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► To cite this version:

P. Guillotreau, F. Salladarré, M. Capello, A. Dupaix, L. Floc'H, et al.. Is FAD fishing an economic trap? Effects of seasonal closures and other management measures on a purse-seine tuna fleet. *Fish and Fisheries*, 2023, 10.1111/faf.12799 . ird-04304162

HAL Id: ird-04304162

<https://ird.hal.science/ird-04304162v1>

Submitted on 24 Nov 2023

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Is FAD fishing an economic trap? Consequences of a seasonal FAD closure for an Indian Ocean tuna fishery

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Preliminary draft of an article published in *Fish & Fisheries*: Guillotreau, P., Salladarré, F., Capello, M., Dupaix, A., Floch, L., Tidd, A., Tolotti, M., & Dagorn, L. (2023). Is FAD fishing an economic trap? Effects of seasonal closures and other management measures on a purse-seine tuna fleet. *Fish and Fisheries*, 00, 1–17.

<https://doi.org/10.1111/faf.12799>

Abstract

The management of Fish Aggregating Devices (FAD) creates heated debates in tuna fishery management organizations striving to reduce the number of deployed floating objects. Through several econometric models and a machine learning approach, we evaluate the consequences of three management scenarios on the catch and profit of the French purse-seine fleet operating in the Indian Ocean: 1) a half reduction in the number of authorized buoys per vessel, 2) a 72-day closure of FAD fishing with and 3) without re-allocation of effort on free schools. The results show a significant decrease of fleet profits by 7%, 10% and 18%, respectively. We hypothesize an “economic trap” of FAD fishing caused by the far greater efficiency of this harvesting technique for larger vessels searching for economies of scale, and by the overfished status of yellowfin tuna stocks in the Indian Ocean. The results are compared with other studies looking at the impact of FAD management measures in other oceans.

Key-words: FAD closure, economic impact, tuna fishery, purse-seine, Indian Ocean

JEL Codes: Q22, Q38, R15,

Acknowledgement

We acknowledge *France Filière Pêche (FFP)* which has funded the MANFAD project of which this research is carried out. We also express our sincere thanks to ORTHONGEL for making their FAD tracking data available and to the IRD's Ob7 (“*Observatoire des Ecosystèmes Pélagiques Tropicaux Exploités*”) in charge of data collection, processing, management and for sharing the data used in this study.

1. Introduction

The use of drifting Fish Aggregating Devices (FADs)¹ within tuna purse seine fisheries has been a game changer by substantially increasing fishing efficiency over the last three decades. It has also raised vigorous debates within tuna Regional Fisheries Management Organizations (RFMO) resulting in conservation management measures. At the 6th Special Session of the Indian Ocean Tuna Commission (IOTC) held in Mombasa (Kenya) in February 2023, a resolution was adopted by contracting parties to create a 72-day annual ban of FADs (IOTC resolution 23/02), to which several countries have objected². The dispute between Distant Water Fishing Nations (DWFNs) and other contracting parties remains heated, competing for the same migratory stocks of tuna.

The conflict is not easy to address because of entangled interests between DWFN fleets and tuna-dependent coastal states. Tuna is one of the most consumed fish in the world, and one of the most harvested with more than five million tonnes in 2020 for the major species (FAO 2022), representing an end value of USD 40.8 billion in 2018 (McKinney et al. 2020). Three quarters of the caught tuna are sold to fish canneries, and landing ports and processing facilities are often located in developing countries, creating jobs, export revenues and other positive economic effects, not even mentioning substantial government revenues coming from fishing rights fees paid by DWFNs (Bell et al. 2021). The DWFNs also interact or compete with local fisheries targeting the same species and markets (e.g. pole and line skipjack –*Katsuwonus pelamis*- fishery in Maldives, coastal longline yellowfin tuna –*Thunnus albacares*- fishery in Seychelles or Sri Lanka, etc.). Since the early 1990s, the worldwide deployment of artificial FADs at sea has become a critical issue for the whole value chain (Lennert-Cody et al. 2018, Holmes et al. 2019).

Fishing strategies that use FADs are put under pressure by conservationists because of catches of juvenile yellowfin and bigeye tuna (*Thunnus obesus*), bycatch and “ghost fishing” (accidental catches from net entanglement beneath FADs) of vulnerable species (sharks, turtles...), abnormal movements of fish, disturbed pelagic ecosystems, marine pollution and habitat damages due to discarded FAD plastics after sinking or beaching (Marsac et al. 2000, Hallier & Gaertner 2008, Dagorn et al. 2013, Churchill 2021). The four RFMOs managing tropical tuna fisheries strive to restrict the use of FADs by implementing time and area closures, limited numbers of buoys, monitoring plans, bycatch reduction measures, use of biodegradable and non-entangling materials and restricted number of supply vessels, etc. (Lennert-Cody et al. 2018, Holmes et al. 2019). Society also responds to the problem through retailers and

¹ FADs (Fish Aggregating Devices) are floating objects –natural logs or man-made bamboo rafts- tracked by satellite buoys and under which tuna aggregates, thus becoming more easily catchable. This technique potentially doubles the proportion of positive sets relatively to fishing on free schools (Fonteneau & Hallier 1993).

² On May 8th, 2023, at least eight countries had already objected to this management measure: Comoros, Oman, Somalia (but withdrawal of the objection on March 25th), Philippines, Seychelles, Kenya, European Union, France. Objecting members will not comply with the measure, but if more than a third of the 30 IOTC members object, even the non-objecting parties are not bound by the measure.

consumers' associations by deciding on trade bans on FAD-caught tuna (Davies et al. 2014, Leadbitter & Benguerel 2014).

If the literature dealing with the ecological consequences of FAD fishing is abundant, scarcer are research works showing the economic effects of FAD management plans (Hanich 2012, Holmes et al. 2019, Ovando et al. 2021). What could be the consequences of removing FADs for fishing companies and coastal states? Would purse-seine vessels remain profitable in the current economic context? Who should bear the burden of FAD management plans? As other authors have stressed the possible ecological trap of FAD fishing (Marsac et al. 2000, Hallier & Gaertner 2008), we hypothesise the existence of an economic trap for the purse-seine fleets using FADs and benefiting from important increasing returns to scale, technical innovations and efficiency gains for the past three decades. What could be the price to pay to come back to the *status quo ante* situation, with twice as fewer buoys at sea or under a seasonal FAD moratorium?

We propose to answer this question by looking at the profitability of the French Purse-Seine (PS) fishery operating in the Indian Ocean (IO). After some stylized facts showing the generalized use of FADs by the French PS fleet and some of its economic effects, a quadratic catch-effort model is estimated to stress a possible optimal use rate of FADs in order to maximize the catch level. Vessel and time fixed effects behind the technical choice of FAD vs free school fishing are also considered. The effects of fishing effort and strategies on individual profits are analysed by a random forest model to explain the rationale of FAD fishing and the difficulty of shifting to other strategies.

2. Literature review

A great deal of literature about FADs focuses on their detrimental ecological impacts (Hallier & Gaertner 2008, Dagorn et al. 2013, Davies et al. 2014, Hanich et al. 2019, Gomez et al. 2020, Churchill 2021, Tolotti et al. 2022), which are well studied and not at the core of this research. Another strand of research is looking at efficiency gains with a FAD strategy relative to fishing on Free Swimming Schools (FSC) (Guillotreau et al. 2011, Wolff et al. 2013, Maufroy et al. 2015, 2016, Tidd et al. 2016, Wain et al 2021), sometimes in the perspective of standardizing Catch Per Unit Effort (CPUE) for stock assessment objectives (Chassot et al. 2012, Torres-Irineo et al. 2014, Katara et al. 2018, Gaertner et al. 2018). Finally, other authors are more interested by FAD management plans and their consequences on fisheries and ecosystems (Fonteneau et al. 2015, Lennert-Cody et al. 2018, Hanich et al. 2019, Holmes et al. 2019, Gomez et al. 2020, Ovando et al. 2021).

Our contribution lies in this last research arena, attempting to study the economic consequences of more stringent FAD management measures. In particular, an important goal would be to discover, if ever existing, an ecologically optimal number of monitored FADs per vessel (Fonteneau et al. 2015, Lennert-Cody et al. 2018). This is particularly challenging because of many influences affecting the use of FADs (ecological conditions, embodied technology, the assistance of supply vessels, shared equipment, stolen or abandoned buoys, and piracy events). The first step is to know precisely the number of instrumented floating objects at sea. A second research issue is to find a relationship between the own investment of fishing companies in satellite buoys, and the use and efficiency of FADs for purse seine vessels. We expect a significantly positive causality between investment and use of FADs, but skipper may prefer

one fishing technique or another (FAD vs FSC), have opportunistic behaviours when environmental conditions favour FSC fishing, harvest on other vessels' FADs or do not have supply vessels. FAD use can also be stimulated by management measures. For instance, the IOTC has implemented a total allowable catch for yellowfin tuna, active since 2017 (IOTC Resolution 16/01), which led PS fishers to intensify their use of FADs. By doing so the bycatch amount of silky sharks in the IO has increased significantly (Tolotti et al. 2022). Let us review the current knowledge about some of these issues along the historical development of the IO tropical tuna purse seine tuna fishery.

Number of FADs deployed by purse seiners and supply vessels

The number of buoy-tracked floating objects used by the purse-seine fleet worldwide is expanding since the early 1990s (Fonteneau & Hallier 1993, Lennert-Cody et al. 2018). Some observers estimated up to 120,000 buoys at any time at sea, of which 65,000 were found in the west central Pacific Ocean in 2017 (Hanich et al. 2019). In the IO, this number has tremendously increased from a few hundred in the 1990s to more than 2,000 in the late 2000s and certainly beyond 10,000 since the mid-2010s, explaining why over 80% of tuna is now caught on FADs (Maufroy et al. 2017, IOTC 2022a). IOTC reported 16,000 FAD deployments in 2021 by purse-seiners and their support vessels, of which 56% by Spanish-owned vessels and 25% by French ones, but only 10,000 of these objects were daily monitored at sea (IOTC 2022b). The number of buoys seeded yearly by French PS has increased from 41 per vessel in 2004 to 200 buoys a decade later (Gaertner et al. 2018) and it is limited since 2019 to 300 per PS vessel by IOTC resolution 19/02. However, this number of active buoys is not evenly distributed in space and time. A cluster analysis of FAD drifting movements helped to distinguish four fishing seasons and spatial patterns in the IO. The number of operational FADs at sea for the whole French PS fleet fluctuates between 590 in February when the boats are fishing eastward near the Chagos islands (free school season), to 2,252 in October, the peak of the FAD fishing season off the Somalian coast (Maufroy et al. 2017).

The massive deployment of drifting FADs and instrumented floating objects has been made possible by the use of support (supply) vessels, seeding and monitoring FADs for the sake of one or several purse seiners (Hanich et al. 2019). Support vessels were introduced in the mid-1990s in the Indian Ocean, and their number has sharply increased from 7 at the turn of the 2010s to a record number of 22 in 2016, before a gradual decrease to 11 bigger boats in 2021 (32 m long on average in 2003, up to 40 m in 2021), shared by several fishing vessels (IOTC 2022b, IOTC Res. 17/01). Most of these supply vessels are owned and used by the Spanish (domestic or Seychelles-flagged) fleet, with the French fleet operating only one of these support vessels in 2021 (against 3 in the two previous years, according to IOTC 2022b). In the IO, supply vessels contributed to an increase of the catch per day by 45%, the number of fishing sets per day by 20% and the distance travelled per day by 4.5% (Maufroy et al. 2015).

Technical change and strategic efficiency of FADs

The efficiency of FAD fishing has been enhanced by the technical change embodied in buoys, increasing the detection capacity of skippers for fish. Several regime shifts in the CPUE were directly caused by the introduction of new equipment (Torres-Irineo et al. 2014, Lopez et al. 2014, Gaertner et al. 2008, 2018, Maufroy 2016). A first structural break was observed in the early 1990s after the introduction of radio beacons and the deployment of man-made FADs (Torres-Irineo et al. 2014). A second turning point was caused by the use of Global Positioning System (GPS) technology. First introduced in 1996 in the IO, 100% of the buoys adopted a

GPS in the late 2000s (Lopez et al 2014, Gaertner et al. 2018). At the turn of the millennium, a first generation of echo-sounder buoys was able to detect biomass remotely under the monitored floating objects. The year 2009 marked another major shift after the investment in a second generation of echo-sounders, accelerating the use of FADs up to 75% of FAD sets at that time for the Spanish fleet (Lopez et al. 2014), soon followed by the French fleet in the same proportion (Maufroy et al. 2017). Five years later, all buoys were 100% equipped and the detection technology did not stop improving, thus increasing the catchability of tuna stocks (Lopez et al, 2014, Tidd et al. 2016, Gaertner et al. 2018).

This continuously upgrading detection technology, the use of support vessels and the increase of FAD fishing effort make it difficult to standardize CPUE to estimate the biomass level (Chassot et al. 2012, Katara et al. 2018, Gaertner et al. 2018). Maufroy (2016) showed a clear superiority of the FAD strategy over the FSC strategy in terms of efficiency in both Atlantic and Indian oceans. Estimating different types of efficiency (CPUE per day, per set, per travelled distance), the latter study made a distinction between technical efficiency (TE=CPUE under fixed biomass abundance and vulnerability conditions) and strategic efficiency (SE=CPUE under fixed month effect, vessel characteristics and support vessel assistance), total efficiency being the product of TE by SE. With glm and logit models, the author found that increasing the proportion of FOB sets at the annual rate of 3% between 2003 and 2014 in the IO, had increased the total efficiency of the PS fleet at a rate between 0.87% and 2.15% per year in the IO. All CPUE indices and the distance per day would be positively affected, but a higher proportion of FAD sets would also reduce the number of sets per day because of a greater percentage of positive sets on FADs in contrast to FSC sets (Fonteneau et al. 2013).

With non-parametric techniques (Data Envelopment Approach and Malmquist productivity index) over the period 1993-2010 in the West Central Pacific Ocean (WCPO), other authors have found an annual growth rate of 3.8% in productivity, most of it being attributable to technical change (displacement of the technology frontier for all vessels) rather than to technical efficiency (better use of inputs for one vessel's output relatively to others) (Tidd et al. 2016). The difference in growth rates can therefore be easily explained by different contexts (Pacific vs Indian Ocean), periods including various technical shifts and environmental conditions, and methods (linear models with a focus on FADs vs non-parametric approach for all strategies). Interestingly, the strongest efficiency gain in the IO took place after 2008, when GPS-tracked buoys instrumented with echo-sounders were disseminated across the whole fleet (Maufroy 2016). The use of echo-sounders has enhanced FAD efficiency by 10%, i.e. +2.0 to 2.5 tonnes per successful set according to Wain et al. (2021). Considering a unit cost of an echo-sounder buoy is around US\$ 1,000-1,500, with each buoy being used three or four times on average, the net revenue gain would represent between US\$ 5,000 and 7,000 per buoy (*Ibid.*). The return on investment was even estimated at USD 35,000 for a USD 5,200 unit cost in just one set (Gomez et al. 2020)

Catch composition and economic gain of a FAD strategy

Fishing on floating objects does not only improve efficiency, but also affects the catch composition by species towards more skipjack and less yellowfin and bigeye tunas (Fonteneau & Hallier 1993, Dagorn et al. 2013, Escalle et al. 2019). The elasticity of catch to the proportion of FAD sets in a random effect panel data model was deemed significantly negative for yellowfin tuna (-1.690) and positive for skipjack (+1.319) (Guillotreau et al. 2011). In other

words, any 10% increase in the proportion of FAD sets would reduce the yellowfin tuna catch by 17% and increase that of skipjack by 13%. The share of FAD sets having increased from 42% on average in the 1984-1995 period up to 49% during the 1996-2007 period, this would have raised by 9% the landings of skipjack and reduced by 13.6% the landings of yellowfin tuna, other things being equal. Theoretically, this should contract the sales value by less than 1.5% because of lower prices for skipjack. However, the loss was more than offset by the greater efficiency of FADs above mentioned: the total catch response to a 1% increase of sets on floating objects was found twice greater than the catch response to the number of sets on free-swimming school (0.453 vs 0.230, respectively, Wolff et al. 2013), considering the greater proportion of positive sets for FADs. Some authors argued that this greater efficiency of FAD fishing could be undermined by the significant reduction in the size of fish (Fonteneau et al. 2002, Hanich et al. 2019).

On a more economic ground, what could be the relative energy costs of FAD and FSC strategies? Some authors may consider that FAD fishing should result in lower fuel consumption per tonne of landed fish because of a reduced searching time (Dagorn et al. 2013, Parker et al. 2015, Hanich et al. 2019, Holmes et al. 2019). Surprisingly, based on individual purse-seine data on fuel consumption by type of fishing, the FAD strategy proved to be more energy-consuming than the FSC strategy, presumably because vessels were moving more frequently at full speed (Maufroy 2016, Chassot et al. 2021, Basurko et al. 2022). Yet this would not degrade the vessel profitability either, because of this higher efficiency of FADs over a FSC strategy (Hamjan & Mallawa 2020). In that respect, what could be the effects of management plans aiming at shortening FAD seasons, limiting FAD sets or the authorized number of buoys at sea?

FAD Management plans and economic consequences

FAD management plans were implemented in almost every ocean by RFMOs for a long time³. In the west central Pacific Ocean, FAD closure periods have been adopted since 2009 in the Parties to Nauru Agreement (PNA) waters. In the IO, due to the pressure on yellowfin and bigeye tunas, IOTC also implemented time-area closures for both longline and purse seine vessels for one month from November 2011 (IOTC Res. 10/1) until 2014 (Song and Shen 2022). However, such resolution was not specific to FADs. An important change occurred in 2012, when IOTC first introduced a resolution requiring the elaboration of FAD management plans from the fleets (Res. 12/08 *Procedures on a fish aggregating devices (FADs) management plan*). Detailed information and reporting about the use of FADs was expected, as well as responsible FAD management (improved design, marking, retrieval actions...), but nothing concerning restrictions on their use. Such measures really started with Resolutions 15/08 and the following ones, including a limitation to a maximum number of active buoys and followed by any purse seine vessel at 550 at any one time, and no more than 1100 instrumented buoys acquired annually. These numbers were reduced the first time in 2016 to 425 active and 850 acquired annually, then to 350 active buoys at sea and 700 instrumented buoys acquired annually by each vessel in 2017, and since 2020 to a maximum of 300 operational buoys at sea and 500 instrumented buoys acquired annually per vessel (IOTC Res. 19/02). At the 25th

³ Reviews of FAD management measures taken by RFMOs can be found in Davies et al. (2014), Song and Shen (2022), Baidai et al. (2022) and https://www.wcpfc.int/system/files/2015_FAD_overview_measures-06-05.pdf

Session of the IOTC in June 2021, a group of nine coastal countries⁴ proposed an amendment to resolution 19/02 so as to halve the maximum authorized number of FADs per purse-seine vessel from 300 to 150 operational buoys at sea at any one time. It just failed to be adopted by voters in November 2021 but the dispute between DWFNs which had objected to the amendment (EU, Japan, South Korea) and other contracting parties remains unsolved. In February 2023, some of the coastal countries coalesced to propose a 72-day FAD moratorium which was voted with a two-third majority for an implementation starting in July 2024 (IOTC Res. 23-02). Several other members (eight countries up to May 8th, 2023) have objected to this resolution and the situation is still very tense.

These limitations represent the most effective way of containing the FAD fishing capacity, rather than the closure of FAD strata or limitations in the number of FAD sets which are fairly difficult to enforce (Fonteneau et al. 2015). A six-month moratorium on FAD sets was simulated by an iterative “fishing-day” model to look at the consequences on catch and bycatch (Escalle et al. 2017). The model took into consideration the probability of occurrence of different fishing events (visual cues, size and species of tuna schools...) and skippers’ decisions based on EU PS data 2005-2014 in both the Atlantic and Indian Oceans. Various scenarios of fishing effort reallocation or changing fishing practices were explored through Monte Carlo simulations. Not surprisingly, the model predicted a decreasing number of FAD sets and an increase in FSC sets with lower catches of small tuna (<10kg) and higher catches of large tuna (equal to or more than 10 kg).

Another attempt was made for the Pacific Ocean to look at the economic benefits of setting FAD set limits instead of closure periods (Holmes et al. 2019). FAD closures were deemed ineffective because they had just the effect of increasing fishing pressure in non-closure periods/areas, except for fleets relying on FAD fishing during lower tuna price periods. A linear operating model was developed for a generic purse-seine vessel to simulate the effect of a FAD closure of three months within WCPO countries’ EEZ, plus an additional two month closure in the high seas. Such a closure period could result in a net loss of US\$ 250,000 per trip with an average skipjack price of US\$ 1,860 per tonne, and even worse under lower skipjack prices because it could not be offset by additional income from the non-closure period. This would also reduce the fisheries revenues of some Pacific small island developing states relying to a large extent on access fees paid by DWFN fleets to the government (Bell et al. 2021). Other authors estimated the effects of FAD removal on catches of bigeye and skipjack (Ovando et al. 2021). With a bioeconomic age-structured model and a random forest model, they calculated the effect of moving from FAD fishing to FSC fishing with respect to the catch rates of both species. They found that the reduction of skipjack catches was greater than that of Bigeye to achieve the Maximum Sustainable Yield (MSY) of the latter species. Two thirds of the FADs covered by Vessel Day Scheme (VDS) licenses should be removed to achieve the MSY of bigeye tuna.

Our research is fairly close to these two last studies looking at the economic effects of FAD removal. Our hypothesis is that a half reduction of authorized FADs at sea from 300 to 150 operational buoys per vessel⁵ would not be profitable for the IO French PS fleet, and that FADs could be “economic traps” for fishing companies. First, larger vessels have joined the DWFN

⁴ Indonesia, Kenya, Maldives, Mozambique, Pakistan, Somalia, South Africa, Sri Lanka, and Tanzania. This group of countries is opposed to intensive FAD use by purse-seiners, preferring small-scale fishing gears like pole and line, gillnet, coastal longline, etc.

⁵ Corresponding to the amendment proposed by a group of IO countries to resolution 19/02 mentioned in footnote 4.

fleets, increasing their FAD dependence. Secondly, because of the quota constraint set on yellowfin catch since 2017 (IOTC Res. 16/01), DWFN fleets might not be able to stay profitable while reducing their use of drifting FADs, creating a sort of irreversible ratchet effect if efficiency was meant to be reduced.

3. Stylized facts about FAD use by the French PS fleet in the IO throughout the past three decades

3.1 Data

The number of large purse-seiners operating in the IO has been more or less stable for the past two decades, around 45-50 vessels, after a peak of 61 boats in 2006, with increasing average size of vessels from 70 to 90 m long over the same period (IOTC 2022b). The French purse-seiners represent one-third of the fishing effort with 15 vessels on average over the sample period, Spain being the undisputable leader of the Indian Ocean large-scale PS fishery with nearly two-thirds when including the number of Seychelles-flagged vessels owned by Spanish companies (*Ibid.*). The analysed data was collected and processed by the Ob7 (“*Observatoire des Ecosystèmes Pélagiques Tropicaux Exploités*”) in Sète (IRD, France). Observations are fishing trips since 2012, described by a set of variables representing the tuna landings by species (skipjack, yellowfin, bigeye, albacore) and by size category (large yellowfin and bigeye tunas > 10kg, skipjack and mixed tunas which are a mixture of juvenile albacore, bigeye and yellowfin tunas < 10 kg), the fishing effort - days at sea, fishing days, number of sets by fishing technique-, the landing date, physical characteristics and identity of vessels, number of buoys per vessel and for the entire fleet –length overall, size category (from 4 to 8), the first year of service-, a skipper identifier. The observations can be easily disaggregated into panel characteristics (time, vessel, skipper). The vessels and skippers with less than 10 observations over the entire period were removed. The vessels realize 9 trips per year on average, with a duration of 28 days per trip, i.e. 254 days at sea per year. Environmental data were collected from different sources: the Spawning Stock Biomass (SSB) of yellowfin tuna was kindly transmitted by the stock assessment division of IOTC (quarterly series). The Dipole Mode Index (DMI) was collected from the NOAA website <https://psl.noaa.gov>. This climate index measures the Indian Ocean Dipole effect represented by anomalous Sea-Surface Temperatures (SST) along a gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial IO (90E-110E and 10S-0N). It is associated to wind and rainfall anomalies (Saji et al. 1999).

Economic data were added to the dataset with monthly price series. Prices of skipjack large yellowfin and mixed tunas were collected from Sovetco, a French trading company setting ex-vessel frozen tuna prices in the Atlantic and Indian oceans on the basis of Bangkok prices and exchange rates between Euro and US dollar. Cost data were also collected to estimate Gross Value Added (GVA). One of the most important variable expenses of fishing activity is fuel cost, because of its dependence on days at sea, distance in miles, power and speed of vessels, auxiliary engines used for freezing the fish aboard, etc. Bunker costs represented 23% of total costs on average between 2012 and 2020 for EU large purse-seiners (Berkenhagen et al. 2021). Using a Generalized Additive Model (GAM) of fuel consumption relying on the number of sets on FADs, sets on free schools, number of days at sea, landing date, year of first service and vessel length (Chassot et al. 2021), we estimated the fuel consumption per day for each fishing trip in our sample. The gasoil price in USD per tonne in Port Victoria in Seychelles was

collected from Seypec, the local petroleum company, between January 2013 and December 2019 and complemented with predicted values from its correlation model with the New York Harbor Heating Oil Future Contract 3 (www.eia.gov)⁶. All tuna and oil prices were converted into USD (with ECB rates) and deflated by the OECD production price index based in 2015 (<https://data.oecd.org>). GVA on variable costs could therefore be estimated (per day, per trip, per year) as a proxy of gross profit. Net profit could be easily inferred by a raising factor of 4.3 on bunker costs to represent total costs. After the elimination of missing values and the truncation of data after 2012, the data set included 1,217 observations (fishing trips) between January 2012 and December 2020.

3.2 Stylized facts on the use of FADs

Figure 1 gathers several charts showing the increasing importance of FAD fishing for the French PS fleet operating in the IO, and its relationship with catch level and composition as well as effects on gross profit.

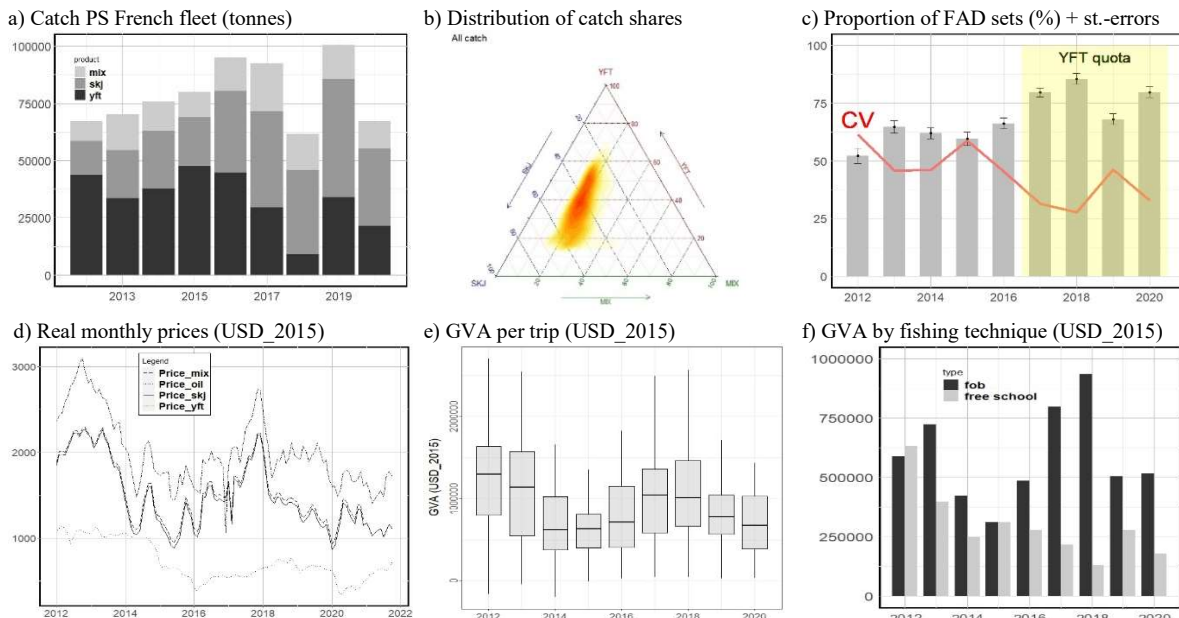


Fig. 1. FAD use and outcomes by the French fleet of purse-seiners in the Indian Ocean.

Data: IRD, Tuna Observatory. GVA: Gross Value Added. CV: coefficient of variation (% st.-dev./mean).

The French purse-seine fleet operating in the WIO between 2012 and 2020 included 14 or 15 vessels. The average yearly catch was 78,665 t, with a minimum of 55,432 t in 2012 and a maximum of 97,731 t in 2019 (Fig. 1a). The bulk of the catch concerned two species: skipjack (46% on average), yellowfin (33%), and mixed tunas for the remaining share (21%), but the variability between the first two species could be high over time (Fig. 1b). FAD sets represented 68.5% of all sets on average, depending on seasons and years (Fig. 1c). Since 2017, a total allowable catch has been implemented on yellowfin (IOTC resolutions 16/01 and 17/01), thus

⁶ The two prices were found non-stationary but had a single long-run (cointegrating) relation without constant: $P_{seypec} - 1.34717 * P_{nyhofc3} = \hat{\varepsilon}$

intensifying the use of FADs by purse-seiners to avoid the big yellowfin (> 10 kg) caught on free schools. The average proportion of FAD sets raised to 78% on average against 61% before 2017 but even more interesting is the homogenous trend of using FADs across the whole fleet, as seen by the declining coefficient of variation (% st.-dev./mean) over the period. Previously, some skippers could prefer the more rewarding technique of free schools, because of higher catches of high-valued large yellowfin, but it appeared to be no longer the case after the quota implementation. Increasing the proportion of FAD sets results in a higher catch of skipjack and mixed tunas, which are sold ~\$325 lower per tonne (Fig. 1d). The real oil price stood around \$1,000 per tonne until 2014, before reaching a lower level since then. Real prices of tunas were fairly volatile throughout time. The yellowfin tuna real price oscillated between constant USD 1,000 and 2,700 per tonne, and the skipjack or mixed tuna prices were between USD 500 and 2,100 per tonne. However, the proportion of positive sets being so much higher on FADs (90% of positive sets vs 50% for free school sets on average, Fonteneau et al. 2013), the larger catch does more than compensate for the decline in unit values, as shown by the gross value added (GVA, proxy of gross profit), i.e. the difference between revenues and fuel costs, which is maintained at a high level between US\$0.5 and US\$1 million in real terms (Fig. 1e). The intensive FAD strategy of the last few years proved to be far more rewarding than the free school strategy, as shown in Fig. 1f. For instance, in 2018, a vessel owner would earn on average \$930,000 of GVA by FAD trip against only \$130,000 per FSC trip, presumably because of success rates of FAD sets and economies of scale.

4. Methods

The approach is defined in three steps. The core of the model lies in a classical catch-effort relationship tested by linear models (Guillotreau et al. 2011, Wolff et al. 2013, Maufroy 2016, Gaertner et al. 2018). However, we considered that the fishing strategy is also determined by the environmental conditions and capital investment, including the number of deployed buoys, hence a simultaneous equation treatment (Fig. 2). SSB and DMI were selected as environmental indices to consider the effects of climate anomalies on the fishing strategy (fishing on FADs or free schools) resulting from the surface catchability of skipjack, large yellowfin and mixed tunas. Finally, the economic consequences of the fishing strategy on revenues and gross profits are also analysed through predicted values with a machine learning approach.

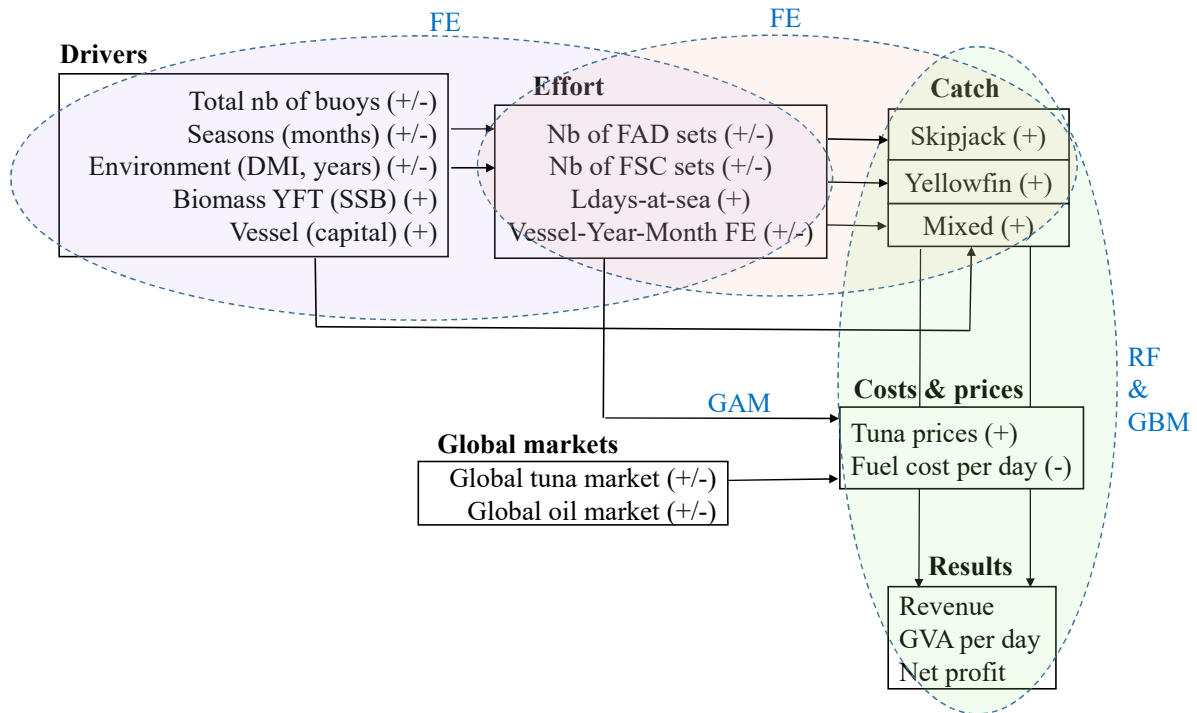


Fig. 2. Three step modelling approach

Note: signs + and – indicate the expected causal effect of variables; FE = Fixed-effect models, GAM = General Additive Model, RF = Random Forest, GBM = Gradient Boosting Model.

Several models with two time fixed effects (month and year) were first estimated for the French purse-seine fishing trips. The models were derived from a Cobb-Douglas production function (Wolff et al. 2013) to explain the catch levels of three tuna product categories: large yellowfin tuna (> 10 kg), skipjack and mixed tunas (bigeye, albacore and yellowfin < 10 kg). The fishing effort was captured by the number of days at sea, but also by the technical choice between the number of FAD sets and FSC sets during a fishing trip. We introduced non-linear (quadratic) terms so as to look at the marginal response of catch to fishing effort, potentially bending beyond a threshold. The increasing size and physical features of vessels (e.g. length, gross tonnage or engine power), were included as vessel fixed effects. The skipper skills were also introduced as individual fixed effects (Squires and Kirkley 1999, Guillotreau et al. 2011) but gave no significant result, as if fishing behaviour and efficiency tend nowadays to homogenize within the fleet.

Econometric strategy

The catches of skipjack, large yellowfin, and mixed tunas were retained as dependent variables. From the review of literature and descriptive analysis of the data, we hypothesize that these catches can be explained by several factors characterizing the fishing effort in a simultaneous equation model combining effects of capital, environment and fishing effort on tuna catch. With such a model, we were able to analyze both the relationships between the variables and their multiple dependencies. This approach allows for the simultaneous estimation of the coefficients and carries out estimates of the standard errors that take into account the contemporaneous correlations for FAD and FSC equations due to their Gaussian error distributions. This is useful

when testing multiple sets of associations between variables simultaneously in a single modeling framework (Fig. 2). The model can be written as:

$$FAD_i = \alpha + \beta B_i + \beta' B_i^2 + \gamma X_i + \gamma' X_i^2 + \varepsilon_i \quad (1)$$

$$FSC_i = \varphi + \delta B_i + \delta' B_i^2 + \eta X_i + \eta' X_i^2 + \omega_i \quad (2)$$

$$SKJ_i = \pi + \nu FAD_i + \nu' FAD_i^2 + \theta FSC_i + \theta' FSC_i^2 + \omega D_i + \omega' D_i^2 + \kappa Z_i + \vartheta_i \quad (3)$$

$$YFT_i = o + \zeta FAD_i + \zeta' FAD_i^2 + \xi FSC_i + \xi' FSC_i^2 + \rho D_i + \rho' D_i^2 + \iota Z_i + \phi_i \quad (4)$$

$$MIX_i = \psi + \zeta FAD_i + \zeta' FAD_i^2 + \eta FSC_i + \eta' FSC_i^2 + \mu D_i + \mu' D_i^2 + \epsilon Z_i + \varsigma_i \quad (5)$$

where FAD_i and FSC_i denote the natural logarithm of the number of FAD or FSC sets per fishing trip. B_i reflects the logarithm of the total number of buoys deployed by the French PS fleet (highly correlated with the number of buoys deployed by each vessel), and X_i is a vector of characteristics influencing the FAD/FSC sets: it includes the quarterly level of yellowfin spawning stock biomass (SSB), the Dipole Mode Index (DMI), monthly effects, yearly effects, and vessel effects. SKJ_i , YFT_i , and MIX_i represent the catch quantity (logarithm of tonnes) of skipjack, yellowfin, and mixed tunas. D_i reflects the logarithm of the number of days, and Z_i is a vector of characteristics influencing the SKJ, YFT, and MIX catches: the DMI, monthly effects, yearly effects, and vessel effects.

Finally, $\alpha, \beta, \beta', \gamma, \gamma', \varphi, \delta, \delta', \eta, \eta', \pi, \nu, \nu', \theta, \theta', \omega, \omega', \kappa, o, \zeta, \zeta', \xi, \xi', \rho, \rho', \iota, \psi, \zeta, \zeta', \eta, \eta', \mu, \mu',$ and ϵ are the corresponding parameters to estimate and $\varepsilon_i, \omega_i, \vartheta_i, \phi_i,$ and ς_i are residual error terms (expected to be uncorrelated with the explanatory variables). Furthermore, the model was estimated with quasi-maximum likelihood estimation.

Machine learning approach

A machine learning approach was developed to better understand the variability of purse seine vessels' gross value added (GVA) per day with predictors issued from the full data set (Breiman, 2001). A classification and regression tree (CART) model helped to identify drivers predicting the level of GVA by fishing trip (R libraries *rpart* and *party*, Scikit-learn Python libraries *sklearn.tree* and *sklearn.linear_model*), sorted out by their relative importance in the result. The accuracy of the model was improved by a random forest (RF) algorithm growing the number of trees to stabilize the influence of variables (R library *randomForest* and Python library *sklearn_ensemble.RandomForestRegressor*), and corrected by a gradient boosting regression tree approach to learning from each preceding tree in the forest. Both linear and machine learning models' outputs could then be used to simulate various use rates of FADs and check whether the breakeven level of profit would be achieved or not.

5. Results.

5.1 FAD deployment, type of fishing effort and catch by species

The results of estimated models are introduced in Table 1. Models (1) to (5) describe both the relationship between capital and environmental conditions on the type of fishing effort (free school - FSC- and FAD sets) and the resulting causality with the catch level by tuna product. Models (6) to (10) estimate the same relationships after including vessel and time fixed effects.

Table 1. Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	FAD	FSC	SKJ	YFT	MIX	FAD	FSC	SKJ	YFT	MIX
Lbuoytot	0.10*** (0.036)	-2.35*** (0.622)				5.07*** (1.287)	-5.58*** (1.536)			
Lbuoytot ²		0.13*** (0.036)				-0.25*** (0.075)	0.32*** (0.091)			
Lssb	-1.04** (0.458)	2.59*** (0.552)				1.29 (0.991)	0.95 (1.230)			
Dmi	0.00 (0.111)	0.08 (0.132)	0.10 (0.104)	-0.55*** (0.146)	-0.27*** (0.097)	0.26* (0.139)	0.04 (0.171)	-0.22* (0.121)	-0.43** (0.179)	0.01 (0.113)
Lsetfad			1.09*** (0.196)	-0.39*** (0.152)	1.18*** (0.169)			1.02*** (0.179)	-0.31** (0.152)	1.14*** (0.162)
Lsetfad ²				0.12*** (0.036)	-0.07* (0.038)			-0.08** (0.039)	0.11*** (0.036)	-0.09** (0.037)
Lsetfsc			-0.02 (0.025)	0.50*** (0.106)	-0.09*** (0.025)			-0.01 (0.027)	0.40*** (0.106)	-0.04 (0.027)
Lsetfsc ²				0.05 (0.033)					0.07** (0.033)	
Lday			-0.34*** (0.086)	1.85** (0.784)	-0.22*** (0.075)			-0.01 (0.098)	1.86** (0.780)	-0.12 (0.088)
Lday ²				-0.29** (0.128)					-0.30** (0.128)	
Constant	15.99** (6.584)	-23.92*** (7.753)	3.77*** (0.294)	1.17 (1.164)	2.74*** (0.264)	-39.25*** (14.810)	12.20 (18.537)	2.65*** (0.282)	1.57 (1.162)	2.17*** (0.313)
Fixed-effects										
Year						X	X	X	X	X
Month						X	X	X	X	X
Vessel						X	X	X	X	X
Cov		-0.23*** (0.031)					-0.10*** (0.025)			
Pseudo-R ²	0.03	0.08	0.39	0.29	0.45	0.23	0.26	0.47	0.34	0.50
Pseudo-likelihood			-10800.75	-14780.61	-10748.41			-1697.18	-5490.33	-1661.17
Observations			1,217	1,217	1,217			1,217	1,217	1,217

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Although not very powerful, the first two models show the influence of buoy investment on the individual fishing strategy, as well as the abundance of yellowfin tuna, with the right expected signs. Greater availability of buoys and less abundant yellowfin tuna result in more FAD fishing, and vice versa. This influence is even stronger when seasonal effects are introduced (models 6 and 7), interestingly with quadratic term estimates of opposite signs with regard to the first parameter. There would be a marginally decreasing use of FAD sets whenever the buoy equipment overcomes a certain threshold, *vs* a marginally increasing effort on free school sets. However, environmental conditions disappear when time fixed effects are introduced, probably because they are captured by the yearly and monthly fixed effects which may also include other characteristics (e.g. technical change, market conditions, etc.). From the estimates, we can compute the mean-centred elasticities of skipjack and mix tuna catch to FAD sets which were 0.64 and 0.71, respectively, but the yellowfin tuna catch was found more sensitive to the free school set (0.59), as found in Wolff et al. (2013). Conversely, small tuna (skipjack and mix) catches do not respond at all to free school sets.

From models included in Table 1, it is possible to show an indirect and positive correlation, although weakly significant, between the aggregate number of buoys of the fleet and the catch per vessel per fishing trip. The catch level by species as a function of the number of buoys deployed by the French PS fleet is obtained from a structural model (Fig. 3). These catch levels were obtained from the predicted values of FAD and FSC sets given by models (6) and (7), and from predicted catches of skipjack, yellowfin and mixed tunas obtained from models (8) to (10).

The fitted values of catch were thereby related to the number of buoys by a smooth quadratic function with a confidence interval of 95%.

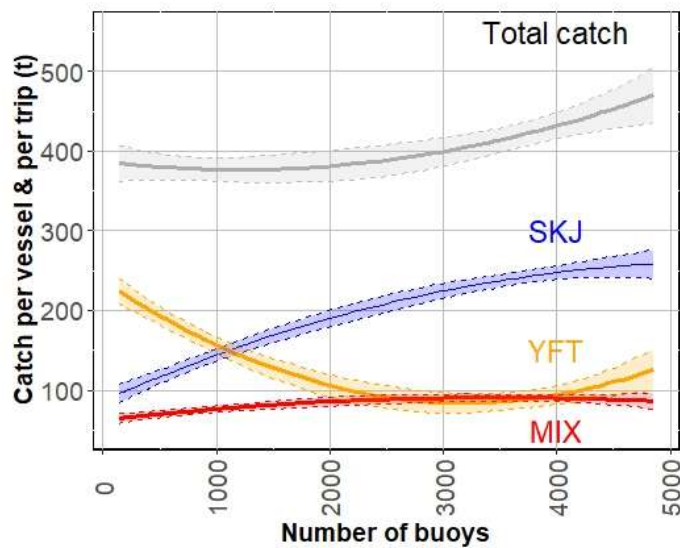


Fig. 3 Predictions of catches by group of species as function of the total number of buoys deployed by the French PS fleet in the IO

Note: Mean predicted catch from models (8-9-10) as function of the reported number of buoys deployed by the French PS fleet (IOTC 2022b). Because of shared buoys, the adjustment factor is approximately 18% of the number of buoys included in the dataset. Shaded colours depict the 95% confidence intervals of fitted values.

In overall, we observe that catch (hence profit) would significantly decrease by reducing the number of buoys at sea from 4,500 to half of this number. Decreasing further the number of active buoys at sea would reduce the catch of small tunas (skipjack and mixed tunas) but increase that of large yellowfin tuna if a full reallocation of effort on free schools is made possible by the national quota. Symmetrically when augmenting the number of buoys at sea, the catch of small tunas describes a marginally decreasing yield pattern resulting from the quadratic models (6), (8) and (10) in Table 1, showing that a reduction in the number of FADs would not affect too much the catch of skipjack and mixed tunas. In this trade-off between catching less small tunas on FADs and more yellowfin tuna on free schools, reducing the number of buoys from 4,500 to 3,000 (i.e. from 300 to 200 per vessel) would represent a 14% decrease of catches in overall while minimizing the tonnage of yellowfin tuna harvested, which can be an option to restore the level of stocks for this vulnerable species.

5.2 Converting catches into profits with a machine learning approach

Thirteen selected variables were introduced in a random forest model to explain the GVA per day on the basis of the model shown in Fig. 2: catches on FSC and FOB per day, real prices of yellowfin tuna, skipjack, mixed tunas and marine diesel oil (in USD_2015 per tonne), the aggregate number of buoys, fuel consumption in tonnes per day, vessel length, DMI, SSB, landing month and year. The full sample was split into a training set for 70% of fishing trips (840 obs.) and 30% for the test set (360 obs.). The accuracy rate (predicting capacity measured by the mean squared error of Out-Of-Bag –OOB– trips,

comparing observed and fitted values) on the training set was 93.1%, and 87.0% on the test set, which indicated a possible overfitting effect on the training sample. We used fivefold-cross validation⁷ to check the accuracy of the model, with a mean score of 66% with a certain sensitivity to the selected subsets. This is why we compared the results with a GBM approach, where each tree learns from previous ones. This approach narrows down the gap between training and test subsets (99.6% and 95.4%, resp.) and improves the average validation score (88%). The GBM was marginally enhanced by reducing the maximum depth of trees and changing the learning rate from previous trees. We can accept this short lag, meaning that a few fishing trips belonging to one of the two sets are probably outliers which were difficult to predict whatever the model.

Both RF and GBM approaches estimated the Variable Importance (VI) in a similar way. The absolute importance of each of the thirteen variables is measured by the permutation of the variable in the OOB sets. The percentage increase of mean squared errors by changing the position of variables is a good indicator of the VI (Breiman 2001). Both RF and GBM gave more or less the same ranking order of variables: FSC catch (49.9% of variance), FOB catch (40.4%), YFT price (4.8%), SKJ prices (1.8%). Other variables, including the number of buoys, year, seasonality, fuel consumption, etc. played a marginal role in the model. In other words, the gross profit per fishing day and per vessel depended to a great extent on the catch levels rather than unit values and variable costs. The R-package VSURF allowed us to estimate the marginal effects of each feature on the GVA per day variable (Fig. 4).

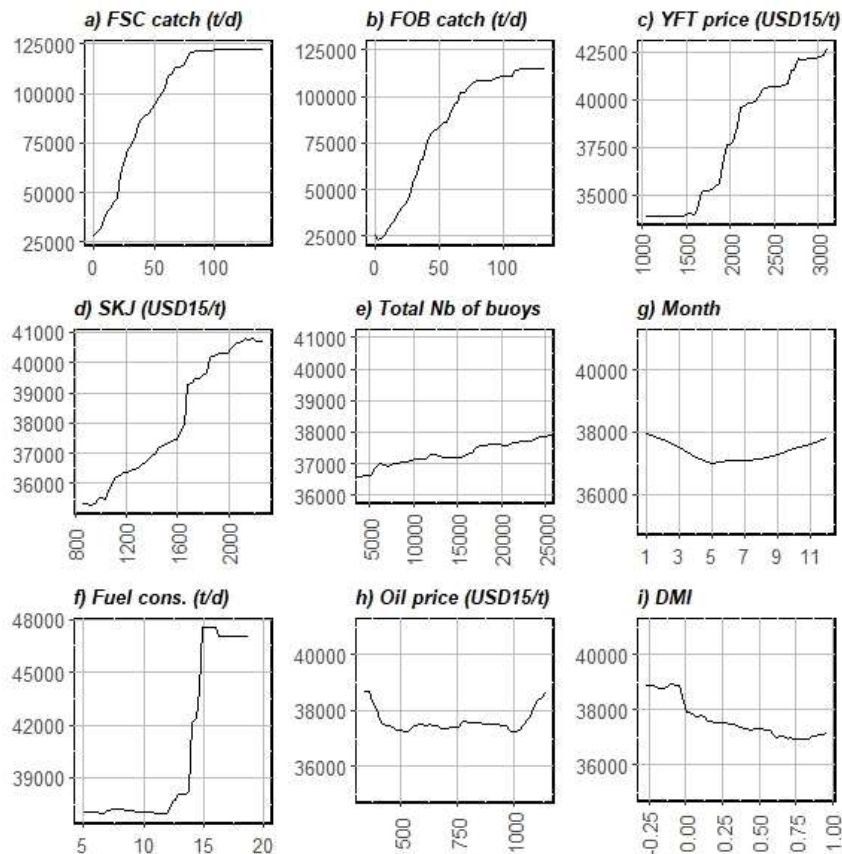


Fig. 4 Marginal effects of nine variables on GVA per day (in USD₂₀₁₅, y-axis): predicted values from a random forest (500 trees, max-depth=4, accuracy rate on test data set= 0.87)

⁷ The full dataset was divided into 5 sub-sets where each sub-set plays the role of test set alternatively, the 4 others represent the training sets. The accuracy rates are then averaged.

GVA per day is mostly sensitive to catch quantity on free schools and FOBs, far beyond any other feature. Fifty tonnes per day in one or two sets provide nearly USD 100,000, which is far beyond the breakeven point between ~USD 30,000 and 35,000 per day. To a lesser extent, GVA relied on tuna prices, with positive profit margins whenever the yellowfin and skipjack prices are greater than USD 1,700 and USD 1,400 per tonne, resp. The total number of active buoys deployed at sea by the French PS fleet has also a positive influence on gross profits, but to a much lesser extent at about +2-3% when doubling the number of buoys from 10,000 to 20,000. The fuel consumption, despite the cost it may represent, would enhance profits beyond 13 tonnes per day through a more effective effort, especially on FADs. Seasonality (month), oil unit price and climate oscillations played a minor role in wealth creation, although positive dipole anomalies (warmer sea surface temperatures) would reduce the GVA per day by ~USD 250 by additional 0.25 points of DMI, other things being equal.

5.3 Predictions under three scenarios of FAD management

Our hypothesis was to consider an economic trap behind FAD fishing, like the so-called ecological trap emphasized by some fishery scientists (Hallier and Gaertner 2008): shipowners have little alternative but to keep on fishing on floating objects to remain profitable.

Fixed effect and machine learning models were used to test this hypothesis through predicted values. Three scenarios were considered with respect to the various resolutions or amendment proposals about FAD management above mentioned. The first one relied on a 50% reduction of authorized FOB buoys for the fleet. The second scenario explored the impact of a 72-day closure of FAD fisheries (IOTC Res. 23-02). In this second scenario, the PS vessels would re-allocate the effort on free schools during the yearly FAD ban, providing that the yellowfin quota implemented annually since January 2017 is not exhausted. In the case where the yellowfin tuna quota would not be sufficient to keep on fishing during this ban period, a third scenario envisaged a full stop of vessels remaining idle at port for this 2.5-month period. The predicted economic results of the PS fleet are presented below.

Scenario 1: 50% reduction of the total number of buoys

According to models (6) and (7) in Table 1, the average predicted number of FAD sets per trip is 35% lower and the average predicted number of FSC sets per trip is 36% higher with half the number of buoys. Re-injecting these changes of actual sets into catch-effort equations (8) to (10) would shift the average catch combination of SKJ-YFT-MIX from 193, 146 and 88 tonnes per trip to 150, 173 and 66 tonnes after halving the number of buoys, respectively. The first impact of the measure would therefore lie in lower yearly catches at the fleet level (-12%). Other things being equal, this would represent a catch reduction of SKJ by 22% and of mixed tuna by 24%, while catches of large YFT would increase by 18% if the quota for this species is not exhausted. New catch levels on FADs and FSC were introduced in the random forest model for predictions of GVA per day explained by 13 selected variables displayed in Fig. 2. With the respective average prices of species and variable costs per fishing day, this would result in 7.1% GVA loss per vessel. When aggregated to the whole French PS fleet over the year (for nine trips on average and fifteen vessels), the GVA loss would amount to some USD 6.5 million per year and a net profit decreasing by USD 1.2 million when extrapolated to actual fleet costs and earnings of the French PS fleet operating in the Indian Ocean (STECF 2022). However, if the yellowfin tuna quota was fully fished out and no re-allocation of effort towards FSC fishing was made possible, then the catch would decrease by 17.4%, the fleet GVA by USD 11 M and the net profit by USD 1.7 M.

Scenario 2: 72-day ban of FAD fishing with transfer of effort to FSC

In the second scenario, vessels would not be authorized to seed and use FADs during a 72-day period starting from July 1st to mid-September. However, they could re-allocate their fishing effort to free

schools during the FAD ban period, thus increasing the FSC catch (with larger yellowfin tuna) by 18% and decreasing the FAD catches by 24%. The consequences on the total yearly catch for the fleet are approximately the same as in the previous scenario, i.e. -14%. The median GVA per day would fall down from USD 24,117 per day per vessel to USD 21,780 (i.e. -9.7%), hence a USD 8.9 M GVA loss and USD 1.6 M decrease in net profits for the French PS fleet.

Scenario 3: 72-day ban of FAD fishing with vessels staying at port

In the third scenario, vessels would stop fishing and remain idle at the port between July 1st and September 10th, not incurring the variable costs of fishing operations (crew, fuel expenditure, communications, etc.) but still paying fixed costs (financial charges, insurance, port dues, etc.). The main reason to immobilize vessels is to avoid the risk of fishing large yellowfin tuna on free schools beyond the authorized quota. The national quota is set at 29,500 tonnes for the whole fleet, i.e. less than 2,000 tonnes per vessel. This quota can be rapidly exhausted during the high season of free school fishing, usually between November and February (Maufroy 2016). Consequently, fishing companies would not perceive any revenue during two or three months in this scenario, although facing fixed costs. The impact on total fleet catch per year is stronger than those in previous scenarios (-19%). The GVA per day and per vessel would decrease from USD 24,117 to USD 19,732 (-18.2%). At the fleet level, this would represent a loss of USD 16.7 M per annum, equivalent to a USD 3 M reduction of net profits for the fleet.

A synthesis is proposed in Fig. 5a comparing the outcomes of the three scenarios to the actual case in terms of GVA per day per vessel in constant USD of 2015. The third scenario represents the worst case in economic terms. The actual and predicted values of GVA being non-normally distributed, Wilcoxon and Kruskal-Wallis tests are performed and showed that median values are equivalent between the actual case and the first two scenarios ($p > 0.10$) but are different between the actual and third scenario ($p < 0.00005$). However, if the YFT quota was exhausted and no-reallocation was possible in scenario 1, then the median would also have differences between the actual and scenario 1.

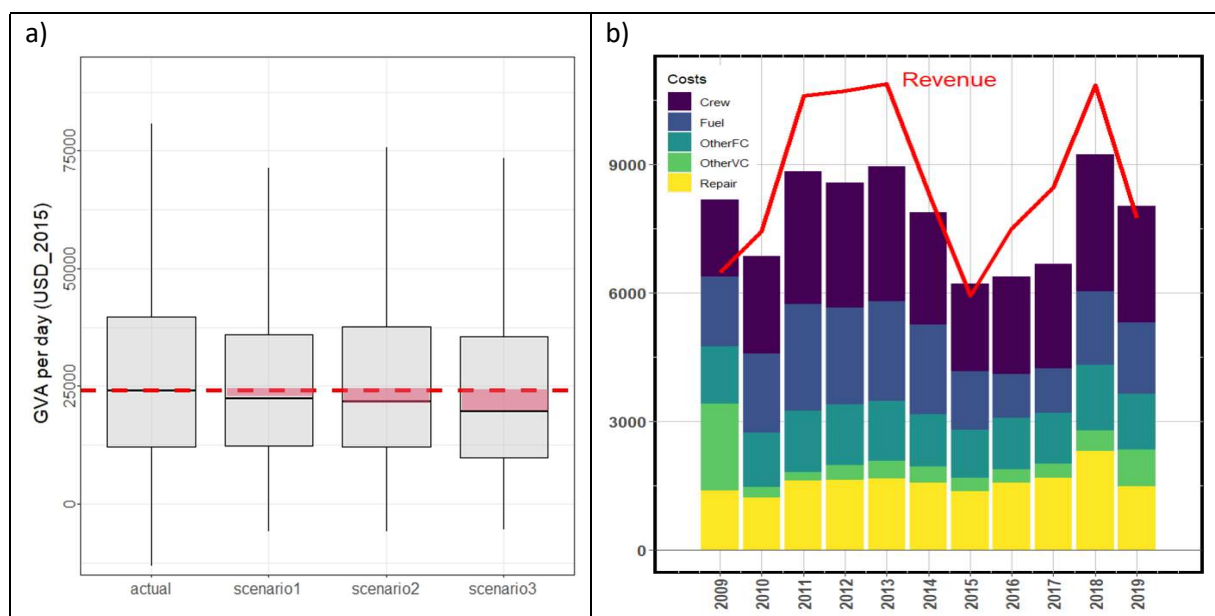


Fig. 5 a) GVA per day under three FAD limitation scenarios and b) Actual revenues and costs per vessel in the French PS tuna fleet (in '000 USD). Notes: 5a) dashed red line = USD 24,117, actual median value with no FAD limitation, the red rectangles = GVA loss w.r.t. actual case; 5b) Actual STECF 2022 data = average results of 18 to 22 vessels; red line = revenue; OtherVC = other variable costs, OtherFC = other fixed costs; Repair = repair & maintenance costs).

When compared to the actual net profit margins in Fig. 5b, we can realize how the French fleet could be severely affected by the FAD limitation measures. Sales value can be very close to total costs for some years. We have seen that revenues rely to a great extent on landings and a reduction between 12% and 19% may certainly jeopardize their activity. This was all the truer as the transfer of effort to free school fishing is bounded by the national quota of 29,500 tonnes of YFT. Catching around 2,000 tonnes of yellowfin tuna per year and per vessel, there is just enough quota for 15 vessels. As a result, increasing by 18% the catch quantity of yellowfin, as observed in scenarios 1 and 2, is impossible under the yellowfin tuna quota limit.

6. Discussion

This study looked at the consequences of management measures restricting the use of FADs for the French industrial purse-seine fleet in the Indian Ocean. We showed a significant impact of an increasing number of buoys on the fishing strategy followed by purse-seiners over the past decade, amplifying the fishing effort on FADs and reducing that on free schools, as revealed by previous studies (Wolff et al. 2013, Torres-Irineo et al. 2014, Maufroy et al. 2016, Wain et al. 2021). The catch composition changes towards smaller tunas (skipjack and juveniles of bigeye and yellowfin tuna) and fewer large individuals of the two latter species (Dagorn et al. 2013, Escalle et al. 2019). In the IO, this strategic shift of effort and catch has been intensified after the implementation of the IOTC resolution setting a TAC on yellowfin tuna since January 2017, because skippers have avoided fishing thereafter too heavily on free schools, from which large yellowfin are harvested (IOTC Res. 16/01). Some unintended effects occurred with an increasing number of silky sharks caught accidentally by PS vessels, particularly in the northern area of the IO where tuna vessels were not used to fish with fewer active FADs at sea (Tolotti et al. 2022). Because of important social costs related to bycatch, ghost fishing, beaching, ocean pollution, etc. FADs are under close scrutiny by RFMOs and many experts around the world advocate for a more stringent limitation of their use (Fonteneau et al. 2015, Lennert-Cody et al. 2018, Hanich et al. 2019, Gomez et al. 2020, Song and Chen 2022).

In the Indian Ocean, FAD management measures have been implemented by IOTC since 2012, reducing gradually the number of authorized buoys per vessel (from 550 to 300 between 2015 and 2019, IOTC Res. 19/02), the latter helping to track remotely floating objects by GPS and echosounder transmission across the ocean, thus tremendously increasing FAD efficiency (Maufroy et al. 2016, Gaertner et al. 2018, Tidd et al. 2016, Wain et al. 2021). In June 2021, a group of coastal countries having an interest in tuna fisheries suggested through an amendment to IOTC resolution 19/02 to further reduce the number of authorized buoys to 150 per vessel, which was approximately the number in use by the French fleet at the turn of the 2010s. In February 2023, the IOTC Commission voted on a new resolution creating a 72-day FAD fishing ban per year starting from July 2024 (IOTC Res. 23/02). Several countries, among which Seychelles, Philippines, Oman, Comoros, France, European Union... objected to this resolution, claiming that this measure was not scientifically grounded. More analysis is therefore needed to better understand the economic consequences of FAD use restrictions.

Our findings highlight some important economic consequences for the French PS fleet, supporting the hypothesis of an “economic trap” behind FAD fishing. Actually, there is little alternative for PS vessels because of the overfished situation in which the yellowfin tuna stock stands in the Indian Ocean⁸. Due to the negative relationship between the number of FAD buoys in use and the effort on free schools, vessels cannot compensate the resulting lower use of FADs by a more intensive effort on FSC, because they would be likely then to catch larger quantities of large yellowfin tuna, far beyond their quota limit set by IOTC. Furthermore, there is also a positive relationship between the carrying capacity of vessels and the number of deployed floating objects (Davies et al. 2014). In the IO, the share of PS vessels

⁸ IOTC, access April 15th, 2023, <https://iotc.org/node/3379>

longer than 80 m of LOA, has increased from 15% in the early 2000s to 75% of the fleet in 2022, and the mean LOA has increased from 70 m to 88 m within the same time frame, not even mentioning the increasing role of supply vessels in the deployment of FADs (IOTC 2022b). The massive investment in larger vessels, fishing equipment and supply vessels, may well create economies of scale for the fleet, but makes the fishery less sustainable and more vulnerable to stricter conservation management measures. Under all these aspects, PS vessels remain trapped between the greater efficiency of FAD fishing and the impossibility to re-allocate the fishing effort on free schools.

Some economic consequences must also be expected for small island economies (Seychelles, Mauritius, Comoros, etc.). Many studies have shown the importance of PS landings for local economies. Several pre-harvest and post-harvest industries create value added from the presence of domestic or foreign vessels through the revenues collected from fishing rights agreements, port dues, bunkering and stevedoring operations, processing facilities, other port services, etc. (Robinson et al. 2010, Bell et al. 2021). The mere example of Seychelles illustrates the entanglement of interests between its coastal and offshore fleets (36 coastal longliners, 54 offshore longliners and 13 purse-seiners were Seychelles-flagged in 2021, source www.sfa.sc), the reliance on fish exports (95% of merchandise exports are made up with canned tuna from the local cannery which is the main private employer of the archipelago with 2,000 workers) (source: www.nbs.gov.sc). During the COVID-19 pandemic crisis, the volume of exports has even increased by 20%, and the value by nearly 40% between 2019 and 2020 (NBS Trade statistics, same source). The storage capacity of frozen tuna available for the canning plant does not allow to maintain the processing activity for too long in case of FAD fishing ban. According to the managers of the Thai Union factory in Seychelles, the cannery could shut down for a period between two and six weeks per year, causing a drop of sales between 4% and 12% (CEO of IOT Ltd, personal communication, May 2nd, 2023). The loss for the coastal economies would be even more important when considering the number of suspended port operations and other activities relying on the national landings of frozen tuna. The Seafood hub in Mauritius, located quite far away from the landing site of Seychelles, must also include a shipping delay that would even extend the shutdown of processing units to 130 days (pers. com. of an IBL Seafood manager, March 28th, 2023). The economic impact of FAD use restrictions has also been estimated for small island developing economies in the western and central Pacific Ocean. The four months of FAD closure would cost a 15% cut in fisheries revenue for one of them, Tokelau, where fishing rights fees reach 84% of the public revenue (Holmes et al. 2019, Bell et al. 2021). Finally, another economic effect created by the shortage of tuna during the summer period because of fishing bans in the three major oceans (West and East Pacific + Indian Oceans) would be a substantial increase of tuna prices, which is detrimental for consumer welfare around the world.

The estimated economic impact of FAD restrictions can also be usefully compared to other studies. Previous authors have estimated the impact of a 6-month FAD moratorium in the Atlantic and Indian Oceans, with a re-allocation of effort on free schools, thus increasing the proportion of large tunas. In overall, the moratorium resulted in a decrease in tuna catch of about 600-1800 t per year and per boat (i.e. 12 to 37% of yearly catch) in the IO, and a reduction of bycatch for all fishing groups (Escalle et al. 2017). By the proportion of catch decrease, our results (-12% to -19%) are consistent with these estimations. In the Pacific Ocean, a 4-month closure was also evaluated, resulting in a net loss of USD 250,000 per trip (Holmes et al. 2019). Our estimation would fetch a bit lower for a 3-month closure, ~USD 200,000, which seems again fairly consistent.

Holmes et al. (2019) considered many advantages of replacing the FAD closure with a FAD set limit scheme, such as creating incentives for fishing operators to change their fishing strategy and stabilizing market prices while increasing the value of access fees for coastal nations, just like the VDS regime did. This study suggested also that incentives could be created through tradeable FAD sets in a Coasean market, just like other authors did when estimating the effects of FAD removal on catches of bigeye and skipjack (Ovando et al. 2021). The authors reported a too high opportunity cost of lowering skipjack catches to achieve maximum sustainable yield for bigeye tuna. The required two-third cut in the number

of FADs would result in a net loss of US\$ 3.3 billion for skipjack revenues which is not offset by the additional net present revenues of adult Bigeye catch by longliners (US\$ 1.9 billion only), not even mentioning the distributional aspects of this trade-off, i.e. increasing welfare for Japanese consumers but decreasing surplus for the WCPO small island developing states (SIDS). Only limited FAD removals (-15%) could produce benefits exceeding costs (Ovando et al. 2021). Obviously, transactions costs can be high for these markets of tradeable fishing rights which should not be considered a panacea for FAD reduction schemes.

These case studies show how thorny FAD management can be, although a scientific consensus exists about the excessive use of drifting FADs in tuna fisheries (Fonteneau et al. 2015, Maufroy et al. 2017, Lennert-Cody et al. 2018, Hanich et al. 2019, Gomez et al. 2020). However, the entanglement of interests with coastal states (employment in processing plants, income from fishing agreements) and with other conservation measures (e.g. yellowfin tuna TAC) demonstrate that the devil is in the details. In the IO, a restriction on FAD fishing had yet been experimented through a time-area closure in November 2011 (IOTC Res. 10/1), with mixed results in reducing total annual catches of bigeye and yellowfin on FADs by less than 3% compared to a reference period (Davies et al. 2014). More scientific work needs to be done in order to search for fair and effective management of FADs. A fair and scientific analysis must also compare the economic loss of DWFN fleets shown in this study with other countries and fleets that could make a profit out of a seasonal closure of FADs, such as the Pole and Line fleet in the Maldives, the longline and gillnet fleets of northern coastal countries (Indonesia, India, Iran,...), not even mentioning the environmental benefits in terms of enhanced ecosystem services (avoided costs of bycatch, pollution at sea, beach clean-up programs, etc.). Such research work of cost-benefit valuation still needs to be undertaken at a greater scale.

7. Conclusion

This study is evaluating the consequences of several FAD management measures on the economic performance of the French PS fleet in the Indian Ocean. It suggests that there is an economic trap of FAD fishing because of far greater efficiency compared to free school sets and because of binding constraints coming from other conservation measures such as the IOTC TAC on yellowfin tuna. On the basis of fixed-effect models and a machine learning approach (random forest and gradient boosting models), we first demonstrated the relationship between the aggregate number of deployed buoys and the increasing FAD fishing strategy. The main outcome lies in a greater proportion of skipjack and small tuna caught by PS vessels. Despite lower unit prices, fishing smaller tunas on FADs is rewarded by the greater efficiency and higher profits.

We built three scenarios of possible FAD management measures in the Indian Ocean: a half reduction in the number of authorized buoys for the fleet with no YFT quota limitation, a yearly 72-day FAD fishing ban with re-allocation of effort on free schools and without such effort transfer, the vessels staying at port during 2.5 months every year. The incurred profit loss would be -7.1%, -9.7%, and -18.2%, respectively. The economic consequences could also be detrimental for coastal states relying on tuna landings (e.g. the Seychelles and Mauritius economies may be heavily affected). Despite the consensus about the excessive use of FADs, more scientific knowledge is required to support the RFMO decision-making process before implementing any stringent regulation that might produce economic damages for both distant fleets and coastal states. Some authors suggested to replacing FAD closures with a FAD set limit scheme, which could effectively contain the effort on FADs while avoiding unintended consequences for other species and some tuna fishery-dependent economies.

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