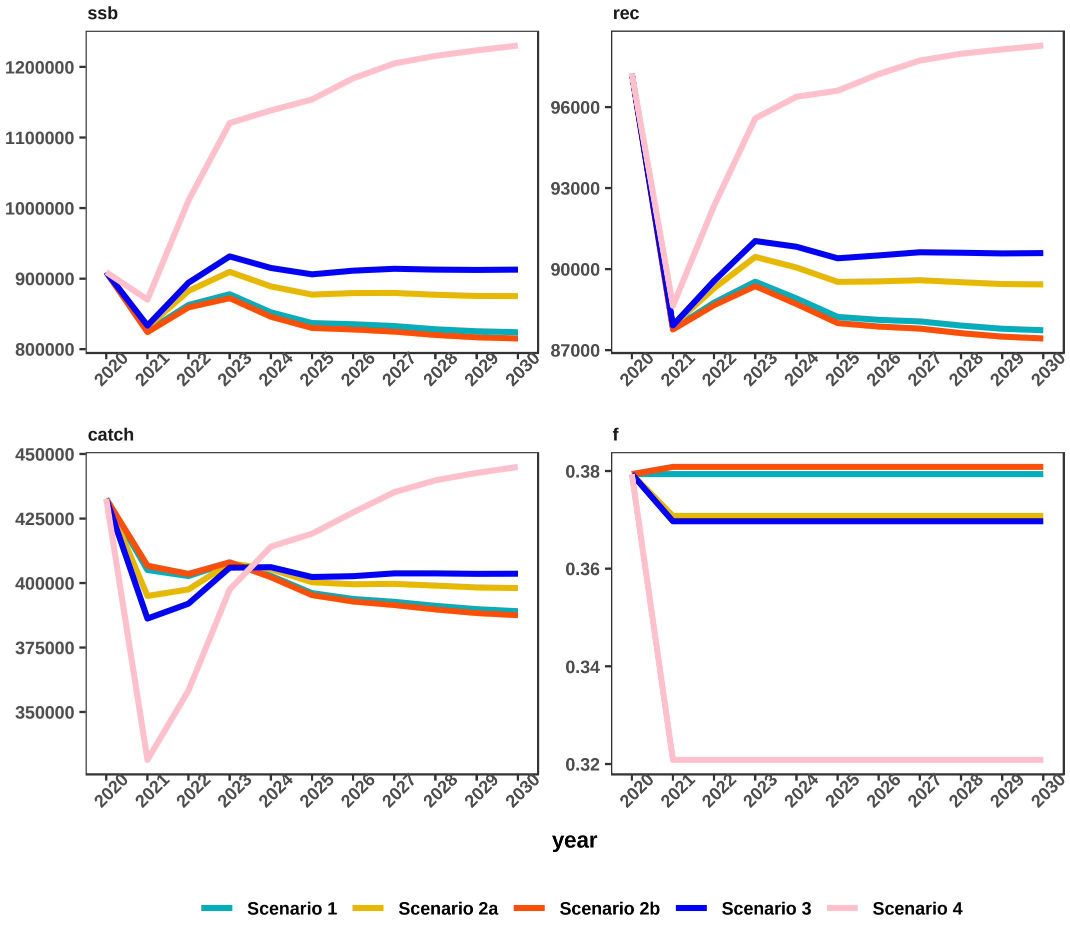

Figure 2 10-year projection results with a steepness of 0.7. **Scenario 1,** (Reference or base case relating to 2020 effort levels), **Scenario 2a** (50% reduction of FAD/FOB sets), **Scenario 2b** (50% reduction of instrumented buoys deployed in the water), **Scenario 3** (Seasonal closure of FAD fishing during the third quarter of the year) and **Scenario 4** (FAD-free, zero FAD sets all year).

4. Discussion

Our research helps to give a useful insight into the potential implications of the reduction of DFAD fishing in the Indian Ocean purse seine tuna fisheries, hence the effects of such management strategies may have on the dynamics of the yellowfin tuna stock. With the current overfished status of yellowfin tuna stock in 2021, which is also subject to overfishing (IOTC-2021-WPTT23-12 accessed 6/6/2023), any increase in fishing mortality or fishing at current levels of fishing effort will subsequently result in future losses in yields, SSB, and recruitment. In contrast, with the introduction of a large decrease (-50% of DFADs sets and/or the annual 3rd quarter periodic closure, IOTC Res. 23/02) within this fishery, the long-term effects would be positive on yields, SSB and recruitment levels relative to the baseline forecast as can be seen in Figure 1, 2 and Table 1.

Our results match those of empirical studies where periodic closures increase biomass and harvesting yields compared to areas continually open to fishing (non-spatial management) (Goetze *et al.*, 2018, Carvalho *et al.*, 2019). For example, we found that when the purse seine had a 50% cut in the number of DFAD sets (Scenario 2a), it did not achieve the same results as that of the periodic closure which shows a higher level of biomass, recruitment and yields after the 10-year projection. This annual closure of the third quarter potentially helps protect the juvenile portion of the stock, thus allowing it to reach adulthood and as such increasing the SSB. Furthermore, the socio-economic benefits are yet to be assessed in this study, although the direction of the results would imply a positive benefit to all IO fleet segments in the long term concerning employment, increased profits and food security in the region. However, it is important to note that the potential consequences of increases in ‘effort creep’ or unquantified fishing efficiency within the fleet (not included in this study) need to be taken into account when developing management measures and maintaining stocks relative to target biomass (Fonteneau *et al.*, 2002). It is also interesting to note the negative elasticity of the yellowfin tuna catch to the instrumented buoy deployments (Scenario 2b), meaning that the catch of this species increases when the number of buoy deployments decreases (Tidd *et al.*, 2023). This result is perhaps counter-intuitive as one would expect that the decrease in instrumented buoy deployments would result in the likely decrease in catches. Too many instrumented buoy deployments represent an excess in fishing capacity, although the small elasticity value suggests only minor changes with a 1% change in the number of instrumented buoy deployments (i.e. the response is insensitive to change). Escalle et al. (2018) also found that the DFAD density in specific areas had resulted in a decrease in CPUE of tunas, because tuna schools are fragmented between DFADs.

Further work will be necessary to check empirically the relationship between the deployment of instrumented buoys and the number of DFAD sets. Nevertheless, this study provides new knowledge for decision-makers when they consider implementing new input-based management measures of FAD use in the region to prevent further risks of overfishing to yellowfin tunas and ultimately to sustainably ensure their important contribution as a global food source. To achieve sustainability of fisheries, we must continue to: i) assess the current sustainability status of fisheries concerning multiple targets (e.g. ecological, social and economic), ii) understand the trade-offs among these targets and iii) use indicators that are robust for use in tracking our progress towards meeting these targets (Hak *et al.*, 2016; Anderson *et al.*, 2015). Further work will also need to include economic dimensions, such as the effects of FAD management on the profitability of the whole fishery to achieve a Maximum Economic Yield (MEY). Other externalities of DFAD fishing need to be valuated and internalized in a sustainability science analysis, such as bycatch indicators to assess changes in the ecosystem, marine litter resulting from discarded buoys, as well as the rent distributional effects for the different interacting fleets involved in this fishery. A Management Strategy Evaluation (MSE) framework would be a useful approach for testing alternative candidate harvest control rules to develop harvesting strategies and balance trade-offs with competing management objectives (Punt *et al.*, 2016). Given the uncertainties associated with DFAD fishing efficiency and the implications for achieving the biomass targets of the Indian Ocean tuna stocks, the MSE approach would be the necessary step forward to choose the appropriate strategy meeting IOTC management objectives.

4. Acknowledgements

The research conducted here has received funding from the French fishing inter-profession France Filière Pêche (FFP) through the (MANFAD project). We would also like to thank IOTC for their help in acquiring the stock assessment data. Thanks also to Iago Mosqueira from the University of Wageningen for the interesting discussions on the use of FLR and ss3om, and Hilario Murua from ISFF for kindly taking the time to offer advice on every step/aspect of the work involved.

5. References

Anderson, J.L., *et al*. (2015). The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes. *PLoS ONE* **10**, e0122809.

https://doi.org/10.1371/journal.pone.0122809

Baranov, F.I. (1918). K voprosu o biologicheskikh osnovaniyakh rylmogo khozyaistva. [On the question of the biological basis of fisheries.] Nauchn. Issled. Ikhtiologicheskii Inst. Izv. 1: 81–128.

Baske, A., Gibbon, J., Benn, J., and Nickson, A. (2012). Estimating the Use of Drifting Fish Aggregation Devices Around the Globe - Pew Environment Group. https://www.pewtrusts.org/~/media/legacy/uploadedfiles/FADReport1212pdf.pdf

Beverton, R.J.H., and Holt, S.J. (1957). On the dynamics of exploited fish populations. Fishery Investigations Series II Vol. XIX, 1-533. Ministry of Agriculture, Fisheries and Food, London.

Carvalho, P.G., Jupiter, S.D., Januchowski-Hartley, F.A., Goetze, J., Claudet, J., Weeks, R., & White, C. (2019). Optimized fishing through periodically harvested closures. *Journal of Applied Ecology* **56**(8), 1927-1936. https://doi.org/10.1111/1365-2664.13417

Davies, T., Curnick, D., Barde, J., and Chassot, E. (2017). Potential Environmental Impacts Caused by Beaching of Drifting Fish Aggregating Devices and Identification of Management Solutions and Uncertainties (IOTC-2017-wgfad01-08 Rev_1, Indian Ocean Tuna Commission, 2017). https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers18-02/010071786.pdf

Escalle, L., Brouwer, S., Pilling, G., and the PNA Office. (2018). Estimates of the number of FADs active and FAD deployments per vessel in the WCPO. A paper submitted to the 14th Regular Session of the WCPFC Scientific Committee, Busan, Korea. https://www.researchgate.net/publication/327154403_Estimates_of_the_number_of_FADs_active_and_FAD_deployments_per_vessel_in_the_WCPO?utm_source=twitter&rgutm_meta1=eHNsLWNzN0d5dHVaQS9FSmh6UEJxMHJrTFhRcXJLYnNhZm16NFNFS0tEL21JbDRIa3pVckhLQXNJUUhJN0wzOHNwZGdXVGpITlI3d1VTaGFKNzh3dldXS0MvOD0%3D

Fonteneau, A., Pallares, P., Sibert J., and Suzuki, Z. (2002). 'The effect of tuna fisheries on tuna resources and offshore pelagic ecosystems’. 16 Ocean Yearbook 142–170.

Fonteneau, A., Chassot, E., & Bodin, N. (2013). Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs):

Taking a historical perspective to inform current challenges. *Aquatic Living Resources* **26**(1), 37-48. https://doi.org/10.1051/alr/2013046

Gaertner, D., & Pallarés, P. (2002). The European Union Research Project, Efficiency of Tuna Purse-Seiners and Effective Effort (ESTHER): Scientific report of project. Doc. SCTB15-FTWG-3. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=88e3494f48a3f744b069dd688d450833cfd4adae

Goetze, J.S., Claudet, J., Januchowski-Hartley, F., Langlois, T.J., Wilson, S.K., White, C., and Jupiter, S.D. (2018). Demonstrating multiple benefits from periodically harvested fisheries closures. *Journal of Applied Ecology* **55(**3), 1102-1113. https://doi.org/10.1111/1365-2664.13047

Gulland, J.A. (1983). Fish stock assessment, Vol. 1. Chichester: A manual of basic methods. FAO/Wiley. 233 pp.

Hák, T., Janoušková, S., and Moldan, B. (2016). Sustainable Development Goals: a need for relevant indicators. *Ecological Indicators* **60**, 565–73. https://doi.org/10.1016/j.ecolind.2015.08.003

Hanich, Q., Davis, R., Holmes, G., Amidjogbe, E., and Campbell, B. (2019). Drifting Fish Aggregating Devices (FADs).*The International Journal of Marine and Coastal Law* **34(4)**, 731-754. doi: https://doi.org/10.1163/15718085-23441103

Hicks, C.C., Cohen, P.J., Graham, N.A., Nash, K.L., Allison, E.H., D'Lima, C., Mills, D.J., Roscher, M., Thilsted, S.H., Thorne-Lyman, A.L. (2019). Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**(7776), 95–98. https://doi.org/10.1038/s41586-019-1592-6

Imzilen, T., Lett, C., Chassot, E.,. *et al.* (2022). Recovery at sea of abandoned, lost or discarded drifting fish aggregating devices. *Nat Sustain* **5**, 593–602. https://doi.org/10.1038/s41893-022-00883-y

Lecomte, M., Rochette, J., Laurans, Y., and Lapeyre, R. (2017). Indian Ocean tuna fisheries: between development opportunities and sustainability issues. IDDRI Development Durable & Relations Internationales. https://www.iddri.org/sites/default/files/PDF/Publications/Hors%20catalogue%20Iddri/201811-tuna-indian%20oceanEN.pdf

Lopez, J., Scott, G.P. (2014a). The use of FADs in Tuna fisheries, European Parliament, Directorate-General for Internal Policies, Policy Department B: Structural and Cohesion Policies, Fisheries. https://www.europarl.europa.eu/RegData/etudes/note/join/2014/514002/IPOL-PECH_NT(2014)514002_EN.pdf

Lopez, J., Moreno, G., Sancristobal, I., and Murua, J. (2014b). Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic. Indian and Pacific Oceans. *Fish. Res.* **155**, 127–137. doi: 10.1016/J.FISHRES.2014.02.033

Methot, R.D. and Wetzel, C.R. (2013). Stock Synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research* **142,** 86-99. https://doi.org/10.1016/j.fishres.2012.10.012

Maufroy, A., Kaplan, D. M., Bez, N., De Molina, A. D., Murua, H., Floch, L., and Chassot, E (2017). Massive increase in the use of drifting Fish Aggregating Devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. *ICES Journal of Marine Science* **74**, 215–225. https://doi.org/10.1093/icesjms/fsw175

National Research Council (NRC) (1992). Dolphins and the tuna industry. National Academy Press, Washington, D.C.

Peterman, R.M. (2004). Possible solutions to some challenges facing fisheries scientists and managers. *ICES Journal of Marine Science* **61**, 1331–1343. https://doi.org/10.1016/j.icesjms.2004.08.017

Punt, A. E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A., and Haddon, M. (2016). Management strategy evaluation: best practices. *Fish and Fisheries* **17**(2), 303-334. https://doi.org/10.1111/faf.12104

Sasidharan, A., Rustad, T., and Cusimano, G.M. (2023). Tuna sidestream valorization: a circular blue bioeconomy approach. *Environ Sci Pollut Res*. https://doi.org/10.1007/s11356-023-28610-w

Sainsbury, K.J. (2008). Best Practice Reference Points for Australian Fisheries. Australian Fisheries Management Authority, Canberra, Australia, 156 pp. https://www.researchgate.net/profile/Keith-

Sainsbury/publication/277664781_Best_Practice_Reference_Points_for_Australian_Fisheries/links/56f1634908ae4744a91eec62/Best-Practice-Reference-Points-for-Australian-Fisheries.pdf

Tidd, A.N., Reid, C., Pilling, G.M., and Harley, S.J. (2016). Estimating productivity, technical and efficiency changes in the Western Pacific purse-seine fleets. *ICES Journal of Marine Science: Journal du Conseil* **73**(4), 1226–1234. https://doi.org/10.1093/icesjms/fsv262

Tidd, A.N., Floch, L., Imzilen, T., Tolotti, M., Dagorn, L., Capello, M., Guillotreau, P. (2023). How technical change has boosted Fish Aggregation Device productivity in the Indian Ocean tuna fishery. *Scientific Reports* (in review). https://doi.org/10.21203/rs.3.rs-2894103/v1

Torres-Irineo, E., Gaertner, D., Chassot, E., and Dreyfus-Leon, M. (2014). Changes in fishing power and fishing strategies driven by new technologies: the case of tropical tuna purse seiners in the eastern Atlantic Ocean. *Fisheries Research* **155,** 10–19. https://doi.org/10.1016/j.fishres.2014.02.017