



Unintended effects of single-species fisheries management

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Abstract

Ecosystem-based management is widely recognized as the path to achieve sustainability of ecosystem services. Tuna Fisheries Management Organizations have incorporated an ecosystem approach into their mandate, but their decision-making process essentially relies on individual stock assessments. This study investigates possible unintended consequences of management measures that primarily focus on single target species. In 2016, the Indian Ocean Tuna Commission (IOTC) adopted a plan for rebuilding yellowfin tuna stock. We examined the impacts that this measure might have had on the fishing strategy of purse seine fleets and on silky shark mortality, their main elasmobranch bycatch. The economic dimension of this possible ecological impact was also explored. Logbook and observer data from the French fleet, coupled with IOTC data from Spain, Seychelles and Mauritius, were used. After the implementation of the measure, an increase on the number of fish aggregating device (FAD) sets and an expansion of the fishing effort were observed. These resulted in a 35% increase on silky shark bycatch for the French fleet and a 18% increase for all fleets combined. Based on the estimated catches, the mean forgone consumptive value of silky shark bycatch was evaluated at US\$ 1.6 million. Taking the conservation value into account, the social cost of this forgone ecosystem service could increase up to USD 14 million. This work is a first exploration into the socioeconomic dimension of trade-offs between the use of FADs in tuna purse seine fisheries and shark bycatch and can be applied to other FAD-associated species.

Keywords Tropical tuna fisheries · Fish aggregating devices (FADs) · Bycatch · Silky shark · Ecosystem approach to fisheries (EAF) · Indian Ocean

1 Introduction

Ecosystem services illustrate how nature processes and outcomes can directly or indirectly benefit humans and human societies (Costanza et al., 1997; MA, 2005). As a framework, the concept of ecosystem services describes the interconnections between nature and society, rendering value to the awarded benefits (cultural and provisional) in both monetary

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and nonmonetary ways (Cavanagh et al., 2016; Pascual et al., 2017). For the past two decades, the concept of ecosystem services is increasingly becoming the focal point in policy management, development and environmental research (Chaudhary et al., 2015; Costanza et al., 2017), with trade-off assessments being at the center of the debate (Börger et al., 2014; Ferreira et al., 2017; Martino et al., 2019; Naidoo et al., 2008). The fundamental challenge of valuing ecosystem services is providing an accurate description of the multitude of connections that outline the network of social-ecological systems.

The challenges encompassing marine ecosystem services are among the most complex, given the practical difficulties in studying the ocean and the low visibility of some of the resources and services provided (Cavanagh et al., 2016; Villasante et al., 2016), which can often exceed local boundaries and reach global scales (Drakou et al., 2017). Tuna fisheries generate ecosystem services to a great number of beneficiaries that transcend countries and ocean borders, contributing to socioeconomic well-being and food security worldwide (Drakou et al., 2018; Hamilton et al., 2011). Accordingly, the social-ecological systems originating from the tuna-supply chain are numerous and their intricate relationships compose a delicate balance between humans and nature, as well as within humans. Sustaining the balance of these systems is extremely challenging, as stressors like market fluctuations, flawed legislation, overfishing and climate change can trigger disturbances at any level (Drakou et al., 2018; Mullon et al., 2017). These disturbances have the potential to generate a cascade effect that could jeopardize the well-being of the different beneficiaries involved in tuna fisheries systems across the globe.

Ecosystem-based management is the path to actively monitor ecosystem services and prevent their collapse. This approach recognizes the complex interactions governing socio-ecological systems and ultimately seeks to deliver sustainable ecosystem services through integrative and transdisciplinary management (CBD, 2004; Granek et al., 2010). The notion of ecosystem-based fisheries management is not novel (Pikitch et al., 2004; Pitcher, 2001), and scientists, as well as policy makers, have been advocating its implementation for a long time (Rosenberg and McLeod 2005; Garcia & Cochrane, 2005; Berkes, 2012; Möllmann et al., 2014; Crespo et al., 2019). However, despite being conceptually well established, ecosystem-based fisheries management still remains a practical challenge and its implementation has been limited. One of the issues lies in the fact that the valuation of ecosystem services still gravitates toward the more obvious services, like fishery targets, neglecting biodiversity and ignoring the wider ecosystem context and impact (Cavanagh et al., 2016), including socioeconomic aspects. Accurately evaluating the trade-offs between services, as well as the impacts their use generate, is an essential step for a successful ecosystem-based management. Nonetheless, this step will unlikely be achieved if the value of less visible ecosystem services is systematically overlooked (Cavanagh et al., 2016; Villasante et al., 2016).

Tuna fisheries fit well in the scenario described above. Tuna Regional Fisheries Management Organizations (RFMOs) have all incorporated an ecosystem-based approach into their mandate, typically by monitoring and adopting conservation measures for target and bycatch species alike. Still, the decision-making process of tuna RFMOs essentially relies on individual stock assessments, which focus on maximizing the catch of target species without jeopardizing their reproductive capacity, and few conservation measures consider the multifactorial aspects of an ecosystem-based fisheries management (Gilman et al., 2014; Karim et al., 2020). Single-species management is certainly not adapted to the complex network of social-ecological systems originating from tuna fisheries and can lead to substantial socioeconomic and ecological costs (Drakou et al., 2018; Hamilton et al., 2011). An example of such costs is given by Pikitch et al. (2004), who highlighted how the

mortality of white marlin (an ecologically threatened species) caused by tuna and swordfish longliners could threaten a \$2 billion dollar recreational fishing industry. Moreover, when shifts in market, governance or the environment take place, fleets tend to adapt their fishing strategy in order to maximize their well-being (Branch et al., 2006; Salas & Gaertner, 2004) and these adaptations could equally generate unintended ecological and socio-economic effects (Escalle et al., 2016; O'Keefe et al., 2014; Sardà et al., 2015).

The aim of this study is to investigate possible unintended consequences of implementing management measures that primarily focus on single target species. We wish to encourage fisheries scientists and management bodies to use a more holistic approach, founded on transdisciplinarity, to achieve sustainability. With that aim, we selected the example of the Indian Ocean Tuna Commission (IOTC) and its interim plan, first adopted in 2016, for rebuilding the stock of yellowfin tuna (*Thunnus albacares*) (CMM 16-01), one of the main target species of tropical tuna fisheries. The primary measure mandates that, as of January 2017, contracting parties whose purse seine catches of yellowfin tuna reported for 2014 were above 5000 metric tons shall reduce their catches by 15% from the 2014 levels. This particular measure targets purse seine fleets, which account for 44% of Indian Ocean tuna catches (IOTC Secretariat, 2020), with the objective of reducing the fishing pressure on the yellowfin tuna stock. In response, the purse seine fleets have likely adapted their fishing strategy to maximize catches of skipjack (*Katsuwonus pelamis*), also one of the main target species, while reducing their yellowfin catches due to the total allowable catch (TAC).

In the Indian Ocean, the tropical tuna purse seine fleets have two main fishing strategies: They either set on free-swimming schools or set on schools that are associated with fish aggregating devices (FADs). Free-swimming schools sets mostly yield large yellowfin tuna, while FAD sets mostly yield skipjack as well as small bigeye and yellowfin tuna (Dagorn et al., 2013; Fonteneau et al., 2013). We hypothesize that, as a result of the yellowfin TAC, the purse seine fleets would favor to fish on FADs. This would have consequences on the catch of other species, as the composition of FAD sets is much more diverse and includes sharks, turtles, billfishes and other teleost fish (Amandè et al., 2012; Bourjea et al., 2014; Lezama-Ochoa et al., 2018; Torres-Irineo et al., 2014). We here focus on silky sharks (*Carcharhinus falciformis*), a species of global concern due to the vulnerable state of its population (Rigby et al., 2017), which accounts for up to 90% of purse seine elasmobranch bycatch (Gilman, 2011). Besides quantifying the impacts of the yellowfin tuna TAC on silky shark catches, we also explore the economic dimension of this possible ecological impact, as a practical illustration of the strong links between ecological and economic effects.

2 Material and methods

2.1 Fisheries data: French purse seine fleet

Logbook and observer data from the French tropical tuna purse seine fleet were used in the analyses. The data were provided by the Observatory of Exploited Tropical Pelagic Ecosystems (Ob7). Logbook data spanned from 1981 to 2019, while observer data were limited to 2014 to 2019. During this period, the observer coverage ranged from 37 to 51%. Both datasets contain information on set type, date and geographic position for each purse seine set. Logbook data also include a unique vessel code, making it possible to quantify the number of operating purse seine vessels and to calculate their average

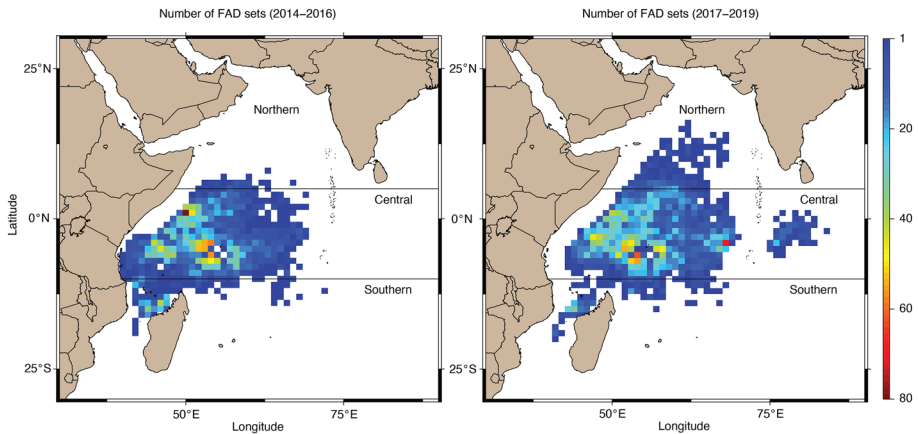


Fig. 1 Number of FAD sets per $1^\circ \times 1^\circ$ squares, conducted by the French purse seine fleet in the Indian Ocean before (left) and after (right) the introduction of the yellowfin tuna TAC

Table 1 Number of FAD sets conducted by the French tuna purse seine fleet by area and period

	Logbook data		Observer data	
	2014–2016	2017–2019	2014–2016	2017–2019
Northern	81	388	31	271
Central	4297	5425	1857	2621
Southern	408	304	189	166

number of sets. Silky shark bycatch data, reporting the number of caught individuals per set, are only available from the observer dataset. This dataset also includes size information from a sample of the captured sharks.

To evaluate the possible effects of the yellowfin tuna TAC implemented in 2017, the datasets were divided into two periods of equal duration, consisting of three years before the TAC (2014–2016) and three years after (2017–2019). The datasets were further divided into three distinct areas based on the spatial pattern of fishing sets, as shown in Fig. 1: (1) Northern, comprising sets above 05°N ; (2) Central, representing the core of the fishery and ranging from 10°S to 05°N ; and (3) Southern, below 10°S . Table 1 shows the numbers of FAD sets for each period and areas in both datasets.

2.1.1 Raising observed silky catch to total catches

To estimate the total number of silky sharks caught by the French purse seine fleet, the proportion of observed FAD sets ($P_n^{A,T}$) with the presence of n silky sharks was calculated for each area A and period T (Fig. 2). Based on these proportions, total silky shark catches were estimated considering the total number of FAD sets declared in the logbook data for each period and area as described in Eq. 1

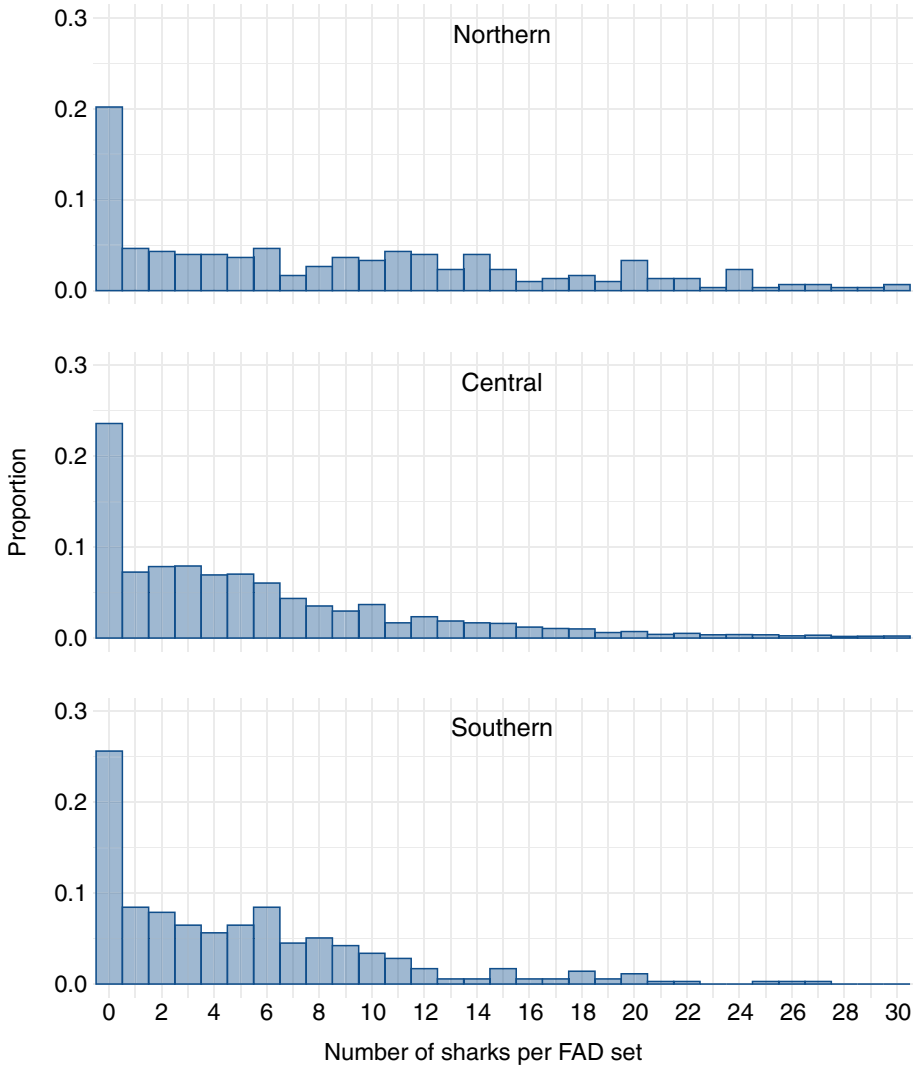


Fig. 2 Proportion of silky shark catches (number of individuals) per FAD set in the Indian Ocean, including sets with 0 sharks. For visualization purposes, the histograms are truncated at sets with 30 sharks. For each area, the observed maximum number of sharks per set is: Northern = 116, Central = 200 and Southern = 90

$$TCatch^{A,T} = S^{A,T} \sum_{n=1}^{N^{A,T}} nP_n^{A,T} \tag{1}$$

where $TCatch^{A,T}$ is the estimated total number of silky sharks caught by the French purse seine fleet within a given area A and period T , while $S^{A,T}$ is the total number of FAD sets declared in the logbook dataset within the same strata. The value $N^{A,T}$ represents the observed maximum number of silky sharks caught within a purse seine set in each spatial stratum.

Table 2 Summary statistics of the French observer data grouped into squares of $1^\circ \times 1^\circ$ for the GLM model fitting (N=701). Catch=number of silky sharks; Catch rate=average number of sharks per fishing set; Sets=Number of observed purse seine sets; FAD prop=proportion of observed FAD sets

	Mean	Median	Minimum	Maximum	1st quartile	3rd quartile
Catch	47.1	32.0	0	413	14.0	65.0
Catch rate	5.5	4.5	0	31	2.5	6.8
Sets	9.6	7.0	2*	69	4.0	12.0
FAD prop	0.8	1.0	0	1	0.7	1.0

*Squares with less than 2 sets were excluded from the analysis

2.1.2 GLM modeling of observer's data

To better understand the factors affecting silky shark catches, a Poisson GLM with a log link function was performed using observers' data. Silky shark catch was the response variable, while catch rate (average number of sharks per fishing set), number of sets, proportion of FAD sets relative to the total number of purse seine sets, area (classified as Northern, Central and Southern) and period (classified into before and after the implementation of the TAC) were the independent variables. Due to the nonuniformity of the fishing sets across areas and periods, an interaction term between sets and areas was also included. The data were grouped into squares of $1^\circ \times 1^\circ$ degrees, and squares with only one FAD set were excluded from the analysis.

The numeric predictors included in the GLM (number of sets, proportion of FAD sets and catch rates) have different units. Therefore, in order to compare the magnitude of their effects, their corresponding coefficients were standardized according to the Agresti method. This standardization method is the most recommended and consists of multiplying the coefficients of each numeric variable by the standard deviation of their estimate, so that each regression coefficient represents the effect of a standard deviation change in a predictor, controlling for the other variables (Agresti, 2007). All analyses were performed in the statistical computing software R using *stats* and *dplyr* packages (R Core Team, 2019) (Table 2).

Sample selection bias is inherent to fisheries-dependent data because samples are not random. However, silky sharks are not the target of purse seine fisheries and their presence at FAD sets are indeed subject to some degree of randomness. Sample selection bias is, therefore, a negligible issue in this case.

Nevertheless, the GLM model contains other intrinsic biases pertaining to endogeneity, correlation and heteroscedasticity. To make sure those biases did not lead to incorrect parameter estimations, additional models were tested. Two main approaches were used: spatial regressions based on the Manski (1993) generic model, and a panel data framework, comparing pooling, random effect, fixed-effect (within) and between methods. The heteroscedasticity issue was considered by testing the standard errors with a pooling regression. All results confirmed the robustness of the original GLM model. The additional models are fully detailed and discussed in the Supplementary Materials section.

2.2 Fisheries data: Main IOTC purse seine fleets

To evaluate how the implementation of the yellowfin tuna TAC affected other CPCs operating in the western Indian Ocean, additional FAD fishing information was obtained from

Table 3 Number of FAD sets conducted by the Spanish, Seychellois and Mauritian tuna purse seine fleets by area and period

	2016	2018
Northern	524	1432
Central	6278	5937
Southern	664	318

the IOTC Secretariat. Specifically, information on the number of FAD sets per area and period was collated through IOTC 3FA forms which are used to report to the IOTC Secretariat mandatory information on FAD activities (deployment, retrieval, encounter, loss at sea, etc.) as well as catch and effort on FADs for all purse seine fishing fleets in activity in the IOTC area of competence, according to IOTC Resolution 19/02 “*On a Fishing Aggregating Devices (FADs) management plan.*” The IOTC 3FA forms included data from 2014 to 2018; however, inconsistencies were noted in some of the forms that prevented their inclusion in the analysis, as alternative sources for verification were lacking. This as was the case with the Korean and Japanese fleets.

Nonetheless, data from Spain, Seychelles and Mauritius could be verified through CPCs reports (Assan et al., 2019; Báez & Ramos, 2019; Kawol et al., 2019) and were exploitable for the purpose of this study. Together with the French fleet, Spain and Seychelles are the main industrial purse seine fleets operating in the western Indian Ocean, accounting for 34% of total tuna catches (IOTC Secretariat, 2020). The IOTC dataset was divided into the same areas as the French datasets. Available data within each time interval (before and after the yellowfin TAC) had to be limited to a single year (2016 and 2018, respectively) because Spanish data for 2017 have not been submitted to IOTC (Table 3).

By combining the French and IOTC datasets, total silky shark catches for the western Indian Ocean were estimated for each area and period as described in Eq. 1, considering $S^{A,T}$ as the total number of FAD sets declared in both French and IOTC datasets. For this estimation, the proportion of FAD sets with n sharks ($P_n^{A,T}$) obtained from the French observer’s data (Fig. 2) was used.

2.3 Economic assessment

In terms of welfare economics, the bycatch issue can be seen as an external cost (or social cost) issue (Pascoe, 1997), i.e., not embodied in the private (market) value of fish. Because society values canned skipjack, the whole social costs and benefits of FAD fishing have to be considered before deciding how to internalize these external costs (Ovando et al., 2021). As a result, the amount of acceptable bycatch is the trade-off between the social costs and the benefits of FAD fishing.

With such an approach, bycatch represents a marginal abatement cost or, symmetrically, a decreasing marginal benefit for the fishing fleet.¹ However, increasing the level of bycatch may also represent a social damage that is not taken into consideration by the market. At a wide extent, such damage depends on the forgone value of ecosystem services attached to silky shark bycatch. As a first and approximate valuation, we developed a meta-analysis

¹ For instance, increasing the fishing effort with additional FAD sets in the northern part of the Indian Ocean would provide a declining profit per set because the yield per unit effort would be decreasing and the trip cost might be increasing simultaneously.

of the potential ecosystem services associated with sharks in general to propose a range of potential values for the external cost of bycatch. The various ways of internalizing this cost are examined in the results section as well.

Considering the most suitable ways of internalizing the cost of shark bycatch, an approximated value for the forgone social cost of silky shark bycatch was also proposed. The proposed value consists of the product between the estimated number of shark bycatch (Sect. 3.2.), the average weight (kg) and the unit price in USD per kg as defined by the literature (meta-analysis). To account for the variability of these 3 factors, their range was incorporated into a Monte Carlo analysis across 1500 iterations. A normal law with a 32% standard deviation (SD) was chosen for the unit weight of silky sharks. This distribution corresponds to the weights of silky shark bycatch reported by French observers. A random uniform law distribution of integer numbers between the minimum and maximum values was preferred for the estimated silky shark bycatch to account for the uncertainty surrounding the implementation of the yellowfin TAC (before/after). For the unit price of sharks, a normal law centered on the recreational value with a 20% SD was selected to reflect the random distribution of consumptive values reported by the literature.

3 Results

3.1 Fishing strategy adaptations

The number of FAD sets conducted by the French purse seine fleet has consistently fluctuated over the years. However, it has never been as high as in the past four years and after the implementation of the yellowfin tuna stock rebuilding plan (Fig. 3: panel A). A maximum of 2315 FAD sets was reached in 2018, one year after the implementation of the TAC. It is important to mention, however, that the number of FAD sets started to increase in 2016—the year of the TAC adoption and one year before its implementation. In 2019, the number of FAD sets has decreased to the levels of 2016 and 2017. Following the same trend as the number of FAD sets, the average number of FAD sets per vessel as well as the FAD to FSC sets ratio has considerably increased since 2016, reaching their peaks in 2018 (Fig. 3: panels B and C). In contrast, the number of operating vessels decreased over the years, but has remained relatively stable since 2014 (Fig. 3: panel C).

It appears that there was also a spatial component to the fishing adaptive strategy. In the three years that followed the yellowfin TAC implementation (2017–2019), the distribution of the fishing effort expanded to the north and to the east of its core (Fig. 1). The most marked change was the increase of FAD sets in the Northern area, toward the Arabian Sea, from 81 in the years preceding the TAC (2014–2016) to 388 in the years following the TAC (2017–2019) (Table 1).

When combining the data from the French fleet with the main industrial purse seine fleets operating in the same area, which include Spain, Seychelles and Mauritius, only a slight overall increase in the number of FAD sets is observed (Fig. 4). However, in the Northern area, the number of FAD sets tripled, going from 538 in 2016 to 1604 in 2018

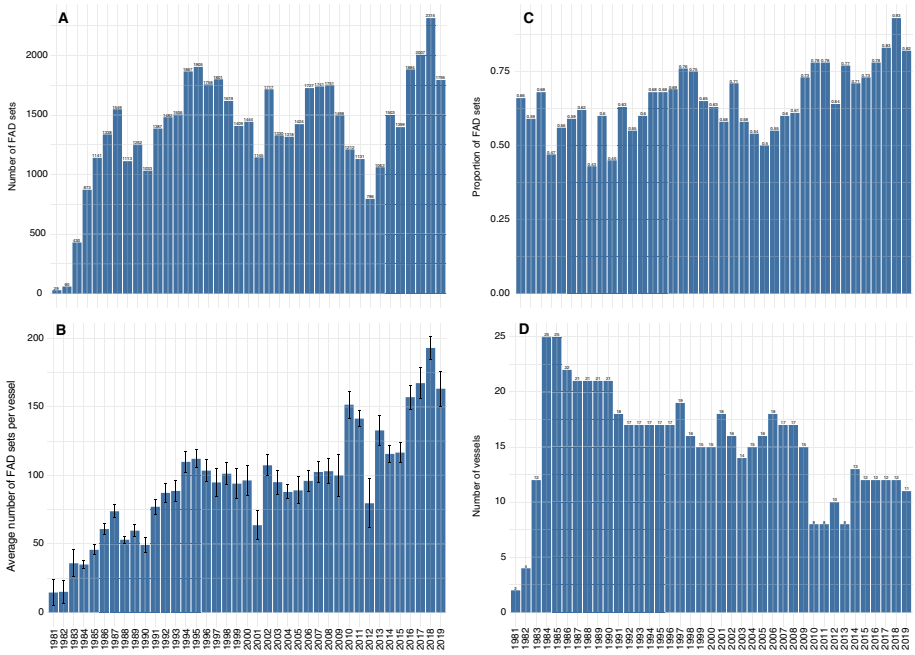


Fig. 3 Yearly evolution of the fishing strategy of the French tropical tuna purse seine fleet in the Indian ocean. **a** Number of FAD sets; **b** Average number of FAD sets per vessel (vertical bars represent the standard error); **c** Overall proportion of FAD sets and **d** Number of operating vessels

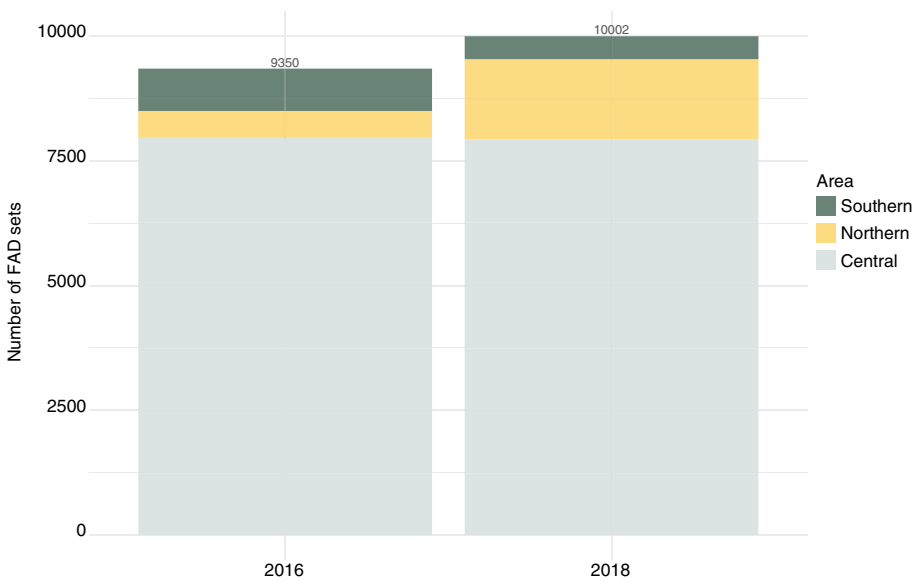


Fig. 4 Yearly number of FAD sets by area conducted by the industrial tuna purse seine fleets operating in the western Indian Ocean (Spain, France, Seychelles and Mauritius) before (2016) and after (2018) the introduction of the yellowfin tuna TAC

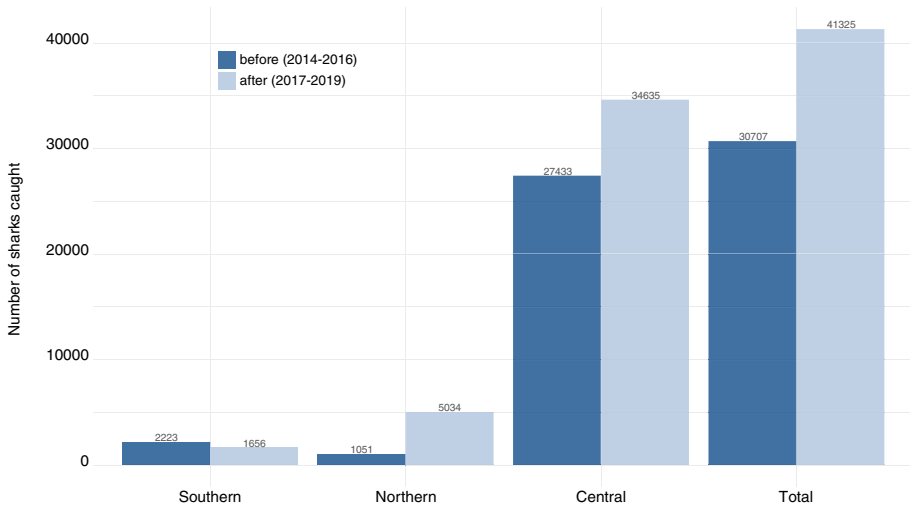


Fig. 5 Estimated total catches of silky shark by the French purse seine fleet in the Indian Ocean, before and after the implantation of the yellowfin tuna TAC

(Fig. 4). On the other hand, FAD effort remained relatively stable in the Central, while in the Southern area a decrease was observed.

3.2 Increase in silky shark catches

In the years preceding the TAC implementation (2014–2016), the estimated number of silky sharks caught by the French fleet corresponded to 30,707 individuals, while after the TAC, the estimated silky shark catches increased to 41,325 (Fig. 5) corresponding to a 35% increase. The most significant increase in silky shark catch occurred in the Northern area, where catches were estimated to be 379% higher than the pre-TAC years.

The estimated silky shark catches for the main industrial purse seine fleets operating in the western Indian Ocean (including France, Spain, Seychelles and Mauritius) reached 73,987 individuals in 2018, against 62,442 in 2016—an increase of 18% (Fig. 6). This trend was entirely led by the increase in the number of FAD sets in the Northern area, where catch estimates were 198% higher in 2018.

The GLM model fitted on French observer's data provided a good fit and all factors were significant ($p < 0.05$) (Table 4). The number of FAD sets was the most important variable, followed closely by silky shark catch rates. The period before the implementation of the yellowfin TAC had a negative impact on silky shark catches when compared to the period after. The interaction term between sets and areas showed a higher importance of the Northern area. Model predictions and residuals are shown in Supplementary Figs. 2 to 4.

3.3 Economic loss associated with silky shark bycatch

On the basis of a meta-analysis of shark ecosystem values found in the literature, we attempted to estimate the external cost of bycatch through some potential forgone uses

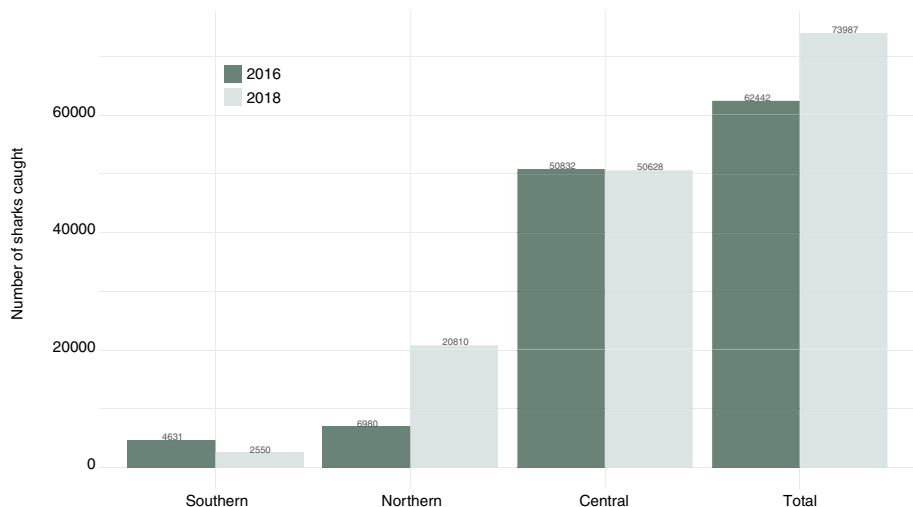


Fig. 6 Estimated catches of silky shark for the main tuna purse seine fleets operating in the western Indian Ocean (Spain, France, Seychelles and Mauritius) before (2016) and after (2018) the introduction of the yellowfin tuna TAC

Table 4 Model summary (Catch ~ Catch rate + Sets + FAD prop + Period + Sets:Area, family = Poisson)

Term	Estimate	SE	Statistic	p.value	Conf.low	Conf.high
(Intercept)	3.7079	0.0085	438.3404	0.00E+00	3.6913	3.7245
Catch rate	0.4418	0.0051	87.3393	0.00E+00	0.4319	0.4517
Sets	1.0623	0.0298	35.6356	3.93E-250	1.0035	1.1204
FAD prop	0.2374	0.0087	27.3178	2.61E-150	0.2204	0.2544
Period (before)	-0.2368	0.0124	-19.0950	2.78E-67	-0.2611	-0.2125
Sets:Area (Northern)	0.4301	0.0430	10.0096	1.38E-09	0.3461	0.5146
Sets:Area (Central)	-0.5379	0.0301	-17.8479	3.00E-43	-0.5966	-0.4785

Std.error = standard error, Conf.low and Con.high = lower and upper bound of the 95% confidence interval for each estimate.

ranging from consumptive values to ecotourism and recreational services. The ecological (existence, option and bequest) values of silky sharks were left out of the analysis because of incomplete knowledge regarding the abundance of stocks and the ecological importance of this species for the whole oceanic ecosystem.

3.3.1 Consumptive value of provisioning ecosystem services

Silky sharks are caught as bycatch and discarded by purse seine fleets operating in the western Indian Ocean. Consequently, the economic damage begins with the forgone commercial value of sharks. The consumptive value of sharks was valued to US\$630 m per year (Cisneros-Montemayor et al., 2013). According to Dent and Clarke (2015), the value of shark products would even approach US\$1 billion per year in the early 2010s. Most official

data presumably underestimate the total tonnage and value of marketed sharks because of an opaque and sometimes illegal business for this very high-valued product (particularly shark fins sold in Asia). The mere trade of shark fins (including skates and rays) would be worth valuing half of this amount for 15,000 t traded of net products in the mid-2010s and 10,500 t in 2018, and a unit value reaching around US\$25 per kilo (FAO). It is important to highlight that the practice of finning (cutting off the fins of the shark and discarding its carcass at sea) is banned from many fisheries worldwide, including those under IOTC mandate (CMM 17–05). However, if finning ban requirements are met, the trade of shark fins and meat remains legal. Shark fishing is a sensitive subject, but to fully grasp the economic loss associated with shark bycatch their consumptive value needs to be quantified.

Conversion factors are required to retrieve the live weight equivalent of prices. A common fin ratio (fin weight as a percentage of whole weight) for sharks was estimated at 3.33%, upgrading the conversion factor to 30, although factors could be different between shark species (Francis, 2014). For dried fins, the conversion factor could rise up to 150 because of the water loss weight (Caillart et al., 1996). The LWE price observed in the official trade statistics of FAO varied between US\$0.20/kg for dried fins to US\$3.58/kg for fresh and chilled shark meat in 2018. What matters for the lost value of discards is actually the price paid to fishers. In Palau, the catch value of one single shark was estimated at US\$108 (Vianna et al., 2012), i.e., a price between 5 and 6 USD per kg if we convert it by the average weight of the two most frequent species, the whitetip (*Triaenodon obesus*) and the gray reef shark (*Carcharhinus amblyrhynchos*). The two most important countries harvesting and trading silky sharks reported by FAO are Costa Rica (2279 t in 2018) and Sri Lanka (709 t), with the noticeable exception of Tanzania for year 2018 (2,155 t). Their LWE price would be around \$0.16 per kg for Sri Lanka and \$0.60 per kg for Costa Rica, much more in connection with the price of \$0.75 per kg reported by Sumaila et al. (2007). Taking a conservative value from the trade statistics of FAO converted in LWE, we suggest retaining a minimum price of \$0.40 per kg (average trade price 2015–2016 in LWE) as a possible minimal reference for the forgone consumptive value of silky sharks.

3.3.2 Conservation value and cultural ecosystem services

The ecological role of sharks in pelagic ecosystems has been evidenced in several studies but is rarely described at an ocean-wide scale (Kinney & Simpfendorfer, 2009; Lew, 2015; Murphy et al., 2018). The economic value of alive sharks goes nonetheless far beyond the extractive value of fishing reported above: One may add the nonconsumptive use value of ecotourism associated to shark diving, which is present in many studies (Cagua et al., 2014; Clua et al., 2011; Davis & Tisdell, 1999; Davis et al., 1998; Pires et al., 2016; Vianna et al., 2011; Zimmerhackel et al., 2019), other use values such as the film industry or research (Haas et al., 2017), but also indirect use value through the regulation of the whole ecosystem (Kinney & Simpfendorfer, 2009), and nonuse values such as the existence, option (possible uses in the future such as genetic inputs) and bequest values for future generations (Grafeld et al., 2016; Skubel et al., 2019). If the marginal damage of accidentally fishing a silky shark cannot be the sum of all these values, because some uses represent alternative choices (e.g., shark diving vs fishing), others could be very well aggregated (tourism, ecosystem regulation, existence value, etc.). Most of the literature attempting to demonstrate the value of shark conservation focuses on the economic value of shark diving ecotourism (Table 5).

Table 5 The revealed value of alive sharks borne with the diving and ecotourism industries

Study	Area	Activity	Revenue (Million USD)
Cisneros-Montemayor et al. (2013)	World	Watching + diving	314
Haas et al. (2017)	Bahamas	Shark diving	109
Vianna et al. (2011)	Fiji	Shark diving	42.2
Huveneers et al. (2017)	Australia	Shark diving	25.5
Vianna et al. (2012)	Palau	Shark diving	18
Grafeld et al. (2016)	Guam	Shark scuba diving	15–20
Vianna et al. (2018)	Borneo	MPA + shark diving	10
Cagua et al. (2014)	Maldives	Whaleshark diving	9.4
Clua et al. (2011)	French Polynesia	Shark watching + feeding	5.4
Indab (2016)	Philippines	Whale shark conservation	0.7

Globally, the value of recreational ecosystem services would amount to US\$314 m in 2013 (Cisneros-Montemayor et al., 2013). Based on travel cost methods (TCMs) to evaluate indirectly the nonmarket value of sharks through the expenditures of divers or simple watchers and the business of tourist operators, various regional studies have been published for the last decade (Table 5). The shark diving or watching (tourism) industry represents several millions USD of earnings, hence a substantial contribution to GDP for some small island developing states, like in Palau where shark-related tourism amounted to 8% of GDP (Vianna et al., 2012).

Besides this direct valuation through revealed preference methods, other authors combined travel cost approaches with stated preference models (contingent valuation method or CVM, conjoint analysis, choice experiment) to test for the willingness to pay of divers and tourists for various conservation policies (Mieras et al., 2017; Murphy et al., 2018; Vianna et al., 2018; Zimmerhackel et al., 2019). For instance, in addition to the current US\$32.5 ticket to watch Manta rays in the Fiji Islands, 82% of tourists were willing to pay an extra amount greater than US\$2.5 (54% of divers would even pay US\$10 or more) to dive with Mantas and support educational and environmental policies protecting sharks (Murphy et al., 2018). Another study showed that the consumer surplus of divers along with the diving industry revenue would be halved in the Maldives if sharks could not be observed during dive trips or if illegal fishing was exercised (Zimmerhackel et al., 2019). Vianna et al. (2018) developed a survey mixing a TCM approach with a scenario of marine protected area (MPA) creation in Semporna (Borneo, Malaysia). In particular, the authors compared the high value generated by the diving industry revenue, the tax income collected by the Malaysian government and the salaries paid to households working in the diving sector (>\$10 m overall) to the much lower value created by the local fishing industry with the annual 462 tons of harvested sharks (<\$0.5 m). However, in some developing countries, the willingness to pay for a whale shark conservation program is close to zero because the local citizens just cannot afford it, although they are perfectly aware of the environmental stakes of such programs (Indab, 2016).

3.3.3 The recreational value of shark angling

All these studies demonstrate the high nonconsumptive value of sharks. The problem with CVM studies is that they can hardly be used to estimate an individual value of fish so as to apply benefit transfer (or value transfer function) methods (Plummer, 2009). They are more designed to value conservation programs as a whole and do not respond per se to the economic theory of utility when it comes to associate a value to a variable quantity of individuals to be preserved. Some authors go then further by valuating an individual price of an alive shark over its life span, amounting to \$180,000 per year in Palau, and therefore nearly \$2 m over 16 years with a discount rate of 5% (Vianna et al., 2012). Another study reported an individual value by shark of \$316,699 annually (Clua et al., 2011). When comparing these huge amounts to the market price of shark consumed as food stated in previous section (e.g., approximately US\$70 for a 20-kg shark marketed as fresh or chilled meat in 2018), conservation looks like a much better option for society.

Nonetheless, these comparisons are not straightforward as some of the aforementioned species are highly recognizable and charismatic (e.g., whale shark, manta ray), unlike gray reef or silky sharks. Additionally, it is often unknown what proportion of a shark's population visits diving sites and therefore attract tourists. Silky sharks, for example, are a popular attraction for SCUBA divers coming to the central Red Sea but, at present, we are not able to quantify how much of the Indian Ocean population actually visits the area and supports this touristic activity (Clarke Lea, & Ormond, 2011; Clarke, Lea, et al., 2013). One could also argue that the presence of other shark species would be enough to meet the tourism demand if silky sharks no longer visited the site. Therefore, it is possible that only a small fraction of the population would be enough to maintain the economic activity, which would interfere with the utility theory assumption on which the revealed methods of valuation are based. This means that we cannot simply multiply the number of bycaught individuals by the unit value of sharks estimated in shark diving valuations.

Stated preference methods like CVM are more likely to approach the value of an environmental asset when scenarios are closer to market-type conditions. In this regard, recreational fisheries can represent a good proxy of the opportunity cost of discarding silky sharks. Johnston et al. (2006) developed a meta-analysis of WTP values per recreational fish, including what they called big game fish (dogfish, ray, sharks, billfish, swordfish, etc.). For this research, they collected 48 studies including 391 observations of individual WTPs between 1977 and 2001 (all values were converted in constant US\$ of 2003). They could estimate several econometric models to explain the values of recreational fish, while controlling for the method (discrete choice models, TCM, CVM, choice experiment, etc.), the targeted species, the water body type, the catch rate, the angler demographics and the fishing method. The estimated value for big game fish issued by the WTP econometric model would give a value of US\$25 per individual fish, i.e., US\$1.26 per kg for a 20-kg specimen. Converting the constant price of 2003 into a constant price of 2018, it would give a US\$40 per shark (or a US\$2 per kg if discards of silky sharks are estimated in weight). This latter price would represent another reference for the opportunity cost of silky shark bycatch.

3.3.4 The forgone social cost of silky shark bycatch

Summarizing the previous sections dedicated to the monetary cost of the ecosystem services forgone with shark bycatch, we can report the following values (Table 6).

Table 6 Alternative use values of silky sharks

Ecosystem services	Value (US\$ per kg)
Consumptive value (shark fins LWE)	0.40
Recreational value (angling)	2.00
Consumptive value (shark fresh meat)	3.58
Conservation value (ecotourism)*	15,000.00

*Annual discounted revenue per kg of an alive shark exploited by diving tourism in Palau over 16 years with a discount rate of 5% for a 22-kg shark (calculated from Vianna et al., 2012)

The prices reported in Table 6 represent alternative values of the marginal damage (i.e., external cost) of bycatch. Given that silky sharks caught accidentally are not marketed by purse seine fishers, the opportunity cost of discarding lies in the alternative uses which are lost for other end users (other fishers, recreational anglers, divers, ecotourists, etc.). To compute an approximated social cost of silky shark bycatch, we considered the recreational value of \$2.00 per kg with a 20% SD (2.00 ± 0.40), since it reflects the random distribution of consumptive values between \$0.40 and \$3.58 (Table 6). However, we did not consider the discounted conservation value, as it would result in an extremely high figure, by far exceeding the global value of recreational ecosystem services estimated by Cisneros-Montemayor et al. (2013). The other two terms used to estimate the social cost of silky shark bycatch were the average weight of 12.10 ± 3.85 kg (32% SD) and a range of 62,442 to 73,987 sharks caught (estimated in Sect. 3.2.).

The combination of random input values gave a 90% probability of forgone value estimated between US\$ 709,992 and US\$ 2,806,602 for the sole consumptive value (Fig. 7a, b), with a mean at US\$ 1,640,928. The average weight, whose distribution is skewed on both sides, has a prevailing impact on the output value, with a swing between US\$ 0.1 and 3.2 million, exceeding by far the effect of the unit value or the number of harvested individuals (Fig. 7c). However, we used a very conservative range of consumptive values representing the mere loss of provisioning ecosystem services caused by the bycatch of sharks, and not any conservation value as showing the support or cultural ecosystem services.

Looking at the forgone value through the eyes of a conservationist may increase substantially the social cost of shark bycatch, as seen with the net present value of ecological diving. Other studies discounting the value of an alive shark attracting tourists throughout its lifespan have considered values as high as \$180,000 per year (Palau) or even \$316,699*year⁻¹ (French Polynesia). To grant a similar value for every single silky shark killed as purse seine bycatch would be inadvisable, given that not all of these sharks would visit diving sites. However, assuming that a small proportion (say 1% only) of this forgone biomass visits open ocean areas where tourists come to dive, such as the Red Sea or the Maldives, and taking the conservation value of Table 6 (\$15,000 per kg) and the average weight of silky sharks from the observers' sample (12 kg), the social cost of the forgone ecosystem service would increase between USD 11 and 14 million. This amount corresponds to 3 or 4% of the value of landings for the European purse seine fleet harvesting in the Indian Ocean.² Given the non-certain probability of use in other alternatives, the forgone consumptive or nonconsumptive values should be considered alternatively and not simultaneously.

² STECF 19–06—AER—Economic and Transversal data tables; <https://stecf.jrc.ec.europa.eu/reports/economic>. The total revenue of 11 French PS and 13 Spanish PS was US\$ 322 million in 2018.

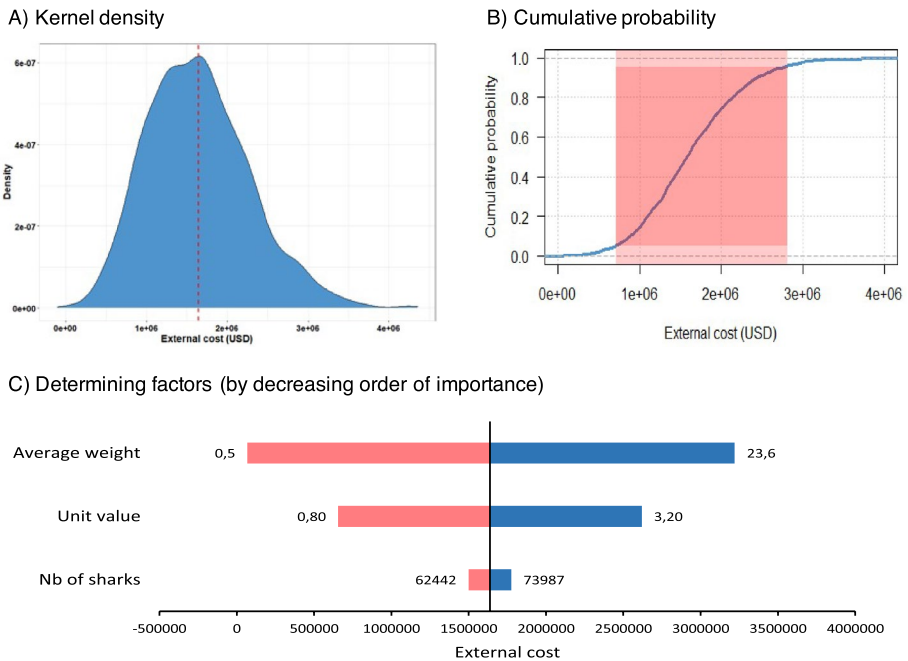


Fig. 7 Estimated value of external costs (USD) for silky shark bycatches. **a** Kernel density of the Monte Carlo (MC) distribution of external costs (USD). The statistics of output values from the MC analysis were the following ones after 1500 iterations: Mean=1,640,928 (vertical dashed red line); Median=1,600,362; SD=636,234; Skewness=0.51; Kurtosis=0.37; **b** Cumulative probability of the MC distribution. The red polygon represents the 90% confidence interval, between 709,992 (5%) and 2,806,602 (95%) USD. **c** Sensitivity analysis by input (upper and lower values for each input, in kg, USD and number, respectively, and USS for the external cost on the horizontal axis)

4 Discussion

This study indicates that the industrial purse seine fleets operating in the western Indian Ocean have adapted their fishing strategy in response to the yellowfin tuna TAC first implemented by the IOTC in 2017 (CMM 16–01) and these adaptations have indirectly resulted in an increase of silky shark bycatch. For the French purse seine fleet, total silky shark catches increased by 35% (Fig. 5). For the main purse seine fleets combined (including France, Spain, Seychelles and Mauritius), the increase reached 18% (Fig. 6). Two major strategy adaptations, consisting of fishing mode shift and effort expansion, were identified. Most large yellowfin tuna are caught on free-swimming schools sets (Dagorn et al., 2013; Fonteneau et al., 2013). Hence, the first obvious adaptation of the French fleet was to stop searching for yellowfin tuna free-swimming schools and direct most of its effort to tuna schools associated with floating objects. This fishing mode shift had a direct impact on the increased shark bycatch, as the overwhelming majority of silky sharks are caught on FAD sets (Amandè et al., 2012; Lezama-Ochoa et al., 2018; Torres-Irineo et al., 2014).

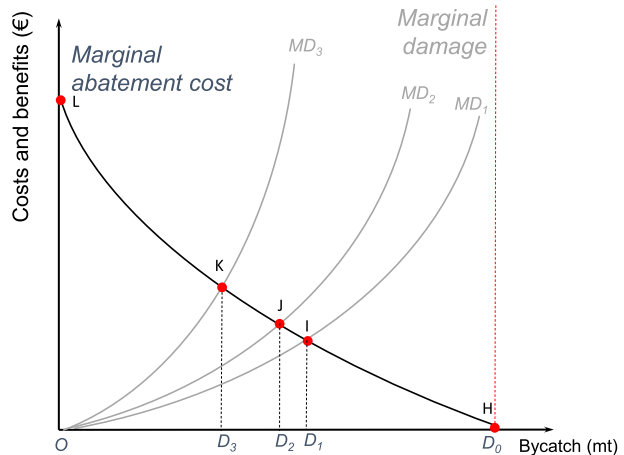
The French fleet particularly targeted free-swimming yellowfin tuna schools before the TAC; therefore, an increase in the number of FAD sets was not as pronounced for the other fleets. The second major strategy adaptation was the effort expansion to the North, toward the Arabian Sea. This area was historically known for its high catch rates of the skipjack tuna (IOTC Secretariat, 2020), but its exploitation was minimal during the years preceding the implementation of the yellowfin TAC (Figs. 1, 4). After the TAC, silky shark catches were 379% higher in the Northern area for the French fleet and 198% for the main fleets combined. This large increase reflects the higher silky shark catch rates in the area, which is a known hotspot for the species (Mannocci et al., 2020). It should be noted that the analyses cannot predict how the fishing strategy of purse seine fleets would have evolved if the TAC measure had not been implemented. The FAD fishing effort could have increased and further expanded in the northern area regardless. However, the results of the modeling approach report a significant dummy period effect (see Supplementary Materials), which can be at least partly explained by the implementation of this management measure. Furthermore, no other major event (i.e., climate oscillation, piracy) was reported throughout the sample period, strengthening the hypothesis that silky catches have collaterally increased due to the yellowfin tuna TAC.

There are obvious ecological impacts caused by an increase in silky shark bycatch. Elasmobranch species exhibit low population growth rates (Cortés, 2000), which makes them much more vulnerable to overfishing when compared to teleost fish (Frisk et al., 2005; Musick et al., 2000). Many studies have laid out the fragile state of pelagic shark populations worldwide due to the increasing fishing induced mortality across their range (Camhi, 2009; Dulvy et al., 2008; Worm et al., 2013). The silky shark is classified as vulnerable to near threatened by the IUCN red list (Rigby et al., 2017); whereas uncertainties still remain due to lack of data, there is a general consensus that its populations have declined (Baum & Blanchard, 2010; Clarke, Harley, et al., 2013). In the Indian Ocean, silky sharks are highly susceptible to longline and gillnet fisheries with the aggravating factor of poor data collection (IOTC Secretariat, 2021). Even if the tropical purse seine fishery is not the main source of silky shark bycatch, any augmentation in fishing pressure on threatened species poses an important ecological risk. Additionally, the at-vessel mortality rate of silky sharks caught by purse vessels is extremely high as most individuals are already dead by the time they reach the deck. Their total mortality (at vessel plus post-release) has been estimated at 80% across several studies conducted in the Pacific, Atlantic and Indian Oceans (Eddy et al., 2016; Hutchinson et al., 2015; Poisson et al., 2014).

Like in many high sea fisheries, there is no specific regulation for bycatch such as a tax penalty or limited quotas of FAD sets in the Indian Ocean tuna fisheries (Dagorn et al., 2013). We saw that the implementation of a TAC for yellowfin tuna in 2017 has shifted the fishing strategy of the purse seine fleet toward an increasing use of FADs over a wider and northward expanding fishing area, resulting in a significant increase of silky shark bycatches. The latter represent external costs for alternative ecosystem services (Pascoe, 1997). Among other users might be considered other fleets targeting sharks for their consumptive value, but also the ecotourism industry making a living out of shark diving or watching (Cisneros-Montemayor et al., 2013; Haas et al., 2017; Huveneers et al., 2017; Vianna et al., 2018; Zimmerhackel et al., 2019). We can also mention a range of other non-use values resulting from conservation: regulation of ecosystems, genetic wealth, cultural value, etc. (Indab, 2016; Kinney & Simpfendorfer, 2009; Skubel et al., 2019).

The lack of regulation means that the purse seine fleet will catch as much as possible until the marginal benefit is exhausted at point H in Fig. 8, for a bycatch quantity D_n . This quantity was estimated at 73,987 individuals for the whole Indian Ocean in 2018. The

Fig. 8 External costs and potential “optimal” levels of silky shark bycatch in the northern area of the Indian Ocean



external cost is illustrated by the marginal damage curves, with different slopes according to the marginal opportunity cost of discarding (e.g., the minimum consumptive value of fins could be represented by MD_1 , the recreational value of angling by MD_2 , fresh meat by MD_3 , etc., in Fig. 8). The social optimum would therefore be achieved at the intersection of the marginal abatement cost (or marginal benefit) curve and the marginal damage curve, respectively, in points I, J or K according to the shape of the damage curve, therefore reducing the level of bycatch (from D_0 to D_1 , D_2 or D_3).

With a more conservationist opportunity cost, such as the ecotouristic or ecological value of sharks fixed at a much higher level (Haas et al., 2017; Vianna et al., 2012; Zimmerhackel et al., 2019), or the net loss of the tuna value chain induced by e-NGO campaigns against bycatch or FAD fishing (Gomez et al., 2020; Teisl et al., 2002), the optimal level of bycatch could even tend to zero (point L in Fig. 8). However, such a limitation of FAD fishing would not be very realistic nor socially desirable because economic trade-offs should compare the discounted value of non-harvested tuna due to FAD prohibition on the one hand, and the conservation value of sharks on the other hand (Hoagland & Jin, 1997; Ovando et al., 2021). A rough estimate of the forgone consumptive value of silky shark bycatch without discounting would result in an annual value between US\$ 1.5 and 1.8 million for the sole consumptive value, i.e., representing 0.5–0.6% of annual revenue for the EU fleet harvesting in the Indian Ocean.

Consequently, the tuna fishing industry could easily afford to compensate for the lost ecosystem services associated with sharks, but the question lies in the incentives to internalize this social cost. Ovando et al. (2021) suggest a Coasean solution through right-based markets rather than a Pigouvian tax or regulation which is costly and difficult to implement in the case of international high seas fisheries, hence poorly enforceable. The authors estimated the revenue loss of longliners because of bigeye bycatches caused by FAD fishing from purse seiners in the west and central Pacific Ocean. They concluded that the economic costs of large-scale reductions in FAD use far outweigh the benefits and proposed a Coasean-bargaining solution where conservationist interests, fishing fleets and any other stakeholder group (states, IOTC, e-NGOs, etc.) could sell or purchase FAD-use rights according to the value placed on silky shark conservation. This could be done through a tax levied on shark diving tourism, or a price premium on FAD-free canned skipjack paid by consumers. In the Pacific case study, a 4% price premium on free-school skipjack would

cover the complete removal of FAD fishing from the Vessel Day Scheme (Ovando et al., 2021).

The problem with Coasean solutions stems from uncertainty and transaction costs to organize and monitor such right-based incentives. In the present case, their implementation would assume that the stocks of yellowfin, skipjack and silky sharks would be better known, as well as their interactions within the ecosystem, that the end users (either consumers of FAD-free tuna or shark divers) would be willing to pay a premium for the sake of conservation interests, that the use of FADs can be monitored and enforced, etc. This is not out of reach but would require a more thorough and comprehensive study about the ecological value of sharks and the awareness about the consequences of FAD fishing by end users. In particular, the valuation of the social cost would be different for nonconsumptive ecosystem services, such as cultural or recreational services related to shark diving and tourism in the Indian Ocean (Seychelles, Maldives, Red Sea, Mauritius, etc.). Assuming only a small proportion (1%) of the forgone biomass visits the diving sites where the tourists like to observe silky sharks, the external cost would be valued between USD 11 and 14 million, i.e., representing 3 to 4% of the annual earnings of the EU fleet. This would make a huge difference and would significantly increase the stakes of the trade-off between the conflicting ecosystem services (provisioning, or recreational and cultural) derived from the presence of sharks, and not even discussing the unknown role of sharks in the regulation of marine ecosystems.

5 Conclusions

Our work narrates a practical example of how managing bycatch and target species that share similar habitats is a challenging task. Tuna RFMOs have been trying to incorporate the principles of an ecosystem-based fisheries management for many years, but, ultimately, the decision-making process remains purely based on single-species management (Gilman et al., 2014; Karim et al., 2020). To assure sustainability in the economic, social and ecological spheres we need to let go of the single-species approach as the foundation of our fisheries management and adopt a more holistic approach.

Efforts to move toward an ecosystem approach have been made by tuna RFMOs in the past few years. These included the creation of bycatch and ecosystem working groups inside the tuna commissions and the development of ecosystem report cards, which consist of a set of indicators to monitor several ecosystem components as a whole (Juan-Jordá et al., 2018). Additional efforts could be directed to the creation of working groups dedicated to the socioeconomic aspects of fisheries at the same level as the other groups that comprise the scientific committees. Discussion groups focused on possible unintended effects of a particular management measure should be conducted on a regular basis. These discussion groups should be composed by scientists from the main tuna RFMOs working groups (e.g., tropical tunas, billfishes, neritic tunas, ecosystem, and bycatch and the *still-to-be-created* socioeconomic group), as well as fishery stakeholders. The possible unintended effects should then be closely monitored, so that mitigating actions can quickly be taken. For the specific case of bycatch mitigation, the implementation of credit systems, such as cap and trade, are certainly worth investigating (Ovando et al., 2021; Squires et al., 2021).

This is a first exploration into the socioeconomic dimension of trade-offs between the use of FADs in tuna purse seine fisheries and shark bycatch. Our work can equally be used as a basis to discuss the trade-offs of other FAD-associated species. It is important to

highlight that fundamental knowledge regarding stock status and population dynamics are essential to support accurate ecosystem services valuations. Undoubtedly, there are many other caveats that need to be considered when shifting tuna fisheries management from single species to ecosystem based, but the work described here certainly outlines changes need to happen more rapidly. Maybe, the effort should be put into an Ecosystem Service-Based Fisheries Management rather than just Ecosystem-Based Fisheries Management.

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Data availability The data supporting the findings of this study are available upon request from the Observatory of Exploited Tropical Pelagic Ecosystems (<https://www.ob7.ird.fr/en/>) and from the Indian Ocean Tuna Commission Secretariat (<https://www.iotc.org/data/datasets>).

Declarations

Conflict of interest The work presented is original and was carried out by the authors. All persons entitled to authorship have been so named, and all authors have agreed to the contents of this manuscript. This manuscript has not been published or simultaneously submitted for publication elsewhere in identical or similar form. The authors also declare that there no competing interests.

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