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Study of the migratory pattern and habitat of the silky shark (*Carchahinus falciformis*) in the Indian Ocean

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Echebastar Sustainability Working Group

Foreword

In 2018, the Echebastar purse seine fishery for skipjack in the Indian Ocean was certified against the MSC Standard for Sustainable Fishing. One of the components comprising the Standard relates to the impact of the fishery om ETP species. We did not meet the standard for PI 2.3.3 leading to a condition to certification being defined requiring demonstration “that information is adequate to measure trends and support a strategy to manage impacts on ETP species”. This condition did not refer to a specific ETP species, rather the need to have sufficient observer data. The work of the Echebastar Sustainability Group allowed this condition to be closed at the third annual audit in mid-2022, albeit after some delay due to various issues related to the COVID pandemic.

The main ETP species taken as a by catch by our vessels is silky shark. However, the number of these taken as a by catch is relatively low and does not hinder recovery of the species.

That being said, we remain strongly aware of our obligation to minimise the impact of our fishing activities on other elements of the ecosystem. In the past, this has led us to adopt a number of mitigation measures such as non-entangling FADs, reduced number of FADs, double conveyor belts on some of its fishing vessels and the application by the crews of good handling practises.

While these activities have proven to be sufficient to meet the MSC Standard, the our stated policy is to go beyond those requirements wherever possible and to further strengthen our sustainability credentials.

In relation to silky shark, a two-step approach was adopted.

- Firstly, to examine the post capture survival of silky shark released from our vessels.
- Secondly, to improve understanding of the migratory patterns and habitat of silkies in the expectation that this could lead to further mitigation measures.

We financed AZTI to complete research on the first issue (Onandia, I., Grande, M., Galaz, J.M., Uranga, J., Lezama-Ochoa, N., Murua, J., Ruiz, J., Arregui, I., Murua, H, Santiago J. 2021. New assessment on accidentally captured silky shark post-release survival in the Indian Ocean tuna purse seine fishery. IOTC-2021-WPEB(17(DP)-13_rev1. Available at:

file:///C:/Users/usuario/OneDrive/Escritorio/BUREAU%20VERITAS/ECHEBASTAR%20-2SA%202021/Info%20from%20Echebastar/AZTI%20report%20silky%20sharks%20to%20IOTC.pdf

We commissioned further independent research by AZTI, which is the subject of this report.

We will continue to support such work wheresoever possible.

The research would not have been possible without the support of a number entities: Marine Stewardship Council - Ocean Management Fund (MSC-OSF), AZTI, Basque and Spanish Government, ISSF, SIOTI and Bermeo Tuna World Capital.

CONTENTS

1. INTRODUCTION

The Echebastar Sustainability group has identified the need to improve knowledge of the biology of the silky shark (*Carcharhinus falciformis*) in the Indian Ocean in order to **consider** the mitigation measures already implemented and identify new options to reduce fishing mortality. Also, to provide scientific information to improve the management of this species in the Indian Ocean.

Due to increasing fishing pressure, the abundance of silky sharks has decreased markedly over the past half century (Pacoureau et al., 2020). A range of stock indicators have shown population declines in this species across all oceans (Aires da- Silva *et al.*, 2014; Clarke *et al.*, 2018; Ortiz de Urbina *et al.*, 2018). This species is listed as vulnerable in the IUCN Red List of Endangered Species. Additionally, in 2016 the species was included in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CoP17, Notification No. 2016/063). In the Indian Ocean, previous Ecological Risk Assessments (ERAs) identified the silky shark among the species most at risk of vulnerability to longline and purse seine nets (Murua et al., 2012; 2018).

A preliminary stock assessment was carried out in 2018 (Ortiz de Urbina et al., 2018), using a time series of reconstructed catches, but the results of the assessment were extremely uncertain and the status of the stock of silky sharks in the Indian Ocean is considered uncertain (IOTC, 2020).

Silky is the fourth most important shark species in the Indian Ocean tuna fisheries (23,000 tons caught per year, 10% of the total shark catches) (García and Herrera, 2018). Gillnet and longline are the main contributors to the catch of silky sharks (57% and 42%, respectively).

In contrast, the purse-seine tuna fishery is responsible for just 1.3% (García and Herrera, 2018) of that catch. Due to their aggregation behaviour around FADs and the overlap of juvenile silky shark habitat with the tropical tuna purse-seine fishery, the species is a common by-catch in dFAD sets being i the most important shark taken incidentally by tropical tuna seiners (Gilman 2011, García and Herrera, 2018; Ruiz et al., 2018).

In order to reduce shark mortality, EU and Seychelles purse-seine vessels have adopted best practices for the safe handling and release of **incidentally caught** sharks**.** (Poisson et al., 2014; Grande et al., 2019; Maufroy et al., 2020)**. T**o this end**,** some vessels have adapted the upper deck or lower deck by installing release devices (e.g. hoppers, catch release conveyor incidental).

Previous works estimated an overall survival rate of up to 19% for silkies taken on-board the purse seiners. If best release practices are combined with other mitigation measures, both active and passive (i.e., use of non-entanglement FADs, implementation of fishing strategies to avoid bycatch such as avoiding sets on small schools; releasing sharks from the net), shark mortality could be reduced by 60-65% (Restrepo et al., 2016, 2019).

To evaluate their effectiveness of th**o**se mitigation measures, and **identify** new measures that could reduce fishing mortality, it is necessary to expand knowledge about the biology of the species, and in particular study its behaviour, horizontal and vertical migrations and habitat. **A**nalysis of th**e** information **gained should** allow detection of windows (time and space) where the probability of capture is lower and **potentially** reduce **the** catch **of silkies** per set.

Due to the high cost of satellite archival POP-UP tags (e.g., $2,000-4,000 per tag), experiments on post-release behaviour and migration pattern of silky sharks are sparse and often unreported. They are based on small sample sizes.

To advance the implementation of mitigation measures, it is necessary to carry out **reserach** o**n** the behaviour of silky sharks**. T**agging **of individuals** with **the location of** MiniPATs **that provide** information that allows estimati**on of** daily position and depth, **and** the evaluation of **the** movements. of individuals.

The information collected will be useful to analyse in detail the horizontal and vertical migrations of the silky shark. In addition, the data obtained from the tagging are necessary to validate the habitat models or to construct new models**.** . In this way, it will be possible to evaluate the overlap of the fishing activity with the distribution of the silky shark and **identify potential additional** measures that reducing **tuna purse seine related** fishing mortality **of the** species.

Accordingly, this study aims to investigate the behaviour and migratory pattern (horizontal and vertical migrations), carry out a study of the habitat, and evaluate post-release survival.

2. OVERVIEW

2.1 CATCHES AND STOCK STATUS IN THE INDIAN OCEAN

Prior to the early 1970s information on the fisheries was scarce. Both unrecorded, recorded but not reported shark catches, and lack of species-specific statistics were common for most of the fleets in the region. In general, reported catch is considered an underestimation and uncertainties exist due to issues regarding lack of reporting to species level (Murua et al. 2013; IOTC, 2022).

A catch reconstruction exercise (Coelho et al., 2018) showed how before the mid-1980s there were very few reported catches of silky shark. Subsequently, there was a rapid increase in reported and reconstructed catches (Fig. 1).

While the estimated time series indicated that catches continued to increase until the mid-2000s, there was a peak in reported catches in the 1990s followed by an abrupt decrease. Between 2005 and 2015 the reported and estimated catch levels are very different, which suggests a huge underreporting (Fig. 1) (Coelho et al., 2018).

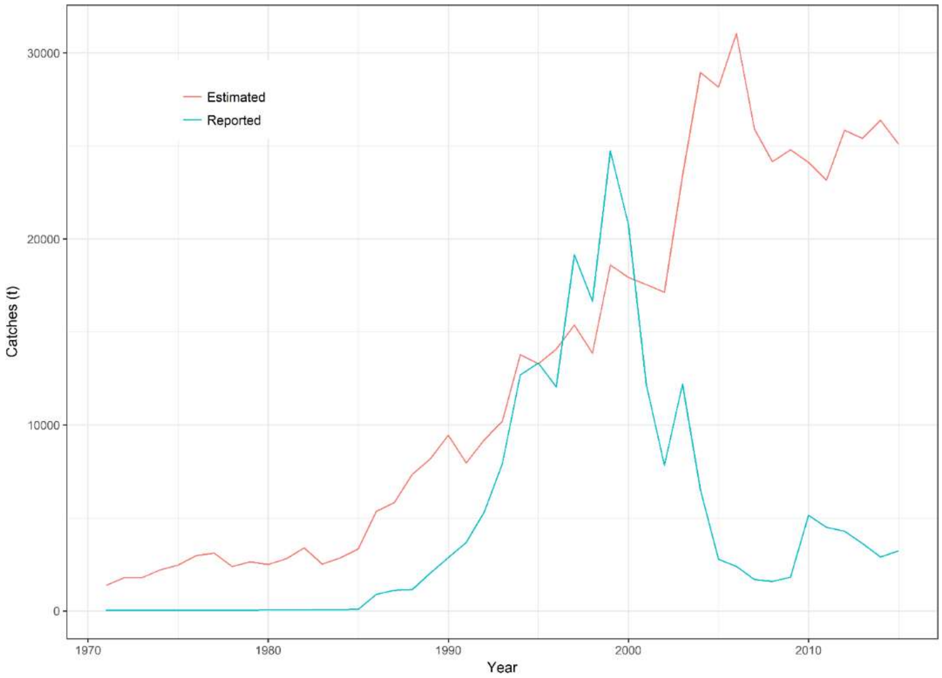

FIGURE 1. TIME SERIES OF REPORTED AND ESTIMATED SILKY SHARK CATCHES, BETWEEN 1971 AND 2015, FOR THE INDIAN OCEAN (*FROM COELHO ET AL., 2018*)

Silky shark is one of the shark species caught in the Indian Ocean (Murua et al., 2013; Coelho et al., 2018). They are targeted by artisanal small-scale fisheries and taken as a bycatch in industrial fisheries (longline and purse seiners). Catches are mainly made by gillnets and longlines(Herath 2012, IOTC, 2022). The purse-seine fishery is responsible for 1.3% of the total (García and Herrera, 2018). This species is the main type of shark in the bycatch of purse seiners (more than 95% of the sharks accidentally caught), being mainly caught in FAD sets due to the aggregation behaviour of the species around FADs (Filmalter et al., 2011; Filmalter et al., 2015; Ruiz et al., 2018).

Due to the increasing fishing pressure, silky shark abundance, as with other pelagic sharks, has markedly decreased during the last half century (Herath & Maldeniya, 2013; Pacoureau et al., 2020). This species is currently listed as vulnerable by the IUCN Red List of Endangered Species[1]. In the Indian Ocean the Ecological Risk Assessments (ERAs) identified silky sharks among the species with higher vulnerability risk for longline and purse seine (Murua et al., 2012; 2018).

A preliminary stock assessment indicated that the population status of silky sharks in the Indian Ocean is uncertain (Ortiz de Urbina, 2018; IOTC, 2022; Cramp et al. 2021). Nevertheless, it was

[1] https://www.iucnredlist.org/ja/species/39370/117721799

suggested that maintaining or increasing fishing likely to lead to declines in biomass, productivity and CPUE in the Indian Ocean (Coelho et al., 2018).

2.2 LIFE HISTORY TRAITS

Although information on life history traits is available for this species worldwide, in the Indian Ocean the studies directed to explore growth and reproductive traits are not numerous and limited in spatial scope (Table 1). The species has slow growth and low fecundity, making it vulnerable to high fishing pressure.

2.1 HABITAT AND MOVEMENTS

The silky shark is a circumglobally distributed, tropical and subtropical species (Rabehagasoa, et al. 2012). It is essentially pelagic species, distribute from slopes to open ocean (IOTC, 2019), from the surface (18 m) down to at least 500 m depth (Compagno, 1984). Adults and older juveniles of this species are found in deep waters just off continental and insular shelves but also commonly in open-ocean waters (Clarke et al., 2015).

Stable isotope analysis performed on muscle tissues revealed that silky sharks have a more inshore foraging habitat (Rabehagasoa, et al. 2012). Smaller specimens are typically found in coastal waters (IOTC, 2019). But juveniles are also found in open oceans, associated with tuna schools and principally with FADs (Filmalter et al., 2015; Hutchinson et al., 2019). High fidelity of adults associated with seamounts, and juveniles with floating objects has been described, moving off at night and returning at sunrise (Filmalter et al., 2015; Ebert et al., 2016; Curnick et al., 2021). Although long-distance movements have been reported for large-body specimens (i.e. from Chagos to Kenya) (Curnick et al., 2021), tagging studies described more limited movements (Clarke et al., 2015) or aggregation behaviours around FADs (Filmalter et al., 2011; Filmalter et al., 2015).

The silky shark undertakes diel vertical migrations spending more than the 90% of the time above the 100 m depths, which overlaps with purse seiners and longline fisheries area, with immersions of more than 300 meters (Curnick et al., 2021).

TABLE 1: LIFE HISTORY INFORMATION OF SILKY SHARK (CARCHARHINUS FALCIFORMIS) FOR FEMALES (F); MALES (M) OR BOTH SEXES COMBINED (C) IN THE INDIAN, ATLANTIC OR PACIFIC OCEAN (IO, AO OR PO, RESPECTIVELY). RND: ROUND WEIGHT; DWT: DRESSED OF CARCASS WEIGHT; TL: TOTAL LENGTH; FL: FORK LENGTH; PCL: PRECAUDAL LENGTH L50: SIZE AT WHICH THE 50% OF THE POPULATION IS MATURE

Reference	Ocean	Linf (cm)	K (yr^{-1})	t0 (yr) or Lo (cm)	W-L Conversion	Longevity (yr)	Maturity (cm and yr)	Fecundity (n)	Sex ratio (F:M)
Ariz, et al. 2007	IO				RND = $6{,}51 \times 10^{-6}$ $TL^{2{,}99}$ RND = $4{,}72 \times 10^{-6}$ $FL^{3{,}18}$ DWT = $5{,}66 \times 10^{-6}$ $TL^{2{,}89}$ DWT = $1{,}30 \times 10^{-5} FL^{2{,}83}$				
Galván-Tirado et al. 2015)	PO						180 (M, L50) 190 (F, L50)	2-14	0.81:1
García-Cortéset al. (2012)	IO				DWT = $1.1 \times 10^{-5}(FL)^{2.915}$				
Grant et al., 2018	PO	261.3	0.14	82.7 cm		23 (M) 28 (F)	183 (L50) / 11.6 yr (M) 204 (L50) / 14 yr (F)	3-13	
Hall et al. (2012)	IO	299.4	0.066	-5,12		20 (M) 19 (F)	207.6 (L50 / 13 yr. (M) 215.6 (L50) / 15 yr.(F)	2-14	1:01
Joung et al. (2008)	IO	332.0	0.0838	−2.761	W = 2.92×10^{-6} $TL^{3.15}$	28.6 (M) 35.8 (F)	212.5 (L50 / 9.3 yr. (M) 210–220 (L50) / 9.2–10.2 yr.(F)		
Romanov and Romanova (2009)	IO				TW = $(0.160 \times 10^{-4}) * FL^{2.92}$				
Stevens, 1984	IO						239 (M) 216 (F)		
Varghese, et al., 2016	IO	309.80	0.10	-2.398			217.0 (M, LT50) 226.5 LT (F, LT50)	3-13	1:0.83

There is almost no information about the stock structure of silky sharks worldwide (Bonfil, 2008). In the Indian Ocean, its population structure is unknown, but a single stock may be assumed (Coelho et al., 2019). However, recent genetic studies on mitochondrial DNA showed that despite its large population size, silky sharks in the Indian Ocean appear to be isolated on relatively small spatial scales, showing certain genetic differentiation between sampled regions (Clarke et al., 2015).

Understanding horizontal movement patterns of pelagic animals is important for developing spatial management and conservation measures. Information of horizontal movements of silky shark in the Indian Ocean is scarce. In recent years, two different works have studied migrations with tagged sharks in the Seychelles area (Filmalter et al., 2021) and in Chagos (Curnick et al., 2020). In previous works where silky sharks were tagged in the Seychelles region, the majority of the large-scale movements were initially westward and along the coast north and southward once the sharks reached waters off the African continental coast. Only two individuals travelled in an easterly direction with movements centred around the 5◦S latitude.

2.2 MITIGATION MEASURES IN THE IOTC

In the IOTC area there is a battery of measures to reduce shark mortality allied with data collection requirements to evaluate their catch and bycatch levels (Table 2). In addition, an MPA in Chagos seems to be beneficial for the silky sharks considering their high fidelity to seamounts (Curnick et al., 2021).

3. MATERIAL AND METHODS

3.1 FIELDWORK

Two samplings were conducted in the Indian Ocean to tag sharks and recover information on their biological traits and physiological indicators. The first trip was conducted in a purse seiner of ECHEBASTAR (Fig 2). It lasted from 29th of September to 17th of October of 2021. Additionally, data obtained from a previous tagging campaign in an ECHEBASTAR purse seiner, conducted from 22nd of October to the 23rd of November 2020, were integrated in this project.

TABLE 2: MANAGEMENT AND MITIGATION MEASURES FOR SHARKS IN THE INDIAN OCEAN

Mitigation measure	Description
Res 05/05	Sets out a scientific and management framework on the conservation of sharks caught in association with IOTC managed fisheries. Includes data reporting requirements, full utilization of shark catches, 5% fin/ body ratio for retained catches, encouragement for management of live sharks, especially juveniles and pregnant females, and research implementation (gear selectivity, identification of shark nursery areas)
Res 12/09	Sets out a scientific and management framework on the conservation of Thresher sharks caught in association with IOTC managed fisheries. Includes prohibition of retention, encouragement for release of live sharks, data report requirements (target and incidental catches and live release), and research implementation (identification nursery areas).
Res 13/05	Sets out a scientific and management framework on the conservation of whale sharks (*Rhincodon typus*) caught in association with IOTC managed fisheries. Includes prohibition of intentional setting on whale shark, safe release of whale shark incidentally encircled and data reporting (encirclement and status of released individuals)
Res 13/06	Sets out a scientific and management framework on the conservation of oceanic whitetip sharks (*Carcharhinus longimanus*) caught in association with IOTC managed fisheries. Includes prohibition of retention, encouragement for research of live sharks, data report requirements (target and incidental catches and live release), and research implementation (identification nursery areas)
Res 15/02	Sets out the mandatory data reporting requirements for IOTC contracting and non-contracting parties, including total catch, catch and effort and size data.
Res 17/05	Sets out a scientific and management framework on the conservation of sharks caught in association with IOTC managed fisheries. Requires the full utilization of sharks, except for shark species prohibited by the IOTC, prohibit the removal of shark fins in fresh fish and having on board fins that correspond to more than 5% of the sharks catch if frozen, purchase and sale of fins is also prohibited. The shark release should be implemented on board for the unwanted catch.
Res 18/02	Sets out a scientific and management framework on the conservation of blue shark caught in association with IOTC managed fisheries. Requires the recording and reporting of blue shark catches. It also encourages to perform scientific Research in biological traits of blur shark.

FIGURE 2 PURSE SEINER VESSELS OF ECHEBASTAR COMPANY.

The survey area comprised the waters north of Seychelles up to 9ºN latitude and between longitudes 53ºE and 63ºE in the Western Indian Ocean.

In each interaction with *C. falciformis*, the following variables were recorded:

- Sex (female, male, indeterminate or unknown),
- Length (cm),
- Number of the brail in which the specimen was taken on board (1st, 2nd, 3rd brail and subsequent),
- Position in the brail (up, medium, bottom),Time when brailed on board and released,
- Mode of release:
    - Using the brailer,
    - Using light equipment such as stretcher, fabric, *sarria* or cargo net,
    - Using specific equipment such as a hopper or lateral doors,
    - Manually from deck,
    - After disentangling from hauling net;
- Vitality index, i.e., status of the animal at release based on the states proposed by Heuter and Manire (1994):
    - Excellent (very active and energetic, strong signs of life on deck and when returned to water);
    - Good (active and energetic, moderated signs of life on deck and when returned to water);
    - Correct (tired and sluggish, limited signs of life, moderate revival time required when returned to water, slow or atypical swimming away);
    - Poor (exhausted, no signs of life, bleeding from gills, jaw or cloaca, long revival time required when returned to water, limited or no swimming observed upon release);
    - Very poor or death: moribund, no signs of life, excess bleeding from gills, jaw or cloaca, unable to revive upon return to water, no swimming movement, sinks.
- Behavior after release (swim vigorously, swim slowly near the surface, sinks with little movement).

Also, for each interaction, the observer recorded if the handling and release practices applied followed the guidelines defined in the Code of Good Practices (Grande et al., 2019).

To evaluate the post -releasing survival, migratory pattern and habitat, sPAT and MiniPAT POP.UP tags were used (Wildlife Computers, Inc.) (Table 3).

TABLE 3. CHARACTERISTICS OF THE TAGS USED IN THE SAMPLING.

Tag Type	Description of the information provided and set-up
SPAT https://wildlifecomputers.com/our-tags/pop-up-satellite-tags-fish/spat/	Max and min daily temperature and depth. Last 4 days: High resolution data of depth (each 10 minutes). Pop-off: 60 days
MINIPAT https://wildlifecomputers.com/our-tags/pop-up-satellite-tags-fish/minipat/	High resolution records of depth (each 10 minutes) of Depth, temperature and light (position). Pop-off: 180 days

To evaluate the concentration of lactate levels, blood samples were taken from the caudal peduncle of silky sharks (Fig. 3) and measured "in situ" using a lactate meter[2] (Lactate plus).

FIGURE 3. BLOOD EXTRACTION IN A SILKY SHARK

[2] https://www.laktate.com/producto/lactate-plus/

3.2 HABITAT MODEL

The objective of constructing a habitat model is to identify the environmental preferences of this species; in order to identify the main areas of distribution of the silky shark in the Indian Ocean with the aim of mitigating the incidental capture of the species in the tuna fishery. The habitat model was developed using catch data for the period 2015 to 2021 as collected by observers on board ECHEBASTAR vessels.

Environmental data comes from GLORYS global ocean reanalysis models (https://www.mercator-ocean.eu/en/oce an-science/glorys/), at a resolution that allows for eddies identification (1/4°) that have as objective to describe the average and variable oceanic circulation state in time. Environmental data is available from 1993. . The following data have been extracted by i) set, position and date (both with presence and absence of silky shark) to adjust the model and ii) in the entire grid of the fishing area with the aim of predicting in areas with presence and absence of sets:

- Surface temperature (SST, ºC);
- Oxygen concentration at 200m (O2, mmol m-3);
- Chlorophyll on surface (CHL, log(mg m-3));
- Mixed layer depth (MLD, m);
- Sea surface anomaly (SLA, cm);
- Primary productivity of the first 200m (PP)
- Sea surface height (SSH, cm)

Prior to including all the variables in the model, a pre-selection is made, eliminating those that are correlated with each other. For this, three different tests have been used:

- Pearson (where it is considered that there is a correlation with r>0.6),
- Automatic VIF (Variance Inflation Factor) and
- Manual VIF (where the correlation is considered with VIF>5).

The variables SSH and CHL showed a strong correlation between them, and therefore they were not included in the model.

Different statistical approaches have been used to understand the dynamics and preferential areas of the silky shark in the Indian Ocean tuna fishing zone. Due to the nature of the data (they are data dependent on fishing and therefore affected by biases in effort, as well as by species aggregating objects), Generalized Additive Models (GAMs), Shaped Constrained Generalized Additive Models, have been considered. (SC-GAMs) and Boosted Regression Trees (BRTs). These are three of the most widely used models in this type of approach

3.3 VERTICAL MOVEMENTS

Both type of electronic tags used in the project (MiniPAT and sPAT) store light intensity, depth and temperature records every 3 second in their internal archival log. However, once they emerge to the surface, they only transmit a summary of the data recorded to ARGOS satellites (due battery issues), allowing work with a time resolution of 10 minutes in the case of MiniPATs and only giving the last 3 days of data in the case of sPATs. Therefore, the following vertical analysis was done with the summary data (every 10 minutes) of the MiniPATs.

Swimming depths were recorded by the tags at ten-minute intervals. For time at depths (tad) and time at temperature (tat) histograms, bins were place together for specific intervals:

- tad_breaks <- c(0, 2, 5, 10, 20, 50, 100, 200, 300, 400, 600, 1000)
- tat_breaks <- c(0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30,32.5,35)+

This was done on an individual basis and then the average values and standard deviations for each bin were calculated across all individuals.

In addition, data corresponding to moments in which the tags weren't attached to the animals (i.e. when the sharks died and sank to the bottom or when the tag was floating for several days) were discarded. Finally, to determine the sunrise-sunset and day-night periods the *classify_DayTime* function from *RchivalTag* R package was used.

3.4 HORIZONTAL MOVEMENTS

Most probable tracks were generated using the online software tool GPE3, provided by Wildlife Computers. This software uses a state-space modelling approach to generate time discrete and gridded probability surfaces throughout the deployment period based on light level data collected and transmitted by the tag. These 12-h likelihood surfaces are output at 12-h intervals and correspond to 50%, 9% and 95% location probabilities (Filmalter et al., 2021). Geolocation estimates are refined by matching recorded Surface temperatures and depths with sea surface temperature (NOAA OI SST V2 High Resolution) and bathymetrical (ETOPO1-Bedrock) databases within GPE3 (Filmalter et al., 2021). With regards to the animal speed selection for the tracks, after generating multiple tracks for each individual at 2 m/s, 2.5 m/s and 3m/s, an overall convergence of the three tracks was observed, being the 2.5 m/s one smoother than the others, and therefore, selected for track estimations.

Distance traveled by the sharks was determined by calculating the difference between successive locations of the estimated track, using *distm* function in R, from the *geosphere* package, with the *distGeo* method, that assumes an ellipsoidal Earth (WGS84 ellipsoid). For MiniPAT tags, *Total distance traveled (km)* represents the cumulative kilometers traveled by the shark, while for the sPATs the distance between deployment and pop-up locations, as we only dispose of these two locations.

3.5 POST-RELEASE SURVIVAL ANALYSIS

For each tagged shark a fate was given (dead or alive) based on the depth records transmitted by the sPATs or MiniPATs and the time elapsed from tagging to detachment date. Sharks were considered to survive the fishing operation if tags showed they remained alive ≥15 days.

In tagged specimens, differences in survival rate depending on vitality index categories were assessed by the Chi-square test. This analysis includes individuals that were not finally tagged due to their poor condition but were considered as dead. The percentage of survivorship by vitality index category was applied to predict survival for all sharks bycaught in the trip.

Moreover, for silky sharks tagged and blood sampled a Wilcoxon rank sum test was used to evaluate differences in lactate between survivors and dead sharks. This analysis also included dead individuals blood sampled but not tagged. A logistic regression model was done to relate survivorship (based on tagging) and lactate concentration estimated from blood samples. This logistic regression model and maximum likelihood estimation were used to predict the probability of survival for sharks with blood analysis taken but were not tagged (using as a survival threshold the 50% of probability of the survivorship curve) (Hutchinson et al., 2015). The fitted values were then used to predict survival rates by fishing operation stage and applied to predict survival for all the sharks captured during the fishing trip (Hutchinson et al., 2015).

4. RESULTS & DISCUSSION

4.1 TAGGED ANIMALS

A total of 28 sharks were tagged with POP-UP satellite archival tags (24 sPAT[3] and 4 MiniPATs[4]) in the first trip when 278 silky sharks were captured (101 - 188 cm) (Table 4). In the second trip 248 silky sharks were captured (97 - 198 cm) and 32 sharks were tagged (13 sPAT and 19 MiniPATs) (Wildlife Computers, Inc.) (Fig 4, Table 4).

TABLE 4 NUMBER OF SHARKS TAGGED, AND TYPE OF POP-UP TAGS USED BY TRIP

Trip	Start date	End date	nSPAT	nMINIPAT
1	22/10/2020	23/11/2020	24	4
2	29/09/2021	17/10/2021	13	19

[3] https://wildlifecomputers.com/our-tags/pop-up-satellite-tags-fish/spat/

[4] https://wildlifecomputers.com/our-tags/pop-up-satellite-tags-fish/minipat/

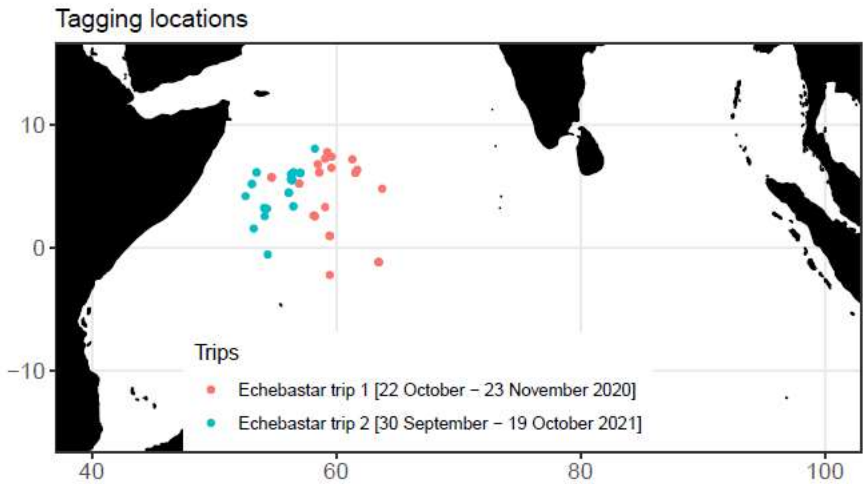

FIGURE 4. TAGGING LOCATIONS

4.2 HABITAT MODELS

4.2.1 Generalized Additive Models (Gams)

The first step to analyse the variables with the greatest impact on the data is to perform a univariate model with each of them. The results show that the selected variables are not capable of explaining a large part of the deviation (see table 5). We proceed to generate the model using the five environmental variables and, as a response variable, the presence and absence of sharks (binomial). The total explained deviation was very low (1.75%). The quality of the model is considered insufficient. It was decided to test another type of statistical approach to improve the model.

TABLE 5. DEVIATION EXPLAINED ON THE PRESENCE AND ABSENCE DATA OF THE SILKY SHARK BY ENVIRONMENTAL VARIABLES.

Variable	Desviación explicada (%)
SST	0.7
O2	0.6
MLD	0.1
SLA	0.1
PP	0.1

4.2.2 Shaped Constrained Generalized Additive Models (SC-GAMs)

In Shaped constrained GAM models, the shape is constrained to fit the niche theory defined by Hutchinson in 1957. This is widely used in habitat models for different species. They tend to be more restrictive than normal GAMs but make more ecological sense. In this case, the approximation has been tested, despite the fact that the GAM model gave poor results.

As expected, the SC-GAM presented the same problem as the GAM, being unable to adjust the data with the environmental variables and explaining only 1.8% of the deviation. The quality of the model was considered insufficient.. Another type of approach wass tested for constructing the model.

4.2.3 Boosted Regression Trees (BRTs)

This approximation can be understood as an additive regression model in which the individual terms are simple trees, fitted in a progressive and stepwise fashion. This type of model is capable of automatically dealing with interactions and correlated variables and tends to be more robust during fitting, although it tends to overestimate predictions. The model, adjusted to the environmental variables (i.e. SST, O2, MLD, SLA and PP), explains a deviation of 33.6%, much higher than the previous approximations. The response curves of the variables and the relative influence can be seen in Figure 5.

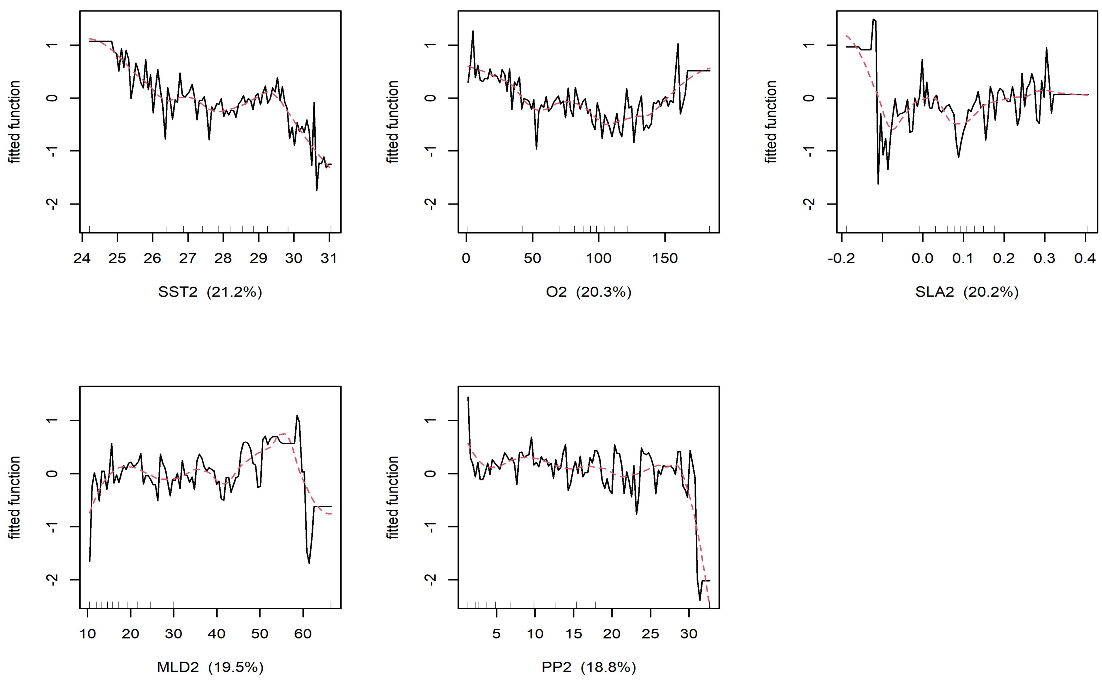

FIGURE 5: RELATIVE INFLUENCE (IN %) AND RESPONSE CURVES OF EACH OF THE ENVIRONMENTAL VARIABLES INTRODUCED IN THE MODEL

A cross-validation was performed to obtain indicators of the quality of the model (using 75% of the data to generate the model and 25% for validation). The results show a good fit of the model (see Table 6). The explained deviation varies between 0 and 100%, with 33% being a fairly high value when dealing with non-target species data that depend on sampling biases. The Area Under the Curve (AUC) is a threshold-independent measure of precision that measures the performance of ordinal scoring models. An AUC of 0.91 is a good result as it ranges from 0 (incorrect model) through 0.5 (random classification) to 1 (perfect discrimination). AUC values >0.8 are considered good to excellent. The True Skill Statistic (TSS) is a threshold-dependent accuracy measure whose values range from -1 (incorrect predictions) to +1 (correct predictions), with TSS scores > 0.6 considered useful to excellent.

TABLE 6: INDICATORS OF THE QUALITY OF THE MODEL CREATED WITH BRT.

Explained deviation (%)	**AUC**	**TSS**
33.6	0.9073567	0.6605456

Prediction of the probability of occurrence of the species has been carried out over the whole area with a monthly temporal resolution between 2015 and 2021. Figure 6 shows the average for the entire time series, with red being a higher probability of silky shark presence and therefore a higher probability of silky shark bycatch in the tuna target fishery if purse seiners operate in the area.

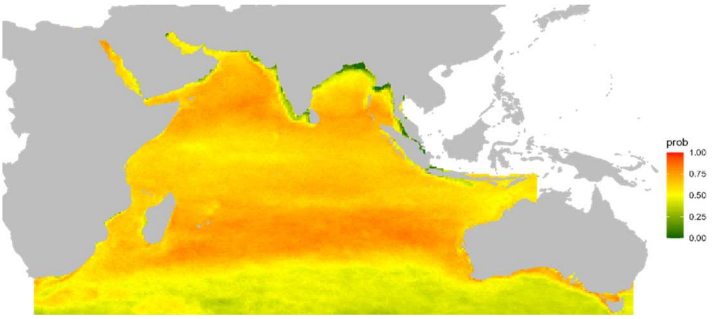

FIGURE 6: PREDICTED PROBABILITY OF SILKY SHARK OCCURRENCE IN THE INDIAN OCEAN. RED REPRESENTS A HIGHER PROBABILITY OF OCCURRENCE AND THEREFORE BYCATCH, WHILE GREEN REPRESENTS A LOWER PROBABILITY.

The probability of silky shark presence by season (monsoon and inter-monsoon) is also plotted (Figure 7).

The highest probability of occurrence is found in the northern part of the western Indian Ocean in front of Somalia and the Arabian Sea being the highest in the summer and winter monsoons, while in the spring inter-monsoon season it is the lowest.

Purse-seine activity expands seasonally to the northern area, mainly in winter-monsoon season and spring inter-monsoon, and this could be an area with high probability of occurrence. Indeed, the Arabian sea has been identified as a silky shark bycatch hotspot detected by habitat modelling which is in accordance with the results observed in this work (Mannocci et al., 2022).

On the other hand, there is a lower probability of occurrence along the equator in the western Indian Ocean, which is at its lowest during the spring inter-monsoon and winter monsoon. In southern latitudes east of Madagascar the probability of occurrence estimated is high during the winter and summer monsoon seasons and during autumn inter-monsoon

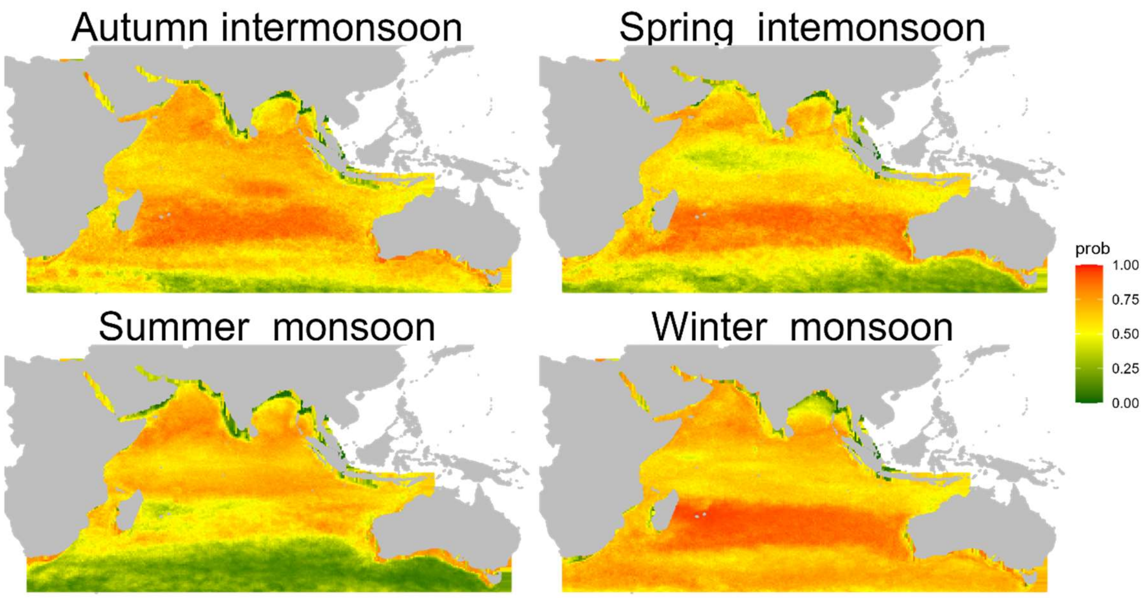

FIGURE 7: PROBABILITY OF SILKY SHARK OCCURRENCE IN THE INDIAN OCEAN AT DIFFERENT TIME PERIODS.

4.3 DAYS AFTER RELEASE

During the first trip, 7 sharks (25% of tagged sharks) showed mortality within the first 24 hours after release (depth of more than 1,700 m or constant depth for at least three days) attributed to post-release mortality events. One of the tags popped off prematurely after 9 days at sea for no apparent clear reason (i.e., due to the pin breaking or the tag becoming detached) but was considered as a death event based on the last horizontal and vertical behavior. Twenty tags remained attached for more than 15 days, i.e. surviving sharks (71.4%). All the tags attached have reported transmission (Fig 8).

During the second trip, 2 tags failed, and 8 tags (25% used in the trip with a correct functioning) popped off within the first 5 days after being released, indicating post-release mortality. The rest of the tags remained attached to the animals for more than 15 days (22 tags or 74% of the tags used in the trip with a correct functioning), indicative that the animals survive the fishing operation (Fig 8).

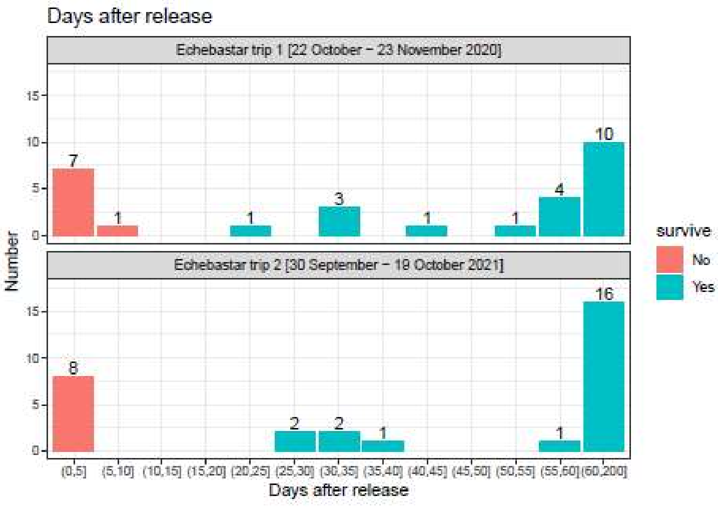

FIGURE 8 NUMBER OF SHARKS BY DAY RANGE AFTER RELEASE FOR EACH FISHING TRIP

4.4 VERTICAL MOVEMENTS

Vertical movements were obtained from 1,665 days from 18 MiniIPATS, from which the depth every 10 minutes was obtained. The summary of the vertical information by tag is shown in the Table 7. The maximum depth recorded was of 455.5 meters.

TABLE 7 MEAN DAILY DEPTHS AND MAX DEPTH BY TAGGED SHARK WITH MINIIPATS TAGS.

DeployID	Avg daily mean depth (m)	Avg daily median depth (m)	Max depth (m)	Avg daily Q25 depth (m)	Avg daily Q75 depth (m)	Days at liberty	Size (cm FL)	Sex
21P1137	44.77	43.01	426.0	26.87	59.85	180	193	Female
21P1135	43.98	43.01	455.5	26.98	59.19	180	169	Female
21P1143	37.10	36.44	425.5	21.83	50.06	179	183	Female
21P1136	35.22	32.58	419.0	20.40	47.69	180	198	Male
21P1144	33.96	31.42	442.0	18.84	45.39	179	140	Male
20P1875	30.85	30.61	134.5	22.48	39.12	60	160	Male
20P1874	30.33	28.13	321.5	18.43	40.37	85	180	Female
20P2101	27.13	27.42	195.5	19.17	34.00	83	164	Male
21P1140	25.42	21.25	233.0	12.88	35.19	7	190	Female
21P1133	24.79	24.97	161.0	13.59	33.17	28	144	Female
20P1828	23.17	22.83	359.0	14.50	30.79	111	137	Female
20P1370	22.29	13.46	190.5	6.89	35.86	9	124	Male
21P1148	21.60	20.40	213.0	12.32	29.25	108	113	Female
20P0916	19.34	18.70	192.0	11.89	25.81	71	134	Male
21P1145	19.07	17.96	134.5	11.87	24.98	38	154	Female
21P1139	17.65	16.45	381.5	9.92	23.95	180	104	Male
20P1366	15.74	12.34	202.0	6.09	22.93	109	110	Female
20P1831	14.76	13.42	107.0	6.90	20.90	26	102	Male

Sharks displayed very shallow depth distributions and spent more than 95% of the time in depths of less than 150 m (Fig 9.), and about 80% of the time in depths shallower than 50 m. The shallow depths are occupied during day and night-time. Occasional deep dives were observed. Previous research in the western Indian Ocean observed similar shallow behaviour (Filmalter et al., 2021). Water temperature ranged between 26 and 30ºC with a preference to temperatures from 28º to 30ºC. A peak in this range is also observed in the influence plots of the habitat model (see previous section).

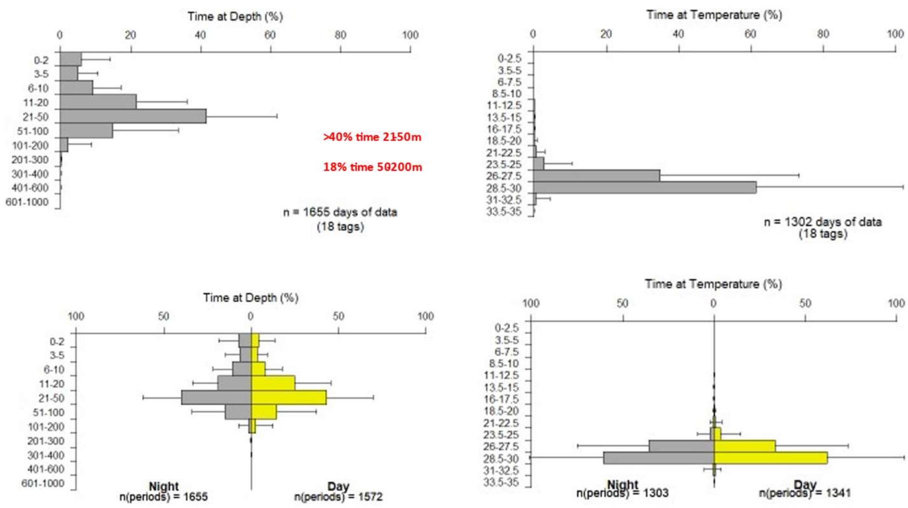

FIGURE 9 PERCENTAGE OF TIME AT DIFFERENT DEPTHS AND TEMPERATURE INTERVALS FOR SILKY SHARKS TAGGED WITH MINIPATS.

A clear pattern was not observed during day/night vertical behaviour. Some sharks remain in a more constant depth during daytime and show more immersion and larger vertical movements during night-time, and vice versa. Even changes in individual behaviour during the tracking period have been observed. In previous research in the Indian Ocean, sharks tended to be at a constant depth (> 25 meters depths) during daytime hours, with larger vertical excursions (from the surface to deeper layers) and deep dives being recorded during night-time, which could be related with foraging activity (Filmalter et al., 2015). Examples of this vertical behaviour were observed in tagged sharks in this reserach (Fig 10).

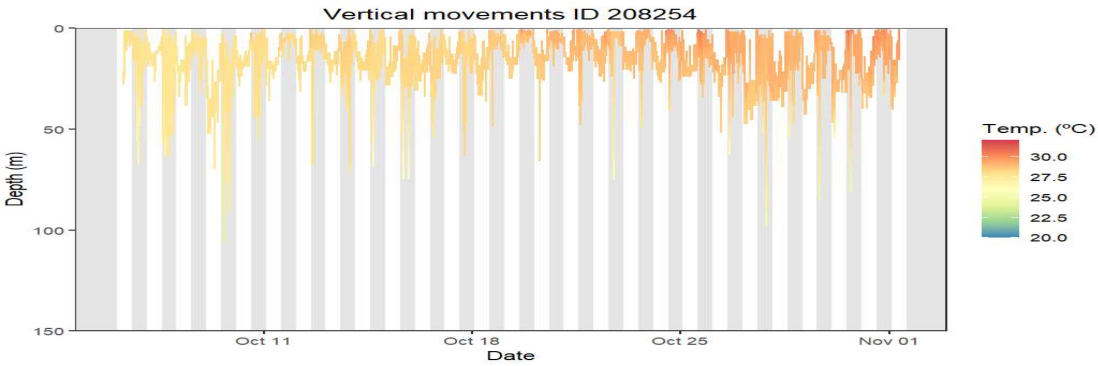

FIGURE 10 EXAMPLE OF A VERTICAL BEHAVIOUR

Other biological traits such as size and sex do not seem to be related to a specific vertical behaviour. Nor was there a clear relationship with position. Those following the coast tended to show a deeper night-time behaviour but this should be further explored, as this pattern has also been observed sharks in open ocean (Fig. 11). Previous work has found that oceanographic conditions and mainly prey availability could be linked with changes in vertical movements (Hutchinson et al., 2019),

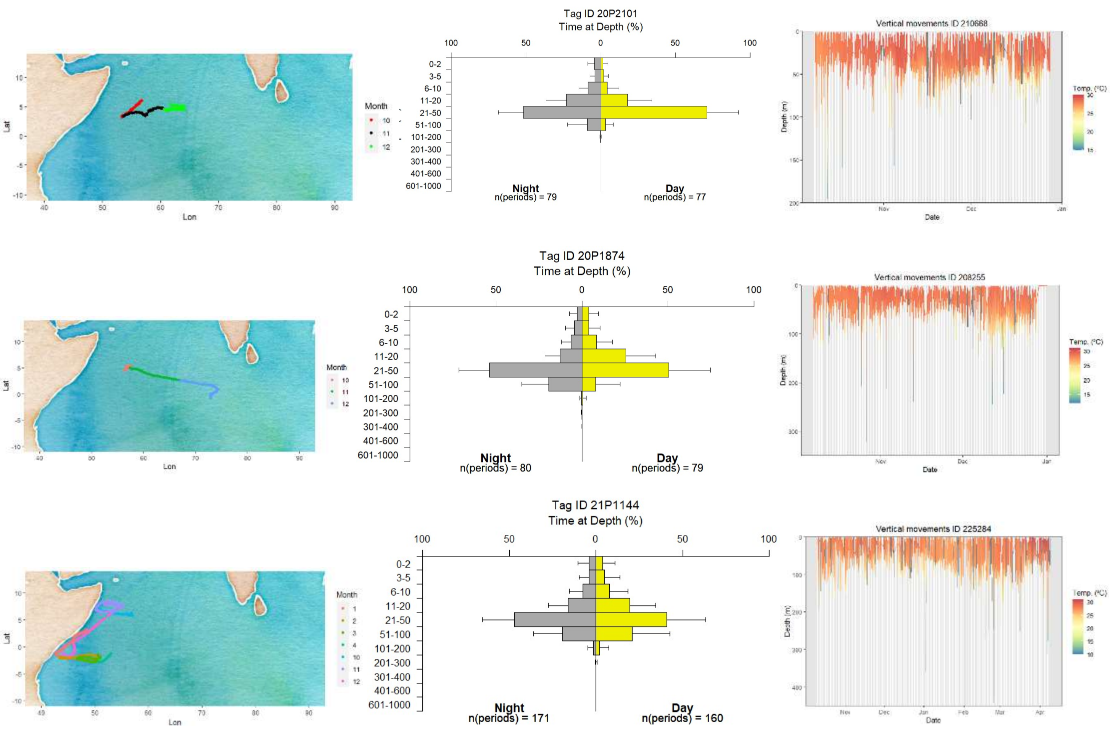

FIGURE 11 EXAMPLES OF THE VERTICAL BEHAVIOUR IN SHARKS MOVING IN OPEN OCEAN AND IN COASTAL REGIONS.

An understanding of the vertical behaviour of sharks can help in identifying alternative mitigation options e.g. gear modification or an adaption of the fishing strategy. The data obtained in this study confirms previous observations, and conclude that mortality reduction of this species would not derive from gear depth reduction, due to the shallow behaviour of the sharks (i.e. 80% of the time in less than 50 meters) and the overlap with tuna vertical behaviour (Forget et al., 2015). Nowadays, sets are typically made shallower than 150 m with the majority occurring between 60 and 70 m (IOTC, 2015).

4.5 HORIZONTAL MOVEMENTS

Horizontal movements were assessed using MiniPATS and sPATs. While MiniPATS provide high resolution data enabling the study of fine scale movements, sPAT provide the tagging and released position.

From the MiniPATS used, 5 sharks seem not to have survived the fishing operation with the released recorded from 0 to 9 days from tagging day. The minimum distance travelled was 616.87 km in 26 days with the maximum distance of 8,813 km in 180 days (mean of 4,123.10km).

In the case of SPATs (programmed to be detach in 60 days), the maximum displacement from the origin was 3,856.71 km (mean of 1,589 km).

Silky sharks have been observed to be highly mobile (Hutchinson et al., 2019; Schaefer et al., 2019; Filmalter et al., 2021), but shorter displacements and long residency has been also observed in seamounts and FADs (Filmalter et al., 2015; Hutchinson et al., 2019; Curnick et al., 2020).

The tracked distance observed in this study are the maximum recorded to date in the area and worldwide. The previous maximum was observed in sharks tagged in Chagos that travelled to Kenya with a tracked distance of 4,782 km (Curnick et al., 2020). This suggests a large distribution range of the species, even juveniles, in the Indian Ocean. The summary of the distance travelled and daily distance displacements by tagged sharks with MINI PATs and SPATs are shown in the Table 8 and 9, respectively.

TABLE 8 DISTANCE TRAVELLED AND DAYS AT LIBERTY OF SHARKS TAGGED WITH MINI PATS TAGS

DeployID	Total distance traveled (km)	Avg daily dist (km)	Sd (km)	Max daily dist (km)	Min daily dist (km)	Days at liberty	Size (cm FL)	Sex
21P1144	8,813.03	50.07	24.17	121.57	9.46	179	140	Male
21P1139	7,530.67	41.61	24.84	186.80	5.56	180	104	Male
21P1136	6,485.42	36.23	29.84	207.18	0.00	180	198	Male
21P1135	6,374.00	35.61	23.20	104.33	0.00	180	169	Female
21P1137	6,014.64	33.41	22.72	164.51	0.00	180	193	Female
20P1366	5,191.15	48.97	37.18	198.33	2.78	109	110	Female
21P1143	4,929.12	27.54	16.31	102.83	0.00	179	183	Female
21P1148	4,462.36	41.32	26.40	128.42	0.00	108	113	Female
20P1828	3,373.16	30.95	18.67	131.75	2.78	111	137	Female
20P1875	2,850.04	47.50	24.88	101.40	7.86	60	160	Male
20P1874	2,751.38	32.75	23.85	120.26	3.93	85	180	Female
20P2101	2,407.18	29.00	14.90	94.85	8.34	83	164	Male
20P0916	1,498.37	21.41	12.34	69.88	6.18	71	134	Male
21P1133	1,470.18	52.51	38.74	164.15	3.94	28	144	Female
21P1145	1,344.77	34.48	14.30	70.31	0.00	38	154	Female
20P1831	616.87	22.85	9.79	39.31	8.34	26	102	Male
21P1140	207.53	29.65	8.60	36.46	11.47	7	190	Female
20P1370	203.01	20.30	9.92	34.32	5.57	9	124	Male
21P1141	38.31	38.31		38.31	38.31	0	190	Male
20P0893	32.51	32.51		32.51	32.51	0	147	Female
21P0702	9.46	9.46		9.46	9.46	0	180	Male

TABLE 9 DISTANCE TRAVELLED AND DAYS AT LIBERTY OF SHARKS TAGGED WITH SPATS TAGS

DeployID	Total distance traveled (km)	Days at liberty	Size (cm FL)	Sex
21P0635	3856,71	61	140	Female
20P2077	3609,73	60	143	Male
20P1414	3595,27	60	119	Female
20P1411	3295,18	60	117	Female
20P1416	3125,59	60	139	Female
20P1412	3114,51	60	120	Female
20P1398	2203,8	44	166	Female
20P1400	2160,84	33	149	Male
20P1437	2151,25	60	134	Male
20P0061	1983	60	127	Male
20P1439	1737,02	60	153	Male
20P1407	1730,96	60	139	Female
20P1829	1690,97	60	130	Male
21P0632	1529,14	61	161	Male
20P1922	967,83	33	97	Female
20P1422	897,97	57	167	Male
20P1001	878,28	60	140	Female
21P0914	754,33	25	171	Female
20P0868	706,19	60	140	Male
20P1433	528,21	60	188	Female
20P1434	501,45	32	142	Male
20P1859	467,07	60	100	Male
20P2079	406,13	60	140	Female
20P0077	376,46	23	164	Female
20P0866	351,66	60	144	Female
20P1805	167,1	61	143	Male
20P1172	116,36	30	144	Female
20P2081	72,02	5	113	Male
20P1757	44,51	0	168	Female
20P1762	44,51	0	170	Female
20P2027	42,88	0	154	Male
20P1469	21,81	0	157	Female
20P1822	17,34	0	136	Male
20P1468	15,66	0	181	Male
20P1420	10,54	0	150	Male
20P1436	4,45	0	128	Male
20P0867	0	0	101	Male
20P1399	0	0	148	Female

No differences were observed on daily distance travelled between sexes. Those in smaller and larger size ranges recorded the highest daily distance travelled, indicating that the horizontal movements could not be dependent of the size. However, it should be considered that the size range is restricted to fish under 200 cm, mainly to juvenile fish (Fig 12).

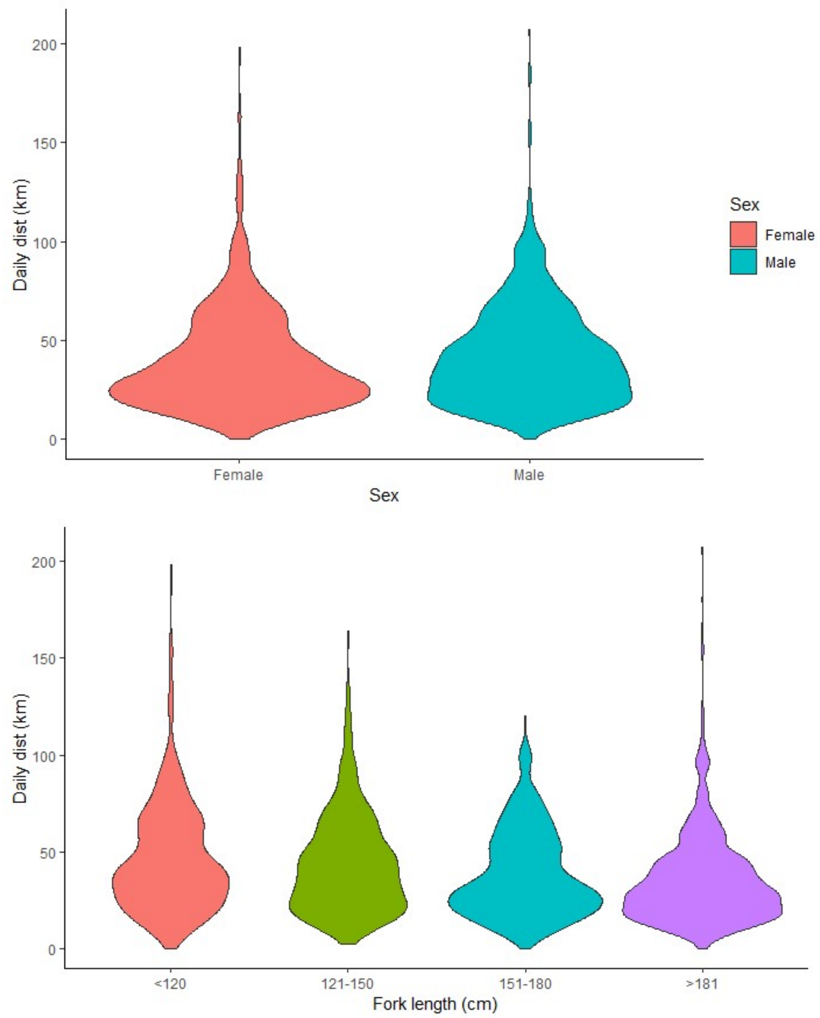

FIGURE 12 SUMMARY OF THE DISTANCE TRAVELLED BY SEX (UPPER PLOT) AND SIZE CLASS (LOWER PLOT).

Both, eastward and westward movement were identified from tags deployed in 2020 and 2021 (Fig 13-15). Nine sharks crossed Maldives or Chagos up to 95ºE. This happened in the initial two months following tagging (i.e. from October to December).

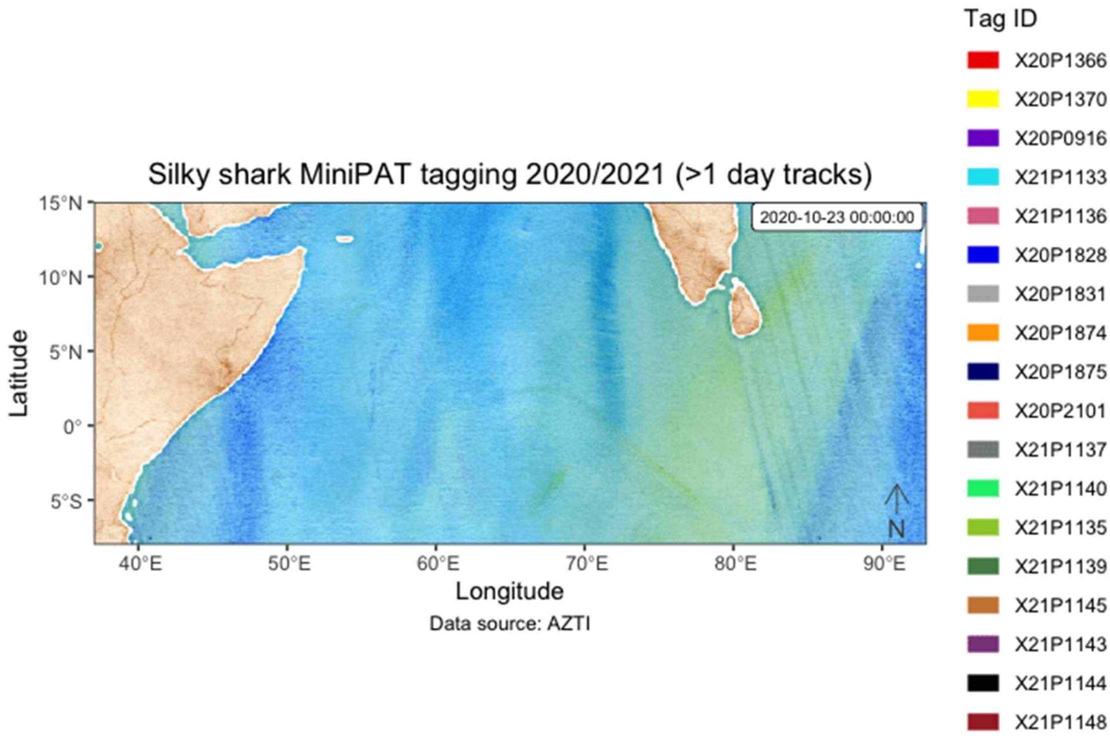

FIGURE 13 HORIZONAL MOVEMENTS OF SHARKS TAGGED WITH MINI PATS

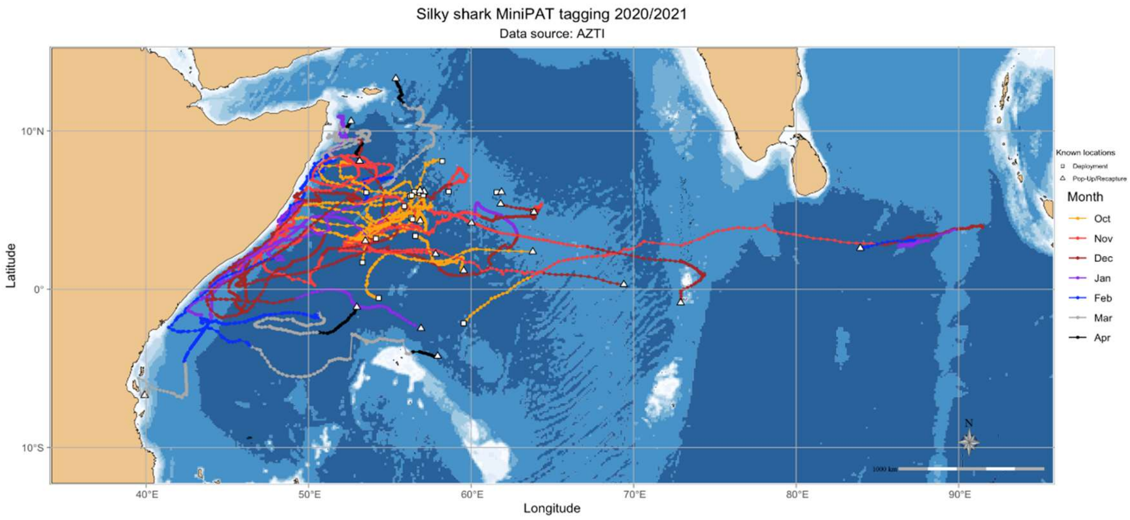

FIGURE 14 HORIZONAL MOVEMENTS OF SHARKS TAGGED WITH MINI PATS BY MONTH

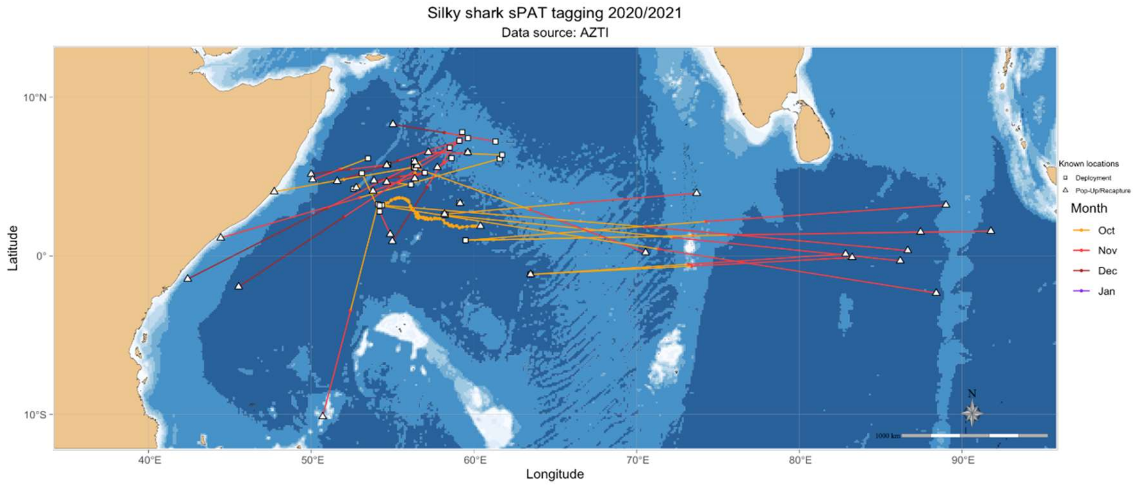

FIGURE 15 HORIZONAL MOVEMENTS OF SHARKS TAGGED WITH SPATS BY MONTH

This eastward movement was also registered by Filmalter et al (2021) in two individuals during Apil and May, from Seychelles to Chagos or Maldives. Also, a silky shark tagged in Chagos in May moved eastward 1,150 km to international waters. During 2020 and 2021 a strong eastward current was observed in the last quarter of the year. This eastward movement could be occurring in the intense periods of Equatorial Counter Current (ECC). Indeed, silky sharks has been observed to move with surface currents (Bonnin et al., 2020). This eastward movements in the area and same period, potentially propelled by the ECC, was also observed in whale sharks (Rowat and Gore, 2007).

Tagged sharks show also westward behaviour migrating southward along the African coast from about 5ºN to 2ºS. This was occurring from November to February, then with an eastward trend in the southern hemisphere from January to April. In addition, northward movements were also identified once sharks reached the coast and followed the coastline. Two showed circular displacement in November between about 5ºN to 10ºN and took south afterwards again following the coast. Other sharks travelled north following the coast from January to April to 15ºN.

Therefore, it seems that the silky sharks in the Indian Ocean are highly mobile, with divergent movements occupying a large oceanic area. They seem to be following main currents and mesoscale features.

Previous research showed that the majority of the large-scale movements were initially westward in the Indian ocean and then south and northwards once sharks reached waters off the African along the coastline (Filmalter et al., 2021). Although this tagging experiment took place in a different season, a similar pattern is observed , , in which southward and northward movement occur following the coast in the western Indian Ocean. As such EEZs in the western Indian Ocean could be passage areas on the north and south movements of silky sharks in the western Indian Ocean. Indeed, stable isotope analysis performed on muscle tissues in the area revealed that silky sharks have an inshore foraging habitat, detected by the high $\delta^{13}C$ values (Rabehagasoa, et al. 2012).

4.6 POST-RELEASE SURVIVAL BASED ON THE VITALITY INDEX

Significant differences were detected in survivorship among vitality index categories (p-value < 0.01). The percentage of tagged sharks that survived according to the vitality index was 100% for those released in excellent conditions, 90.9% for those in good conditions, 68% for sharks in correct condition, 33.3% for sharks in poor condition and 0% for very poor or dead condition (Fig. 16)

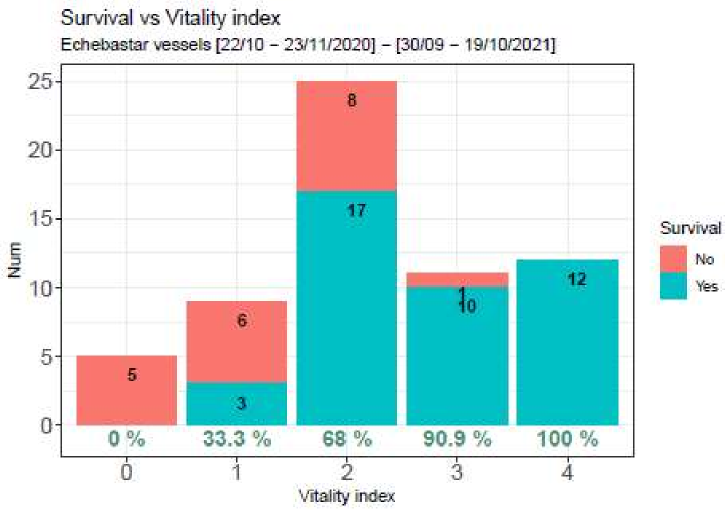

FIGURE 16 PERCENTAGE OF SURVIVORSHIP BY VITALITY INDEX.

Applying the survival rate by vitality index of the tagged individuals to the vitality scores determined by the observer in each of the trips, we predicted an overall survival rate of silky sharks accidentally captured of 38.13% in 2020 and 39.62% in 2021 (Table 10).

TABLE 10 NUMBER OF SHARKS AND SURVIVALS BY VITALITY INDEX STAGE AND BRAIL AND THE ESTIMATED SURVIVAL FOR EACH TRIP.

Zone	Dead (0)	Poor (1)	Fair (2)	Good (3)	Excellent (4)	Total	Estimated survival N	Estimated survival %
Tangled	0	2	8	15	16	41	**35**	87.17
1st_brail	12	12	27	12	0	63	**33**	52.81
2nd_brail	31	26	17	4	0	78	**23**	30.59
3rd_brail	66	21	9	0	0	96	**13**	13.67
(all)	109	61	61	31	16	278	**105**	38.13
Pred. survival (%)	*0*	*33.33*	*68*	*90.91*	*100*			
Survivors	**0**	**20**	**41**	**28**	**16**			

Zone	Dead (0)	Poor (1)	Fair (2)	Good (3)	Excellent (4)	Total	Estimated survival N	Estimated survival %
Tangled	0	2	1	6	7	16	**13**	86.25
1st_brail	7	19	38	10	3	77	**44**	57.48
2nd_brail	18	17	24	2	0	61	**23**	39.02
3rd_brail	49	41	4	0	0	94	**16**	17.44
(all)	74	79	67	18	10	248	**98**	39.62
Pred. survival (%)	*0*	*33.33*	*68*	*90.91*	*100*			
Survivors	**0**	**26**	**46**	**16**	**10**			

The post release survival study indicated that shark mortality is highly dependent on the landing stage at which the animals are handled and released (e.g., entangled in the net, 1st brail, posterior brails) and the state of the specimen at release. Other factors such as size of the set or shark length did not show a significant effect.

The influence of vitality index and brail number were also identified as main factors affecting post release survival in previous work (Poisson et al. 2014b, Hutchinson et al., 2015, Filmalter et al., 2015b, Eddy et al., 2016). However, maximum shark survival rates for purse-seiners were not greater than 20%.

The current research demonstrates that much higher survival rates can be obtained if best practices are applied and if fauna releasing devices such as bycatch-conveyor belt are implemented on-board. The strategy, followed by ECHEBASTAR, leads to almost 40% of overall silky shark post-release survival rates, which are the maximum survival rate estimates worldwide.

4.7 POST-RELEASE SURVIVAL BASED IN LACTATE LEVELS

Analysis of survival rates by lactate level intervals obtained from tagged individuals led to the cslculation of the survival probability curve shown in Figure 8. Assumed is a survival threshold at 7.6 mmol/L, concentration at which the probability of survival was estimated as p=0.5 from the survivorship curve (i.e., if [lactate] < 7.6 mmol/L then is considered "survivor" otherwise "non-survivor"). Based on this survival threshold, the percentage of survival was estimated by fishing operation stage and applied to all sharks in the two trips. The overall survival estimated using lactate level threshold was of 30.94% and 61.29% for the first and second trips, respectively (Fig 17 and Table 11).

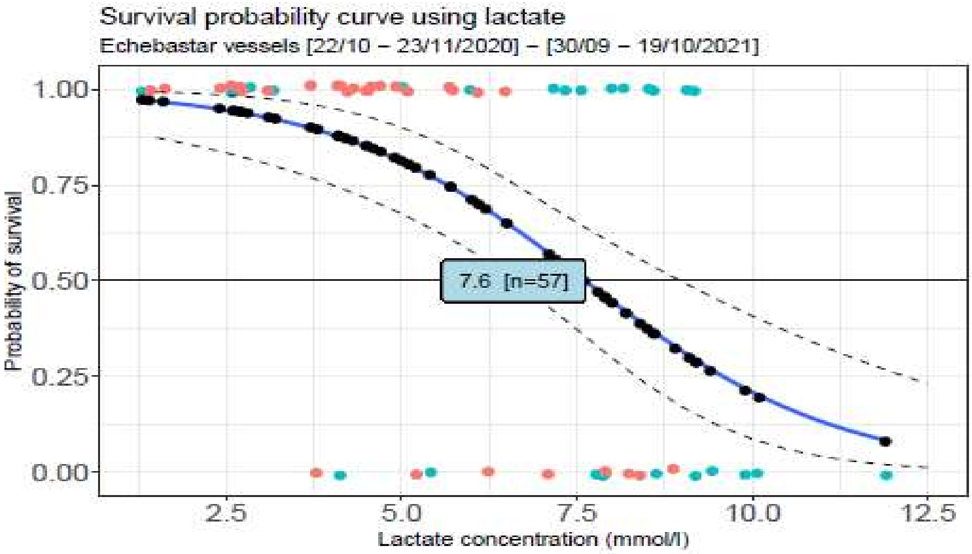

FIGURE 17 LOGISTIC REGRESSION MODEL FOR THE ESTIMATED PROPORTION OF SURVIVAL *C. FALCIFORMIS* AT LACTATE CONCENTRATION (LC) INTERVALS. RED AND BLUE POINTS ARE THE OBSERVATIONS OF SHARK WITH BLOOD SAMPLES THAT WERE RELEASED AND SURVIVED OR DIED. BLACK POINTS REPRESENT THE PREDICTED PROPORTION OF SURVIVAL SHARKS. THE SOLID BLUE LINE IS THE LOGISTIC REGRESSION CURVE.

TABLE 11 NUMBER OF SHARKS FOR WHICH THE LACTATE WAS MEASURED BY BRAIL AND THE PREDICTED SURVIVAL FOR EACH FISHING TRIP WITH A LACTATE LEVEL THRESHOLD OF < 7.61.

Post-release survival of juvenile silky sharks

	Lactate<7.6	N measured	Pred. survival (%)	Total	Survivors
Tangled	10	15	66.67	41	27
1st brail	4	14	28.57	63	18
2nd brail	3	8	37.50	78	29
3rd brail	1	8	12.50	96	12
(all)	18	45	30.94	278	86

	Lactate<7.6	N measured	Pred. survival (%)	Total	Survivors
Tangled	17	17	100.00	16	16
1st brail	21	26	80.77	77	62
2nd brail	11	14	78.57	61	48
3rd brail	6	22	27.27	94	26
(all)	55	79	61.29	248	152

The high overall survival rate estimated from lactate levels in the second trip is likely due to the selection of sharks that tend in a better condition (Fig 18). The second trip had the objective of exploring movements and habitat of sharks and hence the selection of individuals in better shape. Indeed, significant differences were observed between sharks by trip in a given vitality stage (Fig. 18).

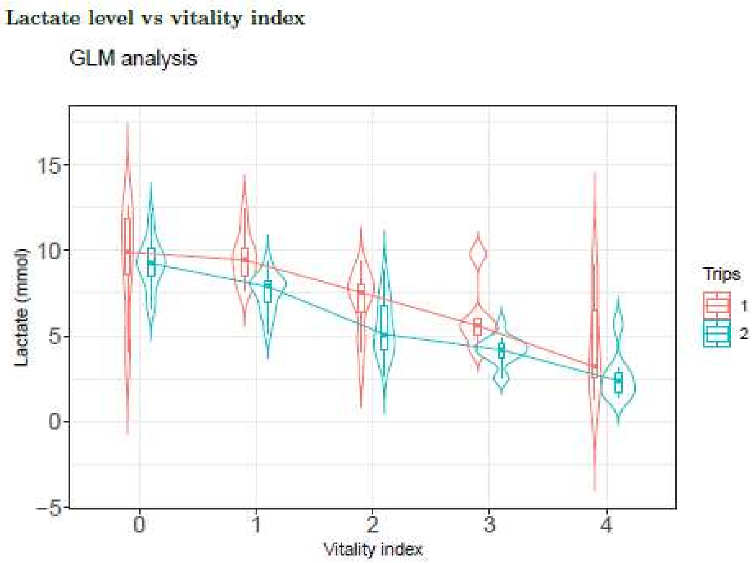

FIGURE 18 MEAN LACTATE LEVELS BY VITALITY LEVELS AND TRIP.

This figure (Fig. 18) also shows that vitality index is a good indicator of the physiological stage of the sharks, as significant differences are observed in lactate levels among vitality indexes, increasing in lactate concentration with the reduction of shark vitality.

5. CONCLUSIONS

Post-release survival rate of sharks released from purse seiners, in which best handling and release practices are implemented, is estimated by satellite POP-UP archival tagging and lactate blood levels. When the the vitality index stage was applied to predict survivorships for all sharks, a 38.13% and 39.62% survival was estimated for sharks caught and released during the first and second trips, respectively. When lactate level threshold was used to predict survival rates, the outcome was 30.94% and 61.29% of overall survival in the first and second trips, respectively.

Due to the objectives of the project (that is, monitoring the migratory patterns and habitat of sharks), sampling of lactate during the second trip was biased towards individuals in a better condition, more suitable for the application of satellite tags from which daily geolocation is obtained. Therefore, the overall survival rate derived from lactate level should be considered as an overestimate in the case of the second trip.

As observed in previous works on tuna purse seiners, post-release mortality is at its lowest when sharks are in good shape and when they are swimming in the net. Mortality starts to increase from the moment the sac is formed and with the number of brails which concomitantly decreases the vitality index.

In this study the at-vessel mortality observed was lower and overall shark survivorship higher than the ratios estimated previously (i.e., previous works in purse seiners estimated a maximum of 19% of post-release survival). The difference could be explained by the fishing operation itself and the time elapsed from the catch to release (which can be influenced for example by set size, brail size or environmental conditions) or shark biological characteristics (e.g. size, age). But mainly, the experience gained by the crew over time since the application of best releasing practices several years ago and the adaptation of the deck by the installation of the bycatch release conveyor belt could have a positive influence to reduce atvessel mortality.

These findings demonstrate that if best handling and release practices are applied and fauna handling/release devices are incorporated on-board, a significant increase in post-release survival of sharks could be obtained on tuna purse seiners. Indeed, the survival rates obtained in this study are the maximums observed worldwide in purse seiners (close to 40% of overall survival). Therefore, it is a valuable mitigation strategy to reduce shark mortality.

The data obtained from the tagging campaigns has also allowed description of the vertical and horizontal movements.

The silky shark has been observed to be mainly occupying the shallower layers (>80% up to 50 meters and >90% of the time up to 100 meters depths) during day and night-time. There is not a clear day-night pattern in vertical behaviour. In some sharks or during an elapse time during the tracking period, sharks remain at a more constant depth during daytime and show more immersion and larger vertical movements during night-time with deeper excursions observed.

However, an inverse pattern has also been identified. Deeper night-time behaviour seems to be more common in coastal regions. However, this assumption should be further explored as the deeper night-time behaviour has been also observed in open ocean.

Differences could be linked with oceanographic conditions and prey availability. The data obtained in this study confirm previous observations, and lead to the conclude that lower mortality of this species cannot come from gear depth reduction, due to the shallow behaviour of sharks (i.e. 80% of the time in less than 50 meters) and the overlap with tuna vertical behaviour (Forget et al., 2015).

The horizontal migrations of silky shark in the Indian Ocean are highly unknown. Horizontal movements registered in this study demonstrated that juvenile silky sharks are highly mobile occupying a large oceanic region. Easterly (to 95º E) and westerly movements (to African eastern coast) have been identified in sharks tagged from October to November north of Seychelles.

These movements could be linked to main currents. Eastward movements for instance were occurring when ECC flowed easterly. The open water movements in the western Indian ocean occur in the operational area of the purse seine fishery. When tagged sharks reached the African coast northward and southward movements have been detected along the coastline. Therefore, these sharks are also highly vulnerable to more coastal fisheries occurring in the area.

Habitat models show that hotspots could be occurring in the northern part of the Indian Ocean, in front of Somalia and in the Arabian sea during Winter monsoon and spring-inter-monsoon periods. Lower probability of occurrence was estimated for the equatorial area mainly during the spring inter-monsoon.

An ecological risk assessment in the Indian Ocean showed a 100% overlap between the purse seine fishery and the distribution of silky sharks (Murua *et al.*, 2018). This assessment categorised the silky shark as moderately vulnerable to the purse seine fishery in the region, largely due to assumed increased post release survival following the fleet-wide adoption of best handling practices for sharks.

The silky shark post release survival rate assessment presented in this work concludes that these handling practices are effective and that fauna releasing devices can make a significant contribution to shark mortality reduction.

In addition, the overlap with the purse seine fisheries seems to be variable with high probability of occurrence detected in the northern western Indian Ocean, and lower probability of occurrence in the equatorial area.

Identification of high-risk persistent areas to fisheries interacting with this species (purse-seiner and longlines in open oceans and other coastal fisheries) could help in decision making. For example, relocating effort from areas in which high fishing inefficiency is occurring can help in shark bycatch mortality reduction without compromising the target catch (Ortuño-Crespo et al. 2022). Other mitigation options, as bycatch risk maps generated with machine learning approaches fed with reported catches and habitat models could be further developed to support the fishing strategy.

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