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Undetected silky sharks (*Carcharhinus falciformis*) in the wells of the tropical tuna purse seine fleet in the Indian Ocean

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ABSTRACT

The catches of the Spanish purse seine fleet targeting tropical tunas in the Indian Ocean have been systematically sampled in port and at sea by scientific research centres since the fleet began to operate in the 1980s. During these samplings, some silky shark (*Carcharhinus falciformis*) specimens were found in the wells of these vessels which had not previously been recorded by at-sea scientific observers. To quantify the occurrence of these undetected incidental catches of silky sharks, this study compared two sets of data: on-board data collected by scientific observers and port sampling data. The European Union's long-term data collection program (PNDB), coordinated by the Spanish Fisheries Secretariat, provides on-board data collected by scientific observers as well as port sampling data which is collected while a vessel arrives to the port to begin unloading. The sampling focused on target species up until January 2021, when sampling started including non-target species as well. The datasets examined in this study are from January 2021 to December 2022. The results show significant differences between silky shark sizes observed on-board and those measured in port. A logistic model indicates a significant probability of observing silky sharks in wells, with a strong goodness of fit and high discrimination capacity as a function of the total catch of the fishing operation. Further analysis reveals differences in average sizes and weights of silky sharks caught in free-schools compared with those caught with tuna schools aggregated beneath Fish Aggregating Devices or FADs. The presence of unnoticed silky sharks suggests unreported captures, indicating that rates of mortality of the species are underestimated. In conclusion, the research emphasizes the need to address undetected silky shark bycatch in the purse seine fishery in the Indian Ocean. Obtaining accurate data and understanding the magnitude of this bycatch are crucial for developing management strategies that mitigate the impact and promote the sustainability of silky shark populations in the region.

1. Introduction

Pelagic species group together to form schools and large pelagic fisheries have taken advantage of this behaviour by developing purse seine nets for their capture. Purse seine vessels specialized in tropical tuna fishing constitute a modern fleet that is constantly growing in carrying capacity, technology, and fishing techniques (ICCAT-2008-3.1.1 Purse Seine Manual). The fleet targets three species of tropical tunas: skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (Delgado de Molina et al., 2006; Báez et al., 2022). Skipjack and yellowfin tuna rank among the top five most harvested fish species globally, with catches in 2020 weighing 2827 and 1569 thousand metric tons respectively (Báez et al., 2023). The European long-distance fishery fleet, which focuses on capturing tuna and tuna-like species from the Indian Ocean, recorded total landings of 303,638 tons of targeted tuna and tuna-like species in 2021 (Báez et al., 2023). The Spanish tuna purse seine fleet operating in the Indian Ocean plays a significant role in tropical tuna fisheries as it is

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responsible for approximately 26 % of catches of skipjack and yellowfin tuna in this ocean, which represents around 3 % of the global catch for both species (Báez et al., 2023).

In the tropical tuna purse seine fishery, the fishing method employed has historically consisted of two primary approaches: sets targeting free-swimming schools (where large yellowfin tuna individuals dominate the catches); and sets targeting schools associated with Fish Aggregating Devices or FADs (which gather mixed schools predominantly composed of skipjack tuna, small yellowfin, and bigeye tuna). Free-school fishing involves identifying schools of fish swimming freely by observing surface indicators in the ocean and other signals like the presence of sea birds (Báez et al., 2020). In the Indian Ocean, tropical tuna purse seine fisheries setting on free-schools results in the lowest levels of non-target species, while catching more than 80 % of the highest value yellowfin tuna and bigeye tunas. In contrast, sets on FAD-schools result in almost five times the amount of non-target species, with skipjack constituting almost 70 % of the target catch (Ardill et al., 2011, Báez et al., 2019). Currently, most of the sets made by the Spanish fleet involve the use of FADs rather than on free-schools, with FAD sets constituting more than 80 % of total sets in recent years (2012–2018 period) (Fonteneau et al., 2000, 2013; Báez et al., 2020, 2022).

Fishing on FADs is not a new trend for the purse seine fleet. Since the mid-80 s, floating objects such as bamboo poles and net panels have been utilized to attract concentrations of tuna schools (Pallarés et al., 1995; Bannerman, 2001; Morón et al., 2001; Báez et al., 2020). In 2007, the first Spanish fleet vessels in the Indian Ocean began to use FADs with echo-sounders (López et al., 2014). These FADs are deployed by the vessels and geolocated using satellite buoys, which are equipped with echo-sounders that can roughly estimate the amount of fish aggregated beneath them (López et al., 2014; Mannocci et al., 2021). The use of these devices has been widespread since the turn of the century (Dagorn et al., 2013; López et al., 2014; Gilman et al., 2017).

Due to the variable amount of time they spend at sea, FADs aggregate not only targeted tropical tuna but also a variety of other organisms, including different fish species and protected species from sensitive groups that should be released alive whenever possible (FAO, 2011; IOTC Resolution 19/05). Groups of sensitive species (sharks, rays and manta rays, billfishes and sea turtles), commonly referred to as ETP species (Endangered, Threatened, or Protected species under local, national, or international legislation), are required to be returned to the sea as soon as possible from the vessel to minimise accidental mortality (IOTC Resolution 12/04; IOTC Resolution 17/05; Delgado de Molina et al., 2006; Garcia, Herrera, 2018). With the exception of species that are prohibited from retention, consumption, or trade through domestic legislation and international obligations, other non-target species that are incidentally caught by the purse seiners such as dolphinfish (*Coryphaena* spp.), rainbow runner (*Elagatis bipinnulata*) or wahoo (*Acanthocybium solandri*), are required to be retained on-board and then landed at port (IOTC Resolution 19/05). Sometimes, the number of interactions with species, whether they belong to sensitive groups or not, is too high, or the individuals are too small to be detected, particularly for large sets. As a result, a fraction of them accidentally goes directly to the wells, where they are stored along with the main catch. According to Lewison et al. (2014), this incidental capture of non-target or unwanted marine organisms during fishing operations targeting particular species, can be defined as bycatch (Lewison et al., 2014).

To mitigate fisheries impacts on ETP species, it is essential to have accurate bycatch estimates from scientific entities, on-board observation programs, port sampling protocols, and statements from Electronic Onboard Logbooks (Ardill et al., 2011; Gilman et al., 2017; Suuronen and Gilman, 2020; Juan-Jordá et al., 2022; IOTC Resolution 22/04). The monitoring of the purse seine fishery by the Regional Fisheries Management Organizations (RFMOs) involves adapting to new strategies, improving both the scientific estimates of the exploited species and the knowledge of the fishery's impact on the ecosystem, which can help strengthen the management and sustainability of fisheries resources (IATTC Recommendation C-12-10–10, (n.d.); ICCAT Recommendation 16–01, (n.d.)).

Regulation methods for fishing activities in the Indian Ocean include the implementation of port sampling scientific protocols that monitor the landing of purse seine catches (IOTC Resolution 22/04). Most of the landings of the Spanish fleet take place in the Seychelles (Ardill et al., 2011; Báez et al., 2020). The port monitoring carried out by the Spanish Sampling Team in Seychelles focuses on scientific sampling of tropical tunas as the target species (Pallarès and Petit, 1998; Pianet et al., 2000; Duparc et al., 2018). Since January 2021, the scientific sampling has included ETP and other bycatch species that have ended up in the wells of the vessels (Pérez San Juan et al., 2021). The most common bycatch species found in the wells are the triggerfish (*Canthidermis maculata*), the rainbow runner (*Elagatis bipinnulata*), and the scads (*Decapterus spp.*) (Pérez San Juan et al., 2021). One of the species that Pérez San Juan et al. (2021) found to have escaped the release techniques carried out by the vessels, is the silky shark (*Cacharhinus falciformis*, also known by its FAO Code, FAL), which is the most common species of shark found (Pérez San Juan et al., 2021). This correlates with findings by Amandé et al. (2008), who, through observer data, found that the main family of sharks caught by purse seine tuna vessels is the Carcharhinidae family, with catches representing 97 % of cartilaginous fish. In this group, *Carcharhinus falciformis* and *Carcharhinus longimanus* stand out, representing 94 % of the individuals (Amandé et al., 2008). Subsequently, Gilman (2011) noted that the silky shark is the most common shark species that appears in the tuna purse seine fishery, comprising up to 90 % of shark catches (Gilman, 2011). More recent studies carried out in the European purse seine fleet in the Indian Ocean (Ruiz et al., 2018) indicate that sharks represent around 15 % of total bycatch, with the silky shark being the most abundant species, representing over 80 % of the weight in the fishing operations. Poisson et al. (2014), carried out a study on French vessels in which they observed that the mortality rate of silky sharks in purse seine fishing is 81 %, reaching 85 % for individuals brought on-board in nets (Poisson et al., 2014). However, Onandia et al. (2021) point out that this high mortality has decreased in recent years to 43.17–43.88 % (estimated mortality and mortality according to the lactate level threshold, respectively). Survival can reach 80 % in the first stages of fishing activity, although it can fall to 25 % in the third brail and continues to decrease as the fishing operation progresses. According to Onandia et al., (2021), the differences in survival rates may be due to the time between the capture and the release, as well as the biological characteristics of the shark. The reduction in mortality is largely attributed to the regulations for the protection of ETP species and the implementation of the Code of Good Practices adopted by the two Spanish vessel-owner associations: OPAGAC (Organization of Associated Producers of Large Freezer Tuna Vessels) and ANABAC (National Association of Vessel Owners Freezer Tuna Vessels). This code, which includes a 100 % level of observer coverage, incorporates measures to develop more sustainable and responsible fisheries, especially regarding FADs (Fishing Aggregating Devices). This Code establishes technical guidelines for FAD designs and the release of incidental catches, including sharks. It requires crew to use all available means to release sharks as quickly and carefully as possible, resulting in an increase in survival rates (Good Practices for Responsible Tuna Purse-Seining, 2020).

The silky shark has moved from the "Low Risk" category on the IUCN Red List of threatened species in 2000 to "Near Threatened" in 2009 and to "Vulnerable" in 2017 (Rigby et al., 2021). In less than two decades the populations have declined significantly, mostly due to fishing for the Asian market (Dulvy et al., 2008), with incidental bycatch in fisheries also playing a smaller role (Wosnick et al., 2022).

The primary aim of this study is to understand the origin of these ETP specimens found in the wells. We have tested two contrasting hypotheses: i) these individuals belong to a size class prone to underreporting or not being observed, and ii) these individuals are a fraction of bycatch from varying size classes that accidentally ended up in the wells.

Distinguishing between these hypotheses is crucial because accurately estimating the volume of bycatch per species is essential for understanding the magnitude of the problem.

2. Material and methods

We used two sets of data: on-board and port sampling data. First, we analysed data collected on-board by human observers and then cross-validated these with the pool of port sampling data. The port sampling protocol, which focuses on non-target species, has been developed and implemented since January 2021 during Spanish-flagged purse seiner vessel landings in Victoria port.

2.1. Observer data

The European Union establishes a collaborative framework for the collection, management, and utilization of data in the fisheries sector, as well as the support for scientific advice regarding the Common Fisheries Policy (CFP) (Regulation (EU) 2017/1004). Coordinated by the Spanish Fisheries Secretariat (SGP), a long-term data collection program (National Data Basic Program, PNDB) is being implemented in collaboration with various research centres: Spanish Institute of Oceanography (IEO. CSIC), Technological, Fisheries and Food Institute (AZTI-Tecnalia Foundation), and Marine Research Institute (IIM-CSIC) of Vigo (https://www.mapa.gob.es/es/pesca/temas/proteccion-recursos-pesqueros/programa-nacional-datos-basicos/).

The General Fisheries Secretariat has been designated as the national coordinator for the exchange of information between the Commission, end users, and the relevant National Organisations (Parliament and Council Regulation (EU) 2017/1004). The data used in this study was collected by the National Basic Data Program carried out by the Spanish Institute of Oceanography under the European Data Collection Framework (DCF). The data was collected by Spanish scientific observers who reported each set with its corresponding catch and associated discard and bycatch, if any.

The observed trips usually correspond to a trip of the tuna purse seiner, which is the period of time elapsed from the departure from port to the arrival at port with either a complete or partial load that is later unloaded. On occasions, and due to varying situations, the unloading may not happen during the observer's trip, so having a significant duration of ship activities of at least 20 days is required.

We employ professional observers who receive specific and standardized training within the European Union, independent of the crews and vessels. To avoid any influence from the crew and ensure unbiased data collection, observers are assigned to different vessels for each deployment. According to Forget et al. (2021), there is a tendency for observers to systematically underestimate sharks when there are more than ten caught in the fishing operation.

For this study, data from all sets observed by Spanish observers between January 2021 and December 2022 were considered.

2.2. Port sampling data

To provide estimates of the species composition and national catches of tropical tunas by European French and Spanish-flagged vessels fishing in the Atlantic and Indian Oceans, a catch correction system called T3 (Tropical Tuna Treatment) has been implemented since the 1990s. Due to the mixture of target species (*Thunnus albacares*, *Thunnus obesus*, and *Katsuwonus pelamis*) and the high volume of catches, this system, based on standardized port sampling, is designed to avoid biases in catch reporting (Pallarès and Hallier, 1997; Pallarès and Petit, 1998; Lechauve, 1999; Pianet et al., 2000; Duparc et al., 2018; Báez et al., 2022). T3 generates an adjustment or correction of the catches based on the extrapolation of the spatio-temporal sampling to the observed catches (Pallarès and Hallier, 1997; Pallarès and Petit, 1998; Lechauve, 1999; Pianet et al., 2000; Duparc et al., 2018).

The tuna port sampling begins with the arrival of the vessel in port. The documents of the trip are requested by the sampling team coordinator. These documents include the fishing logbook and the wells plan. The appropriate wells to work with during unloading in port are selected following the sampling protocol. Wells from a single set are prioritized. If they do not exist, the choice of wells is determined by the set type (they must be the same: free or FAD-schools), by the date (there must not be sets from more than 15 days apart in the same well) and by the geographical area (there must be no more than 5º difference in latitude and longitude between sets) (Bach et al., 2018; Duparc et al., 2018).

In 2021, a specific sampling protocol for the bycatch observed in wells was implemented starting from the first day of January (Pérez San Juan et al., 2021), in order to collect all the available information on the incidental species detected in the wells during the tropical tuna sampling. Following this protocol, the species composition of the bycatch in the wells was identified and length parameters were collected. The wells sampled during the landing were randomly selected, since it did not follow a specific a criterion from the sampling team but rather depended on the vessel's landing plan, which was based on the commercial needs of the company. Generally, the landing is complete. With this we avoid bias on the part of the sampling team. All the species are identified along with their well of origin, and then allocated to a spatio-temporal stratum. The total length (TL) of each silky shark was measured to the nearest centimetre and the sex of each individual was also noted for all cartilaginous fish (sharks and rays). The weights used in this study were obtained using the size-weight relationships for silky sharks obtained from fishbase.org (Froese et al., 2014).

2.3. Statistical analysis

From the pool of bycatch data collected in port from 2021 to 2022 ($n = 511$), the samples of individuals caught during trips observed on-board were selected (in total $n = 306$ matching samplings). The first step was to apply the non-parametric Mann-Whitney U Test to compare the sample means of the mean sizes of the specimens measured on-board by the observers with the sizes of the silky sharks measured in the wells, to check for any size selection (Nachar, 2008).

The possible random effect of observing at least one silky shark in a particular well during sampling (dependent variable) was analyzed by considering the following independent variables: total catch of the fishing operation (abbreviated as "catch"), the well with its corresponding weight (abbreviated as "weight"), the number of silky sharks observed on-board in the fishing operation (abbreviated as "sharks observed"), the number of silky sharks estimated by the scientific observer during the fishing operation (abbreviated as "sharks estimated") and the total estimated discards of the fishing operation (abbreviated as "discard").

A logistic binary stepwise forward/backward regression was performed to test the probability of observing at least one individual of silky shark in wells in relation to the independent variables considered.

Model coefficients were assessed by means of an Omnibus test and the goodness-of-fit between expected and observed proportions of bycatch events along ten classes of probability values and evaluated using the Hosmer and Lemeshow test (which also follows a Chi-square distribution; low p-0.05 would indicate lack of fit of the model) (Hosmer and Lemeshow, 2000). The Omnibus test examines whether there are significant differences between the $-2LL$ (less than twice the natural logarithm of the likelihood) of the initial step, and the $-2LL$ of the model, using a Chi-squared test with one degree of freedom. We used the Hosmer and Lemeshow test, which is a statistical test for goodness of fit and calibration for logistic regression models. The Hosmer and Lemeshow test compares the observed and expected frequencies of each value of the binomial variable according to their probabilities (Hosmer and Lemeshow, 2000).

In addition, the discrimination capacity of the model (tradeoff between sensitivity and specificity) was evaluated with the Receiving

Operating Characteristic (ROC) curve. Furthermore, the area under the ROC curve (AUC) provides a scalar value representing the expected discrimination capacity of the model. The relative importance of each variable within the model was assessed using the Wald test (Hosmer and Lemeshow, 2000).

A General Linear Model was used to account for the fact that the quantities of sharks sampled at port are closely related to the total quantities of skipjack caught in each fishing set, as skipjack is the most abundantly captured species by the Spanish Fleet (Zuur et al., 2013).

3. Results

A total of 1002 silky sharks were observed in port sampling during 2021 and 2022. These were measured (to the total length) and sexed in the wells of Spanish tuna vessels. The weight was obtained by using the size-weight relationships for silky shark available in fishbase.org (Froese et al., 2014). The comparisons between sizes and weights for all silky sharks sampled at the port can be seen in Fig. 1. Out of all the sharks sampled, 50.9 % were male and 48.8 % were female. Only three individuals were not sexed (0.3 %). The size and sex ratio of the sharks sampled in port was taken throughout the sampling period, implying that the sexual ratio varied over time. However, a deeper look into the distribution of sex ratios shows that the ratio of males and females is similar, even when there are differences in the abundance in port sampling by quarter (Fig. 2). This may indicate that small sharks group together, but further analysis should be considered.

Because all wells included in the well plan include the associated geographic positions of every fishing operation, we can plot the position of every silky shark captured by the fleet in this period on a map. Fig. 3 shows the position of the 550 silky sharks captured and all the fishing operations in 2021 and Fig. 4 shows the same analysis of the 325 silky sharks recorded in 2022. The analysis did not include the 127 silky sharks whose origin could not be determined because they were found in various parts of the fishing deck and could not be associated with any well (the record of sharks recorded according to the type of the fishing operation can be seen in).Table 2

We observed significant differences between the mean size of silky sharks measured by observers (mean 113.92 cm) versus those found in the wells (mean 85.74 cm), Mann-Whitney U= 1012,000; No.=242; P<0.001.

A statistically significant logistic model was applied to determine the probability of observing at least one individual of silky shark in particular wells during the sampling, according to the logit function (Fig. 5):

Logit: y= -3.575+ Catch*0.215+ Wells*-0.175

The model's goodness of fit was significant according to the Omnibus test (Omnibus test = 153.792; df = 2; P < 0.001).

Hosmer and Lemeshow test = 2.413 (df = 8, P = 0.966), and its discrimination capacity was outstanding (AUC = 0.99).

We explored the Spearman correlation between the variables (catch, well, sharks observed, sharks estimated, and discard), and the probability of observing silky sharks undetected in the wells, and we observed that there is a negative relationship between estimated and observed silky sharks, with catch (Table 1).

Out of the total sampled sets with silky sharks present, only 19 sharks came from free-school sets, in contrast with the 782 that came from FAD sets. 74 silky sharks appeared in mixed sets with a combination of free-school and FAD sets, so we cannot categorically determine the type of set they originated from. The origin and therefore the type of set could not be established for the remaining 127 sets.

A Kruskal-Wallis Test reveals that there are significant differences (Chi-Square= 12.966; df= 2; P= 0.002) in the average sizes of silky sharks found in wells grouped by type of fishing operation; and in the estimated silky shark weight (Chi-Square vats = 7.075; df= 2; P= 0.029). Therefore, in the case of medium sizes of silky sharks, the average of the sizes observed in wells was (set out by fishing mode origin): FAD-school= 91.16 cm; free-schools = 129.49 cm; mixed and indeterminate= 91.5 cm.

The average weight of silky sharks observed in wells was (set out by fishing mode origin): FAD-school= 14 kg, free-school= 34 kg; mixed and indeterminate= 15.96 kg. Thus, the average size of the silky sharks and the weight in FAD-schools is lower than those found in free-schools.

In Table 2 the fishing operation that defines the well of origin of each shark sampled is displayed. The largest number of sharks appears in FAD-school sets, both in number and in total weight. However, the biggest sharks appear in free-school sets. The "unknown" group corresponds to those sharks for which the origin could not be associated with a well during landing in port and therefore it could not be associated with a geographical area or type of fishing operation, but the medium size and weight suggests that the origin is an FAD-school set. Another group titled "mixed and indeterminate" includes the samples found in wells filled with catch belonging to a mix of set types (free-schools and FAD-schools).

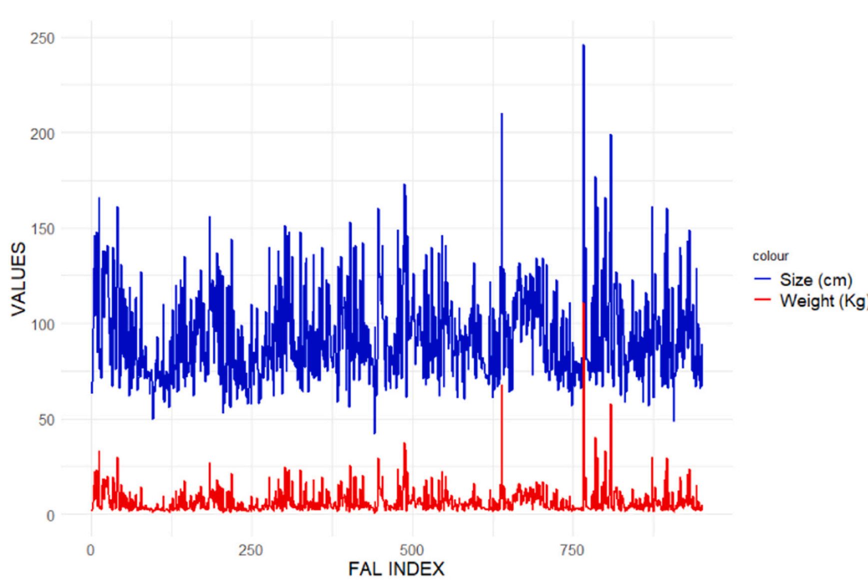

Fig. 1. Size and weight of silky sharks (FAL) sampled in port during the period of the present study.

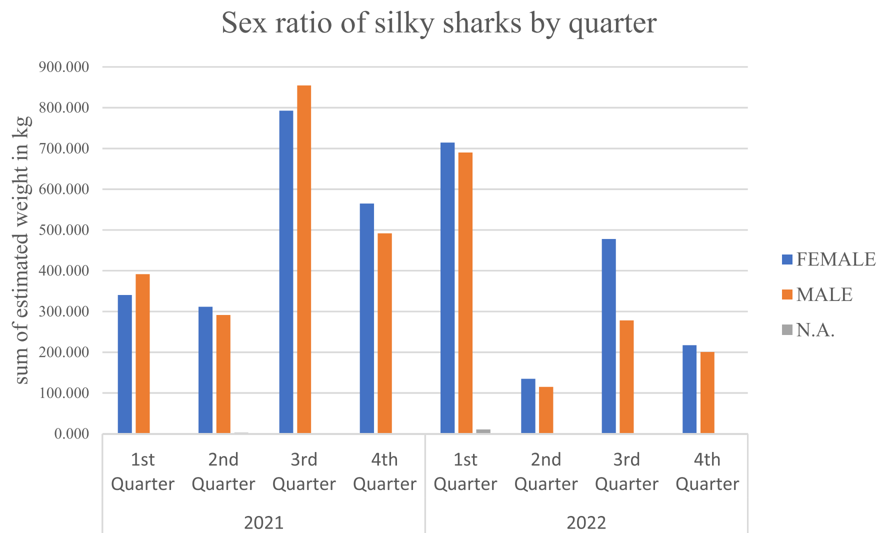

Fig. 2. Sex ratio of silky sharks sampled in port by quarter and year.

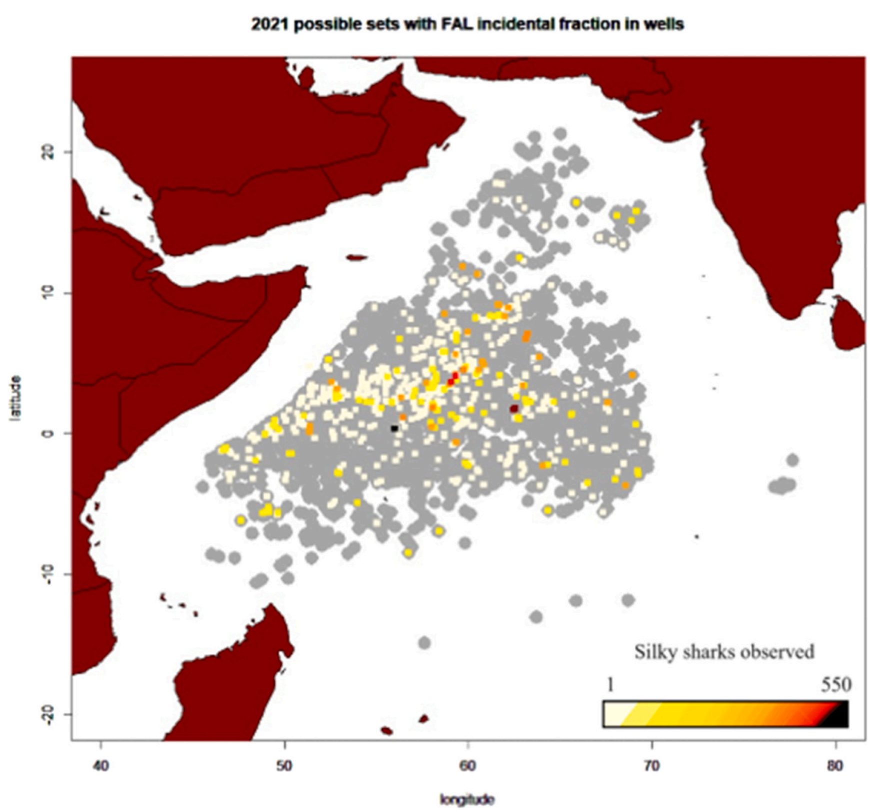

Fig. 3. Possible set locations with silky shark (FAL) captured (from light yellow to black) over the effort of the fleet in 2021 (in grey). Colors gradient range from 1 to 550 silky sharks by set.

Despite the fact that the analyses considered the number and weight of the sharks in each well, the total catch weight in the wells, the weight of the fishing sets in the well, and the quantity of skipjack, we cannot assume that there is a significant relationship between the amount of skipjack stored in the wells and the presence of silky sharks in the wells of the Spanish fleet. Therefore, we can assume that it is a phenomenon independent from the abundance of tropical tunas and cannot be extrapolated from the current data.

4. Discussion

Elasmobranches – a group of organisms exhibiting slow growth and late sexual maturity– are among the vertebrate species most threatened by different types of fisheries (Dulvy et al., 2021). According to recent estimates obtained from 1093 species of elasmobranches, 99.6 % (1082) are threatened by overfishing from industrial fisheries, primarily due to unintentional capture or bycatch. Overfishing is the main primary threat to the survival of 391 species, and it is the only threat to two-thirds of cartilaginous fish species (Dulvy et al., 2021). Despite the often inadequate availability of data regarding incidental catches, it is estimated

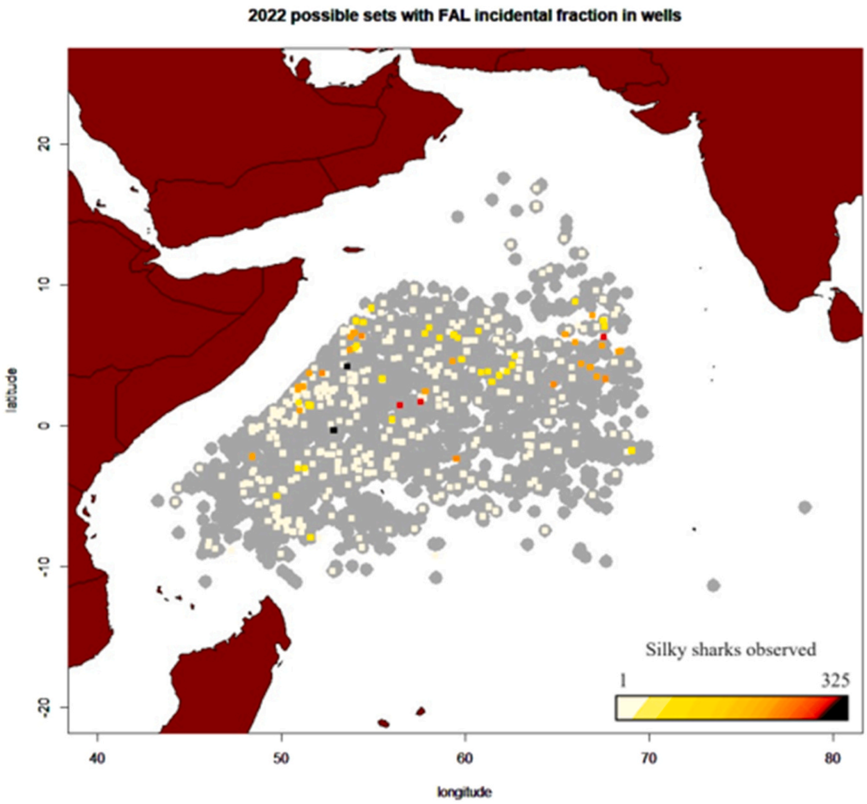

Fig. 4. Possible set locations with silky shark (FAL) captured (from light yellow to black) over the effort of the fleet in 2022 (in grey). Colors gradient range from 1 to 325 silky sharks by set.

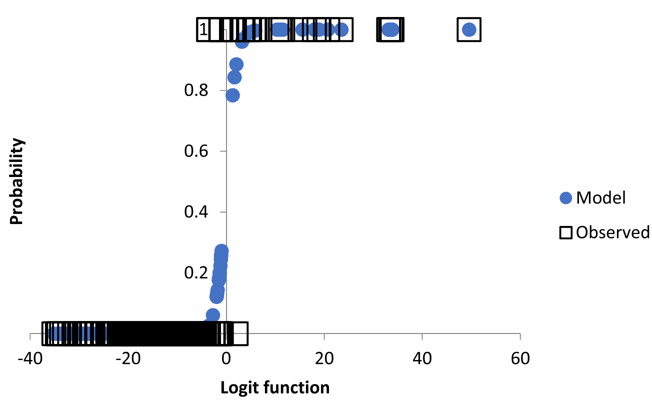

Fig. 5. The probability of the logistic function against the modelled logit function. Both observed presences and absences are indicated.

that approximately 50 % of all elasmobranch captures worldwide are attributed to bycatch (Wosnick et al., 2022).

The silky shark is the most encountered cartilaginous species in the tropical tuna purse seine fishery (Ruiz et al., 2018, Mannocci et al., 2020). Despite a reduction in mortality from 80 % (Poisson et al., 2014) to approximately 40 % (Onandia et al., 2021), this fishery is considered to have a lower impact on associated populations compared to other fisheries (Ardill et al., 2011).

Forget et al. (2021) highlighted that single observers placed on purse seiner vessels underestimate the number of captured sharks by 50–81 %, and these underestimates stem from the rapidity of the brailing process, which is crucial for swiftly transferring the catch from the net to the refrigerated holds in order to optimize fish quality. This speed of brailing impedes the thorough identification and enumeration of species and individuals in the refrigeration process, particularly given the substantial quantities involved (typically 4–6 tons per brailing). Because this operation typically occurs over both the upper and lower decks and observers are limited to being present on only one deck at any given time, they often rely on crew members dispersed throughout the vessel

Table 1
Spearman correlation obtained between the variables. Only significant correlations are indicated. Key: catch: catch of the fishing operation; well: the weight with its corresponding well; sharks observed: the number of silky sharks observed on-board during the fishing operation; sharks estimated: the number of silky sharks estimated by the scientific observer during the fishing operation, discard: total discard estimation of the fishing operation; Probability: the probability of binary logistic model, *P< 0001.

	Discard	Sharks Estimated	Catch	Wells	Sharks Observed	Probability
Discard	1					
Sharks Estimated	0.591*	1				
Catch	- 0.134	- 0.141	1			
Wells	NS	0.168*	0.431*	1		
Sharks Observed	0.941*	0.669*	-0.168*	NS	1	
Probability	-0.149	-0.272*	0.3403*	-0.602*	-0.168*	1

Table 2
Type of fishing set and catch of FAL (*Carcharhinus falciformis*) with size in centimeters and average weight in kilograms, as well as total weight caught by type of set, and taking the 95 % of confidence interval (p-value 0,05).

Type of set of each well	Number of FAL sampled	Mean size (cm)	Confidence interval. α = 0.05	Estimated mean weight (Kg)	Confidence interval. α = 0.05	Total weight (Kg)
FAD-school	782	92,549	±1.60	6635	±0,47	5189,199
Free-school	19	129,495	±13.87	19,131	±6.03	348,537
Unknown	127	90,215	±3.60	5967	±0.90	726,669
Mix free-school and FAD	74	98,770	±6.06	8328	±1.88	616,340
Total general	1002	93,253		6867		6880,745

to improve their assessments of bycatch (Forget et al., 2021). According to our results, there is a positive correlation between the magnitude of the catch and smaller-volume wells, resulting in an increased probability of encountering sharks during port landings. This suggests the existence of an elusive fraction of silky sharks that goes unnoticed by observers and crew members.

Therefore, our findings agree with previous studies such as Forget et al. (2021), and this study demonstrates the presence of an unreported catch component not observed that accidentally enters the wells during fishing operations, increasing the mortality rate of specimens in a way that could go undetected. According to the correlations obtained (see Table 1), there is a negative correlation between the probability of observing a silky shark in the well and the amount of discards. Thus, the higher the volume of discards observed, the more time the observer could be on the upper deck with no possibility of observing the silky sharks that enter the wells. There is a very high Spearman correlation between discard volume and the number of specimens observed in the well (0.941, $P < 0.001$). It is not statistically possible to estimate the fraction of FAL that accidentally enters the wells due to several reasons: 1) both the silky sharks observed in the well and the discards do not have a normal distribution, 2) the observations of silky sharks in wells accumulate a large number of zeros, and 3) it has not been possible to estimate the total weight of silky sharks in wells. During the period of 2021–2022, a minimum of 1002 individuals of silky shark were recorded in the wells. With 16 % of the fishing operations sampled (i.e., 1119 out of 7051 total sets in this period), this observation, if extrapolated to the entire fleet under the same mortality rate, corresponds to an estimated total of 6313 individuals for the Spanish fleet in the Indian Ocean during the 2021–2022 period.

Silky shark captures have been observed in both free-school and FAD-school sets. These captures cannot be clearly associated with any specific target species and are unrelated to the total volume of the catch or the total skipjack catch. Specimens found in free-school sets tend to be larger than those found in the FAD-school sets. In addition, the amount of silky sharks discarded on-board is different to the amount recorded by observers, with a smaller proportion being observed in port landings. While we cannot assume that free-school sets ending up in wells contain fewer silky shark individuals than other sets, we can infer that the average size and weight of silky sharks in free-school wells are significantly greater than those in wells from both FAD-schools and a combination of fishing sets. Silky sharks from free-school sets exhibit larger sizes compared to those from FAD-schools.

The silky shark is a species associated with warm pelagic waters, where they arrive as subadults from coastal regions and whose population is in significant decline (Rigby et al., 2021). According to Clarke et al. (2015), their size at birth varies between 65 and 81 centimeters. According to our study, 44.01 % of the port sampling bycatch data consists of silky sharks measuring 85 centimeters or less, and 67.47 % consists of individuals measuring 100 centimeters or less. This suggests that the recruitment of the population is affected to varying degrees by the mortality induced in an unreported fraction of the catch, which likely extends to the entire fleet of tropical tuna purse seiners. Given this premise, there is a need for more intensive studies on the rest of the tuna purse seine fleet, improved communication of catch data, and new evaluations of silky shark ecology. Because this study provides clear evidence of an unreported fraction of silky shark catches, being able to extrapolate and reconstruct the number of sharks in wells to estimate the unreported fraction is important for stock assessments.

Therefore, it is essential to recognize the potential bias inherent in larger sets, as smaller wells exhibit a higher likelihood of observing silky sharks. Consequently, new methods need to be developed to estimate this volume of misreported catches to mitigate the impact of the purse seine fishery on Indian Ocean silky shark populations.

Besides the data collected in port sampling, scientific observer data were essential to elaborate this document. Fisheries observer programs are the most reliable method for obtaining valuable data for the correct assessment of tuna stocks and bycatch as well as compliance with the conservation measures of each Regional Fisheries Management Organization. However, their coverage is limited, hence there is no continuous and reliable source of data. Furthermore, the efficiency of scientific observers is far from perfect due to the difficulty of a single person covering all fishing activities as some events can occur simultaneously in two different places, which can result in an underestimate of silky sharks caught (Briand et al., 2018; Suuronen and Gilman, 2020; Mannocci et al., 2020; Forget et al., 2021). Electronic Monitoring Systems (EMS) have been developed since the 2000's to support data collection observe everything that a single person cannot do and to support data collection in the purse seine fishery, occasionally replacing observers on vessels that cannot accommodate them (Briand et al., 2023). Despite the fast development of EMS, the data for discards of tuna and species with low commercial value appear to be well estimated by EMS when compared to on-board observers. However, for ETP species such as sharks or billfishes, EMS underestimates the presence and volume compared to data from scientific observers (Briand et al., 2018). These species can be handled in different areas on-boardof the vessels and the EMS has certain blind spots that do not allow a full view of the catch. Therefore, new approaches and adjustments must be applied to the placement of the cameras (Briand et al., 2018, 2023; Forget et al., 2021; Maufroy et al., 2023).

While developing a more effective approach for non-target species in observer programs and electronic monitoring, it is essential to create systems that improve population estimates of undetected species that end up in the wells and, if possible, minimize their occurrence. A good first step to reduce the mortality of sharks and other species stowed in the wells could be the installation of hoppers on tuna vessels, which is a tool that has been used for more than 20 years on some Spanish vessels in the Pacific Ocean It consists of a metal structure to deposit each brailing and that allows the selection of non-target species. With this system, sensitive species can quickly be thrown overboard by the crew from the fishing deck (Murua et al., 2021a, 2021b; Wosnick et al., 2022).

According to Ewel et al. (2020), only two RFMOs, WCPFC and IATTC, require full observer coverage on tropical purse seines, and none of the RFMOs require complete monitoring coverage at sea using EMS (Ewell et al., 2020). Based on these observations, and despite the significant advantage that EMS provides, we believe that that increasing the coverage of scientific observers on-board and working jointly with the EMS would be beneficial. This can help mitigate observer biases, ensuring the best quality data for the entire fishery.

We know that the implementation of this bycatch sampling system in other fleets could be complex since not all countries with tropical tuna purse seine have a port sampling system, nor is there representation in all oceans. This poses an obvious practical challenge to replicating this methodology, but given the ecological implications of this study for silky shark conservation, we believe it is an extremely important approach to open up a new way of estimating unreported mortality.

Ethical statement

No specific authorization was required for any of the activities undertaken during this work. The study was conducted using Spanish statistical of the fishery.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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