**DOI: https://doi.org/10.1111/fme.12320**

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https://onlinelibrary.wiley.com/doi/full/10.1111/fme.12320

# TITLE: DEPREDATION IN PELAGIC SURFACE LONGLINES IN THE ATLANTIC AND INDIAN OCEANS


## ABSTRACT

Depredation has aroused great interest over the last few decades, mainly due to the expansion of distant fishing, in particular longlines. For this study, captures and depredation records were taken by scientific observers on board Portuguese commercial longline vessels in the Atlantic and Indian Oceans, between 2011-2016. A total of 1336 fishing sets were monitored, with a total of 86,183 fish captures, including 1681 depredation events. The percentage of depredation tended to increase along the time series, except in the last year where a decrease was noted. Significant differences between sizes of swordfish (*Xiphias gladius*) damaged by predators were observed in the Indian Ocean but not in the Atlantic. The highest proportions of depredation were observed on tuna and small pelagic fishes in both oceans. For swordfish, the effects of spatial variables were significant on the rate of depredation events. The results presented in this study provide a first overview of the depredation patterns in the Portuguese pelagic longline fishery in the Atlantic and Indian Oceans, which can inform and improve fisheries management and contribute to the development of effective mitigation measures to reduce the impacts of depredation on fisheries.



*KEYWORDS: Depredation, pelagic longline fisheries, swordfish, sharks, Indian Ocean, Atlantic Ocean.*

## Introduction

Depredation has aroused increasing interest over the last few decades due to the expansion of distant fisheries, in particular pelagic longlines. Depredation is usually defined as '*the partial or complete removal of hooked fish or bait from fishing gear... by predators likes cetaceans, sharks, bony fish, birds, squids, crustaceans and others*' distinguishing it from predation, i.e., '*the taking of free swimming fish (or other organisms)* ...' (Donoghue, Reeves, & Stone, 2003; Gilman *et al.*, 2007; Romanov *et al.*, 2013). The partial of even complete removal of the catch and bite off of the gear can lead to significant financial losses to the fisheries (Nishida & Shiba, 2005; Rabearisoa *et al.*, 2012; Kumar *et al.*, 2016).

Depredation events have been documented to some extent in the Atlantic and Indian Oceans. However, detailed information collected systematically is still rare for both areas. Therefore, there is a need for the development of specific indicators to assess the degree of depredation, which remains a poorly understood phenomenon, especially in poorly studied areas of the Indian (Mutombene, 2015; Rabearisoa, Sabarros, Romanov, & Bach, 2015; Varghese, Somvanshi, & Varghese, 2008) and Atlantic Oceans (Hernandez-Milian *et al.*, 2008; MacNeil, Carlson, & Beerkircher, 2009; Mandelman, Cooper, Werner, & Lagueux, 2008).

In this paper, the Portuguese pelagic longline fishery, a surface drifting longline fishery targeting mainly swordfish (*Xiphias gladius* [SWO]) that operates over wide regions of the Atlantic and Indian Oceans, was analyzed. Specific objectives of the paper were to 1) analyze depredation events in relation to total captures, 2) evaluate species-specific depredation events, 3) provide information on the main variables that are related to the depredation events, and 4) discuss this case study within the context of oceanic pelagic fisheries.

## Material and methods

### Data collection

Depredation records were taken by scientific observers on board Portuguese commercial pelagic longline vessels that operate over wide areas of the Atlantic and Indian Oceans. In the Atlantic, data were collected mainly in the Temperate, Tropical, Equatorial and Subtropical waters of southern hemisphere (between 30ºS to 43ºN and 44ºW to 7ºE). In the Indian Ocean data were collected mainly in the Subtropical waters (between 23ºS to 34ºS and 36ºE to 96ºE) (Fig. 1 - A). Data were compiled for the period from 2011 to 2016. A total of 1336 fishing operations, 787 in the Atlantic Ocean and 549 in the Indian Ocean, were covered. In the Atlantic Ocean fleet, the fishing effort per set averaged 1236 hooks and ranged from 668 to 2013 hooks. The fishing effort per set averaged 1438 hooks and ranged from 505 to 2601 hooks for the Indian Ocean.

Data on specimen size (lower-jaw fork length [LJFL] for billfishes and fork length [FL] for other bony fishes and sharks), location, depredation episodes and date were recorded. Within the context of data reporting to the Regional Fisheries Management Organizations, specifically ICCAT in the Atlantic and IOTC in the Indian Ocean, the depredation events and rates are recommended to be reported in the Indian Ocean but not in the Atlantic. As such, depredation episodes in the Atlantic Ocean were recorded exclusively for individuals with high damages, i.e., those individuals with large bites, tears or amputation of some parts of the body, such as the tail or belly area. Predators were recorded only for depredated individuals in the Indian Ocean whenever possible. To identify predator, observers analyzed the bite of the depredated individuals and observed if predators were swimming near the vessel when the longline was being hauled. In some cases, mainly with sharks and pelagic fish, a captured individual contained the remains of other individuals previously depredated in the mouth of this first, sometimes even with the hook inside. In the case of seabird depredation, they were observer biting prey when the longline was being hauled.

Differences between sizes of swordfish damaged by predators were analyzed in the Atlantic and Indian Oceans. Only individuals partially depredated, where size could still be known, were taken into account in this analysis.

**Catch and depredation indicators**

The nominal CPUE (Catch Per Unit Effort), defined as the total number (N) of fish caught (including both damaged or intact) per 1000 hooks was calculated for each fishing set, and summarized by quarter and year for each region.

$$CPUE = \frac{Number\ of\ fish\ caught}{Number\ of\ hooks} * 1000$$

Depredation Per Unit Effort (DPUE), defined as the number of fish depredated per 1000 hooks, was calculated per set and assessed by quarter by using quarterly pooled catch and fishing effort data, including non-depredated sets (e.g., Rabearisoa *et al.*, 2015b; Ramos-Cartelle & Mejuto, 2008; Romanov *et al.*, 2013).

$$DPUE = \frac{Number\ of\ fish\ depredated}{Number\ of\ hooks\ set} * 1000$$

The Interaction Rate (IR) was defined as the proportion of longline sets depredated. IR was calculated using the entire dataset (operational set level data) of longline operations. A fishing operation was considered depredated if at least one fish (either a commercial or non-commercial species) was depredated on the longline ( e.g., Nishida & Tanio, 2001; Rabearisoa *et al.*, 2015b; Romanov *et al.*, 2013).

$$IR = \frac{Number\ of\ depredated\ sets}{Total\ number\ of\ fishing\ operations} * 100$$

The Gross Depredation Rate (GDR) was defined as the total number of fish depredated divided by the total number of fish caught. Quarterly and yearly values of GDR were calculated on the quarterly or yearly pooled catch, including non-depredated sets (e.g., Donoghue *et al.*, 2003; Rabearisoa *et al.*, 2015b; Romanov *et al.*, 2013).

$$GDR = \frac{Number\ of\ fish\ depredated}{Number\ of\ fish\ caught}$$

**Data analysis**

Data from the Atlantic and Indian Oceans were compiled, analyzed and compared. Catch data for each ocean was tested for normality with Shapiro-Wilk normality tests (Shapiro & Wilk, 1965) and for homogeneity of variances with Levene tests (Levene, 1960). Due to violation of those parametric assumptions, univariate non-parametric statistical tests (chi-squared) were used to compare total and depredated captures between oceans.

The annual trends of total and depredated captures were plotted and analyzed, as well as the proportions of depredated captures by species. The size distributions were compared between depredated and non-depredated capture. This analysis was carried out for swordfish, the main target species of the fleet.

A binomial Generalized Additive Model (GAM) with logit link function was created to determine the effects of spatial variables (latitude and longitude) on the depredation rates of swordfish in both oceans. The response variable was the swordfish depredated/non-depredated captures, with each specimen coded as: 1=depredation event occurred and 0=depredation event did not occur. The model also accounted for the year effect, as a fixed categorical factor. Other variables, such as SST were also tested in the model, but were not used due to collinearity with the spatial effects, particularly with latitude. The predicted swordfish depredation occurrences (binomial proportions) from this final GAM model were plotted along the study areas in each ocean.

The analysis for this paper was carried out using the R language for statistical computing version 3.3.2. (R Core Team, 2016). Additional packages that were used included “car” (Fox & Weisberg, 2011), “cowplot” (Wilke, 2015), “descr” (Aquino, Enzmann, Schwartz, Jain, & Kraft, 2016), “ggmap” (Kahle & Wickham, 2013), “ggplot2” (Wickham, 2009), “gridExtra” (Auguie, 2016), “gtable”(Wickham, 2016a), “lattice” (Sarkar, 2008), “maps” (Brownrigg, Minka, Becker, & Wilks, 2010), “mapdata” (Becker, Wilks, & Brownrigg, 2016), “mgcv” (Wood, 2011), “nortest” (Gross & Ligges, 2015), “perm” (Fay & Shaw, 2010), “raster” (Hijmans, 2016), “RColorBrewer” (Neuwirth, 2014), ”reshape2” (Wickham, 2007), “RgoogleMaps” (Loecher & Ropkins, 2015),“Rmisc” (Hope, 2013), “scales” (Wickham, 2016b).

## Results

### Spatial distribution of catches and depredation events

In the Atlantic Ocean, a total of 55,482 captures were recorded and considered within the scope of this study. The sample covered a wide geographical area of the Atlantic Ocean, with most sets taking place in the tropical and equatorial regions, but also in the temperate north and south (Fig. 1 - B). The total number of individuals depredated were 778, representing about 1.4% of the total catch. These depredations events occurred in 54% of the total sets, concretely in 421 of the 784 sets during the study period and area (Fig. 1 - C).

In the case of the Indian Ocean, a total of 30,701 captures were recorded during the study. The sample covered a large geographical area of the south Indian Ocean, with most sets taking place in the SW region (Fig. 1 - B). The individuals depredated represented about 2.9% of the total capture, with a total number of 903 individuals depredated. These depredations events occurred in 395 of the 548 sets during the study period and area, representing depredation occurrences in 72% of the total sets (Fig. 1 - C).

Total and depredated captures per set data were not normally distributed (Shapiro-Wilk test: (Atlantic Ocean) W = 0.834, $P < 0.001$ and W = 0.714, $P < 0.001$. (Indian Ocean) W = 0.985, $P < 0.001$ and W = 0.841, $P < 0.001$). Variances of total captures were heterogeneous between oceans (Levene test: F = 34.814, df = 1, $P < 0.001$) but homogeneous for the depredated captures (F = 0.374, df = 1, $P = 0.541$). Using univariate non-parametric statistical tests revealed that total and depredated captures per set were significantly different between oceans (Permutation test: chi-squared = 82.051, df = 1, $P < 0.001$ and chi-squared = 5.531, df = 1, $P = 0.019$) respectively.

**Depredation indicators**

Quarterly CPUE was variable, dependent on capture distributions and presence/absence of predator attacks. The overall CPUE varied from 47 to 78.6 and 28.1 to 50.4 specimens/1000 hooks respectively for the Atlantic and Indian Oceans (Table 1). High values of CPUE in some year-quarters combinations for the Atlantic Ocean (2014-4=106.6; 2016-1=157.5; 2016-3=243.2) were mainly due to fishing taking place in areas where blue shark individuals were very abundant. Annual DPUE values varied from 0.5 to 1.2 specimens/1000 hooks in the Atlantic Ocean, and slightly lower for the Indian Ocean, specifically varying from 0.7 to 1.8 specimens/1000 hooks (Table 1).

A total of 801 fishing operations were depredated, specifically 406 in the Atlantic Ocean (IR=52.7%) and 395 in the Indian Ocean (IR=71.8%) (Table 1). The main depredation hotspots were located in the tropical and equatorial Atlantic Ocean, and in the southwest and central-south Indian Ocean (Fig. 1 - C). The yearly values of the gross depredation rate varied between 1.1% and 1.9% in the Atlantic Ocean and between 1.5% and 4.9% in the Indian Ocean (Table 1).

**Annual trends of depredated catches**

Total and depredated captures variances were homogeneous between years in the Atlantic (Levene test: F = 0.659, df = 5, $P$ = 0.655 and F = 0.92, df = 5, $P$ = 0.467) and heterogeneous in the Indian Ocean (Levene test: F = 3.586, df = 5, $P$ = 0.003 and F = 3.705, df = 5, $P$ = 0.003). Using univariate non-parametric statistical tests revealed that total and depredated captures were significantly different between years for both oceans (Permutation test: (Atlantic Ocean) chi-squared = 28.275, df = 5, $P < 0.001$ and chi-squared = 29.249, df = 5, $P < 0.001$. (Indian Ocean) chi-squared = 150.73, df = 5, $P < 0.001$ and chi-squared = 60.839, df = 5, $P < 0.001$).

In the Atlantic Ocean, the fraction of depredated captures had an increasing annual trend of 0.26 % per year on average, ranging from 1.1 % in 2011 and reaching 2.1 % in 2015. However, depredation captures decreased by 1 % in the last year, specifically to 1.1 % in 2016 (Table 2). The fraction of depredated captures also increased similarly in the Indian Ocean, with an increasing annual trend of 0.85 % on average, being 1.5 % in 2011 and reaching 4.9 % in 2015. Depredated captures also decreased in the last year (2016), in this case by 2 % and reaching 2.9 % (Table 2).

**Depredated species**

*Atlantic Ocean*

In the Atlantic Ocean, the Portuguese longline fishery catch composition is mostly composed of 6 species, blue shark (*Prionace glauca* [BSH]), swordfish, bigeye tuna

(*Thunnus obesus* [BET]), common dolphinfish (*Coryphaena hippurus* [DOL]), crocodile shark (*Pseudocarcharias kamoharai* [PSK]) and shortfin mako (*Isurus oxyrinchus* [SMA]) (Table 3). These species represent 86.7% of the fish catch in numbers, with particular highlights to blue shark and swordfish with 54.4 and 22.2% of the total catches, respectively (Table 3).

A total of 24 species were depredated, with swordfish representing 49% of the depredated captures, followed by bigeye tuna, blue shark, common dolphinfish, wahoo (*Acanthocybium solandri* [WAH]), escolar (*Lepidocybium flavobrunneum* [LEC]), atlantic sailfish (*Istiophorus albicans* [SAI]), atlantic white marlin (*Tetrapturus albidus* [WHM]) and yellowfin tuna (*Thunnus albacares* [YFT]) (Table 3).

The percentage of depredated individuals against total catch by species is represented in Table 4. Tuna and small pelagic fishes had the highest relative percentages of depredation in relation to their total catches. Atlantic pomfret (*Brama brama* [POA]), driftfish (*Cubiceps* spp. [CUP]), striped marlin (*Tetrapturus audax* [MLS]) and large tunas (*Thunnus* spp. [TUS]) stand out as the most depredated species/taxa, with a range of 14-34% of the individuals captured having been depredated (Table 4).

*Indian Ocean*

In the Indian Ocean Portuguese longline fishery the catch composition is mostly composed of 6 species, swordfish, blue shark, common dolphinfish, escolar, shortfin mako and bigeye tuna (Table 3). These species represent 89% of the fish catch in numbers, highlighting again to swordfish and blue shark captures, with 36.4 and 27.9% of total catches, respectively (Table 3).

A total of 24 species were depredated, with swordfish representing 55.6% of the depredated captures, followed by escolar, common dolphinfish, blue shark, bigeye tuna, wahoo, albacore (*Thunnus alalunga* [ALB]), shortfin mako and long snouted lancetfish (*Alepisaurus ferox* [ALX]) (Table 3).

The percentage of depredated individuals against total catch by species is represented in Table 4. Similarly to the Atlantic, tuna and small pelagic fishes also had the highest percentages of depredation in relation to their total catches. In this case, Wahoo and snake mackerel (*Gempylus serpens* [GES]) stand out as the most depredated species, ranging between 9-12% of individuals depredated.

Predators were recorded only for depredated individuals in the Indian Ocean. It was not possible to identify the predator in 61% of depredated individuals. For the ones that the predator could be identified, 21% of the depredation was from sharks species, including blue shark, shortfin mako, porbeagle (*Lamna nasus* [POR]) and the small cookie cutter shark (*Isistius brasiliensis* [ISB]). Small pelagic fish preyed on about 13% of the depredated individuals. Marine mammals and seabirds were responsible for 1.9 and 0.3% respectively of the depredation events. Only 2.4% of the depredated captures were targeted by more than one predator.

**Size distribution of depredated and total catch of swordfish**

As the main target species in the fishery and the one with more depredation events, a specific size composition analysis was carried out for swordfish. There were no differences in the sizes of swordfish between depredated and total catches for the Atlantic Ocean (Proportion test: chi-squared = 7.0798, df = 17, $P$ = 0.9825), but there were differences for the Indian Ocean (Proportion test: chi-squared = 43.169, df = 17, $P$

= 0.0005) (Fig. 2). It was not possible to compare the sizes of other species due to the limited number of damaged individuals.

## Modelling depredation rates on swordfish

The effects of continuous spatial variables (latitude and longitude) were significant on the rate of depredation events in swordfish specimens in the Atlantic and Indian Oceans (Fig. 3). It is possible to see that in general there were major depredation rates towards western longitudes in the Atlantic Ocean. In terms of latitude, the higher depredation rates are in the tropical zone of the operational areas of the Portuguese fleet. The map of depredation rates spatial predictions showed that spatial depredation rates were closely related to latitude, with two distinct areas of high-depredation rates, one close to the west coast of Africa around 10ºN, and the other located in the southeastern Atlantic Ocean around 15ºS (Fig. 4). In the Indian Ocean, there were higher depredation rates mainly towards eastern longitudes, even thought there was also a peak in the middle of the western areas, closer to the African continent (Fig. 3). Regarding latitude, the higher rates are in the extremes (higher and lower latitudes) of the areas of operation of the Portuguese fleet. The plot with the predictions of the depredation rates along the study area of the Indian Ocean showed an area of moderate depredation rates probability in the eastern of Indian Ocean around 30ºS 90ºE (Fig. 5).

## Discussion

This work provides the first study of depredation in the Portuguese pelagic longline fleet that targets mainly swordfish in the Atlantic and Indian Oceans, compiled by fisheries observers on board commercial longline vessels. The Portuguese pelagic longline fleet is affected by occurrences of depredation events on the catches, with impacts to the fishery, similar to many other fleets around the world (Gilman *et al.*, 2007). This study also reports the extent and spatial distribution of the depredation occurrences and the main species that are impacted in both oceans.

Several depredation mitigation measures have been or are being tested worldwide to mitigate this issue, including physical protection of the catch or acoustic devices, but this remains a challenging work (Tixier *et al.*, 2010; Løkkeborg, 2011; Hamer *et al.*, 2012; O'Connell *et al.*, 2015; Rabearisoa *et al.*, 2015; Straley *et al.*, 2015; Tixier *et al.*, 2014; Werner *et al.*, 2015). For this reason, it is important to know the mechanisms by which depredation episodes occur in pelagic longline fleets.

Very few previous studies have discussed the effects of depredation in pelagic longline fleets. The total values of depredation captures of Portuguese pelagic longline fleet described in this work for the Atlantic Ocean are similar to those obtained by Mandelman *et al.* (2008), that indicated that the damage inflicted in the catch by depredation between 1990 and 1997 in the U.S. Atlantic pelagic longline fishery was 4% of total observed catch. Of those, 68% occurred on captures of swordfish, yellowfin and bigeye tuna collectively, similar to the results obtained in our study. However, this work also report events on other species such as escolar, dolphinfish or blue shark. Our results are also similar with those of Hernandez-Milian *et al.* (2008), whose reports of occurrences of depredation in the Atlantic Ocean were of less than 1% of the total catch. As in our study, Rabearisoa *et al.* (2015b) also did not find annual values of DPUE exceeding 2 specimens/1000 hooks. By the contrary, our results of IR are higher compared with other studies, such as Hernandez-Milian *et al.* (2008) in the Atlantic and Rabearisoa *et al.* (2015b) in the Indian Ocean.

On the other hand, a higher proportion of depredated captures was observed for some species in both oceans, like tunas and small pelagic fishes, possibly showing that there is a depredation preference for some species by the predators. These same results were obtained in the study of shark depredation in pelagic longline fishery in the Northwest Atlantic (MacNeil *et al.*, 2009) and in the pelagic longline fleet of Reunion Island in the Indian Ocean (Rabearisoa, Sabarros, *et al.*, 2015) where tunas showed the highest ratios of depredation. Depth, as well turbidity can determine the catchability of these species, as depredation cases seem to have less success in areas with poor visibility (Ward & Myers, 2005).

Significant differences in the size of fish damaged by predators were observed for swordfish in our study for the Indian Ocean, but not for the Atlantic. Some studies of fishes' prey preference show selection for certain sizes (e.g., Hart, 1986; Løkkeborg & Bjordal, 1995). The results of Barnes *et al.* (2010) suggest that very general rules determine dominant trends in predator–prey mass ratios in diverse marine ecosystems, leading to the ubiquity of size-based trophic structuring and the consistency of observed relationships between the relative abundance of individuals and their body size. However, in our work caution should be taken when interpreting these results as the depredated captures sample size is relatively small.

Very few previous studies have discussed the effects of spatial variables on the rate of depredation events. For swordfish, the effects of the spatial variables (latitude and longitude) were significant on the rate of depredation events both in the Atlantic and Indian Oceans. It is possible that variables such as temperature or depth, related to spatial variables, are related to the distribution of the catches of oceanic migratory species (Hernandez-Milian *et al.*, 2008), which in turn can lead to more depredation situations. GAM models as applied in our study predict the probability of having or not having predation events, but the most likely responsible species in each region was not explored because of the limits in the analysis and specifically in the taxa-specific data availability. Future research recommendations should therefore include exploring with different models for the various predator taxa (sharks, mammals, etc.). The reason being that different depredation rates observed is specific areas might not necessarily be directly related with the economic losses if the predator specific-depredation levels and damage are different (e.g., cetacean or large sharks depredation that creates severe damage *versus* cookiecutter or birds depredation that typically produces much less damage to the catches). As such, the analysis as presented is valid for the purpose of comparing wide oceanic areas where depredation events are more likely to occur, even though it is limited in terms of the most likely predators and consequently the most likely levels of damage and losses.

With respect to the spatial distribution of the data, while the observations reported in part reflect the spatial dynamics of catches, there is also a large influence of the seasonal and spatial patterns of the fishing effort of the fleet. In a study on the salmon troll fishery, Abrahams & Healey (1990) reported that vessels from the fleet differ substantially in their competitive capacity, and also, these differences add to a considerable temporal and spatial variation in catch rates. That is why these aspects have to be taken into account when discussing the analysis of total catches and the ones that are preyed upon.

Depredation events have potential implications for fisheries management and should be taken into account in the stocks assessment of highly migratory species. This new information about depredation events can help future specific studies by taxa or in more specific zones, delimiting different areas according to the predation rates, and providing the fishing industry with relevant information about the fishing areas. In this sense, full bio-socio-economic assessments of the costs and benefits of changing fishing practices are needed. For example, the "move-on" technique may involve increased non-fishing time and motor-fuel consumption that can render this fishing strategy less advantageous to fishers or sustainable to the fishery itself (Janc *et al*., 2018). Besides, new technical means and mitigation measures that can reduce depredation on pelagic longline fishery should be developed, thus reducing the number of discarded dead catches caused by these events.

Depredation is an inevitable part of conducting longline operations in the open ocean (MacNeil *et al.*, 2009), and can cause significant economic losses to the fishing industry and ecological for the marine environment, especially when the captures are discarded (Gilman *et al.*, 2008). For this reason it is crucial to monitor this phenomenon more closely and periodically, even though it has been poorly studied so far. Depredation monitoring should involve both scientists and the fishing sector, and include the collection of standardized data (Romanov, Bach, & Rabearisoa, 2009). In the future such studies should be continued as more data is being continuously collected on the onboard observer programs. Improving knowledge of depredation will provide valuable information for the development of effective mitigation measures, reducing the impacts of depredation on fisheries.

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## Figures

Figure 1. (A): Fishing operations of the Portuguese pelagic longline fleet in the Atlantic and Indian Oceans between 2011-2016 where depredation event data were recorded and analyzed. (B): Distribution in 5*5 degrees of total catches recorded for this study in the Atlantic and Indian Oceans (2011-2016). (C): Distribution in 5*5 degrees of depredated catches recorded for this study in the Atlantic and Indian Oceans (2011-2016).

Figure 2. Size-frequency distributions of total (n=11,967 and n=10,929) and depredated (n=88 and n=224) catches of swordfish in the Atlantic (A-B) and Indian (C-D) Oceans for the Portuguese pelagic longline fishery. Sizes are grouped in 10-cm lower-jaw fork length (LJFL) classes.

Figure 3. Generalized Additive Model (GAM) plots with the non-linear effects of latitude and longitude in the depredation events on swordfish specimens, in the pelagic longline fishery operating in the Atlantic (A) and Indian (B) Oceans.

Figure 4. Prediction of the depredation rates on swordfish (binomial response) from a Generalized Additive Model (GAM), for the Atlantic Ocean study region.

Figure 5. Prediction of the depredation rates on swordfish (binomial response) from a Generalized Additive Model (GAM), for the Indian Ocean study region.

## Tables

Table 1. Catch and depredation indicators per year quarter combination in the Atlantic and Indian Oceans. Nsets is the number of sets; CPUE is the catch per unit of effort (number of fish caught per 1000 hooks); DPUE is the depredation per unit of effort (number of fish depredated per 1000 hooks); IR is the interaction rate (proportion of depredated sets); GDR is the gross depredation rate (percentage of fish depredated within the entire catch).

| | Atlantic Ocean | | | | | Indian Ocean | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Quarters | Nsets | CPUE | DPUE | IR | GDR | Nsets | CPUE | DPUE | IR | GDR |
| 2011-1 | 59 | 40.0 | 0.4 | 33.9 | 1.0 | - | - | - | - | - |
| 2011-2 | - | - | - | - | - | 33 | 56.7 | 0.7 | 57.6 | 1.3 |
| 2011-3 | 23 | 64.7 | 0.8 | 60.9 | 1.2 | 70 | 40.7 | 0.7 | 62.9 | 1.6 |
| 2011-4 | 124 | 54.1 | 0.6 | 37.1 | 1.1 | - | - | - | - | - |
| Annual-2011 | 206 | 51.5 | 0.6 | 38.8 | 1.1 | 103 | 45.5 | 0.7 | 61.2 | 1.5 |
| 2012-1 | 37 | 56.4 | 0.6 | 45.9 | 1.0 | - | - | - | - | - |
| 2012-2 | 54 | 85.8 | 1.4 | 66.7 | 1.6 | - | - | - | - | - |
| 2012-3 | 70 | 54.7 | 0.6 | 50.0 | 1.2 | 43 | 48.1 | 1.2 | 69.8 | 2.5 |
| 2012-4 | 49 | 60.6 | 0.8 | 55.1 | 1.4 | 13 | 57.8 | 0.9 | 69.2 | 1.6 |
| Annual-2012 | 210 | 63.5 | 0.8 | 54.8 | 1.3 | 56 | 50.4 | 1.1 | 69.6 | 2.3 |
| 2013-1 | - | - | - | - | - | 20 | 59.8 | 2.3 | 90.0 | 3.8 |
| 2013-2 | 5 | 40.0 | 0.2 | 20.0 | 0.4 | 67 | 46.1 | 1.1 | 74.6 | 2.5 |
| 2013-3 | 67 | 47.2 | 0.6 | 43.3 | 1.2 | - | - | - | - | - |
| 2013-4 | 1 | 68.0 | 1.7 | 100.0 | 2.4 | 43 | 33.1 | 0.9 | 69.8 | 2.7 |
| Annual-2013 | 73 | 47.0 | 0.5 | 42.5 | 1.2 | 130 | 43.7 | 1.2 | 75.4 | 2.8 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2014-1 | 13 | 44.5 | 1.0 | 61.5 | 2.3 | 49 | 28.3 | 1.1 | 75.5 | 4.0 |
| 2014-2 | 16 | 44.6 | 0.8 | 56.3 | 1.7 | - | - | - | - | - |
| 2014-3 | 69 | 52.3 | 1.1 | 63.8 | 2.1 | - | - | - | - | - |
| 2014-4 | 7 | 106.6 | 0.9 | 71.4 | 0.9 | - | - | - | - | - |
| Annual-2014 | 105 | 53.4 | 1.0 | 62.9 | 1.9 | 49 | 28.3 | 1.1 | 75.5 | 4.0 |
| 2015-1 | 51 | 52.8 | 1.2 | 66.7 | 2.2 | - | - | - | - | - |
| 2015-2 | 41 | 88.9 | 1.2 | 58.5 | 1.3 | 67 | 31.4 | 1.8 | 88.1 | 5.8 |
| 2015-3 | 10 | 71.0 | 1.4 | 80.0 | 2.0 | 41 | 47.2 | 1.7 | 92.7 | 3.7 |
| 2015-4 | - | - | - | - | - | - | - | - | - | - |
| Annual-2015 | 102 | 69.4 | 1.2 | 64.7 | 1.7 | 108 | 37.0 | 1.8 | 89.8 | 4.9 |
| 2016-1 | 13 | 157.5 | 0.7 | 30.8 | 0.4 | - | - | - | - | - |
| 2016-2 | 40 | 55.9 | 0.8 | 55.0 | 1.5 | 38 | 28.6 | 1.5 | 84.2 | 5.2 |
| 2016-3 | 14 | 243.2 | 3.0 | 57.1 | 1.2 | 65 | 27.9 | 0.4 | 44.6 | 1.5 |
| 2016-4 | 24 | 57.0 | 0.6 | 58.3 | 1.1 | - | - | - | - | - |
| Annual-2016 | 91 | 78.6 | 0.9 | 52.7 | 1.1 | 103 | 28.1 | 0.8 | 59.2 | 2.9 |

Table 2. Annual catches, in %, for depredated and non-depredated individuals, during the period 2011-2016, in the Atlantic and Indian Oceans. *n* is the number of individuals.

| | Atlantic Ocean | | Indian Ocean | |
|---|---|---|---|---|
| Year | Not Depredated % (*n*) | Depredated % (*n*) | Not Depredated % (*n*) | Depredated % (*n*) |
| 2011 | 98,9% (*16622*) | 1,1% (*184*) | 98,5% (*6283*) | 1,5% (*95*) |
| 2012 | 98,6% (*13686*) | 1,4% (*189*) | 97,7% (*3629*) | 2,3% (*84*) |
| 2013 | 98,8% (*4025*) | 1,2% (*47*) | 97,1% (*7860*) | 2,9% (*238*) |
| 2014 | 98,1% (*6796*) | 1,9% (*135*) | 96,3% (*2110*) | 3,7% (*80*) |
| 2015 | 97,9% (*6857*) | 2,1% (*149*) | 95,1% (*5506*) | 4,9% (*281*) |
| 2016 | 98,9% (*6718*) | 1,1% (*74*) | 97,1% (*4210*) | 2,9% (*125*) |

Table 3. Percentage of total catches of the main target species recorded for this study in the Atlantic and Indian Oceans (2011-2016) (n=55,482 and n=30,701, respectively) and contributions of species to depredated catches of longline fishery in percentage (n=778 and n=903 respectively). Bigeye thresher (*Alopias superciliosus* [BTH]), pelagic stingray (*Dasyatis violacea* [PLS]), blue marlin (*Makaira nigricans* [BUM]), oceanic whitetip shark (*Carcharhinus longimanus* [OCS]), longfin mako (*Isurus paucus* [LMA]), indo-Pacific sailfish (*Istiophorus platypterus* [SFA]), olive ridley turtle (*Lepidochelys olivacea* [LKV]), toli shad (*Tenualosa toli* [TOL]), smooth hammerhead (*Sphyrna zygaena* [SPZ]), leatherback turtle (*Dermochelys coriacea* [DKK]), silky shark (*Carcharhinus falciformis* [FAL]), devil fish (*Mobula mobular* [RMM]), greater amberjack (*Seriola dumerili* [AMB]), shortbill spearfish (*Tetrapturus angustirostris* [SSP]), longbill spearfish (*Tetrapturus pfluegeri* [SPF]), southern bluefin tuna (*Thunnus maccoyii* [SBF]), opah (*Lampris guttatus* [LAG]), barracuda (*Sphyraena* spp. [BAR]), oilfish (*Ruvettus pretiosus* [OIL]).

| Atlantic Ocean | | | | | | Indian Ocean | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Observed | in % | Species | Depredations | in % | Species | Observed | in % | Species | Depredations | in % |
| BSH | 30167 | 54,37 | SWO | 382 | 49,10 | SWO | 11168 | 36,38 | SWO | 502 | 55,59 |
| SWO | 12337 | 22,24 | BET | 81 | 10,41 | BSH | 8568 | 27,91 | LEC | 110 | 12,18 |
| BET | 1934 | 3,49 | BSH | 46 | 5,91 | DOL | 2787 | 9,08 | DOL | 58 | 6,42 |
| DOL | 1481 | 2,67 | DOL | 43 | 5,53 | LEC | 2185 | 7,12 | BSH | 48 | 5,32 |
| PSK | 1250 | 2,25 | WAH | 35 | 4,50 | SMA | 1518 | 4,94 | BET | 41 | 4,54 |
| SMA | 943 | 1,70 | LEC | 35 | 4,50 | BET | 1082 | 3,52 | WAH | 31 | 3,43 |
| YFT | 868 | 1,56 | SAI | 34 | 4,37 | ALB | 368 | 1,20 | ALB | 21 | 2,33 |
| BTH | 626 | 1,13 | WHM | 27 | 3,47 | ALX | 340 | 1,11 | SMA | 21 | 2,33 |
| PLS | 581 | 1,05 | YFT | 24 | 3,08 | PLS | 326 | 1,06 | ALX | 20 | 2,21 |
| SAI | 574 | 1,03 | BTH | 15 | 1,93 | WAH | 265 | 0,86 | GES | 17 | 1,88 |
| WHM | 520 | 0,94 | BUM | 13 | 1,67 | FAL | 222 | 0,72 | MLS | 6 | 0,66 |
| LEC | 448 | 0,81 | ALB | 9 | 1,16 | OIL | 212 | 0,69 | POA | 4 | 0,44 |
| BUM | 424 | 0,76 | PSK | 8 | 1,03 | GES | 178 | 0,58 | SSP | 4 | 0,44 |
| OCS | 414 | 0,75 | SMA | 7 | 0,90 | YFT | 175 | 0,57 | YFT | 4 | 0,44 |
| LMA | 360 | 0,65 | ALX | 6 | 0,77 | POR | 161 | 0,52 | FAL | 4 | 0,44 |
| WAH | 353 | 0,64 | AMB | 3 | 0,39 | SFA | 142 | 0,46 | OIL | 3 | 0,33 |
| LKV | 271 | 0,49 | TUS | 2 | 0,26 | MLS | 121 | 0,39 | SFA | 2 | 0,22 |
| ALX | 230 | 0,41 | SPF | 2 | 0,26 | SSP | 107 | 0,35 | BAR | 1 | 0,11 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TOL | 205 | 0,37 | POA | 1 | 0,13 | SBF | 86 | 0,28 | LAG | 1 | 0,11 |
| SPZ | 193 | 0,35 | CUP | 1 | 0,13 | POA | 80 | 0,26 | SPZ | 1 | 0,11 |
| DKK | 143 | 0,26 | MLS | 1 | 0,13 | BTH | 78 | 0,25 | BUM | 1 | 0,11 |
| FAL | 135 | 0,24 | OIL | 1 | 0,13 | RMM | 63 | 0,21 | BTH | 1 | 0,11 |
| RMM | 108 | 0,19 | GES | 1 | 0,13 | BUM | 60 | 0,20 | SBF | 1 | 0,11 |
| ALB | 103 | 0,19 | LMA | 1 | 0,13 | PSK | 41 | 0,13 | POR | 1 | 0,11 |

Table 4. Percentage of depredated catches compared to the species-specific total catches for the Portuguese pelagic longline fishery in the Atlantic and Indian Oceans.

| Atlantic Ocean | | | | Indian Ocean | | | |
|---|---|---|---|---|---|---|---|
| Species | Observed | Depredations | Proportion | Species | Observed | Depredations | Proportion |
| *Brama brama* | 3 | 1 | 33,33 | *Acanthocybium solandri* | 265 | 31 | 11,70 |
| *Cubiceps* spp. | 4 | 1 | 25,00 | *Gempylus serpens* | 178 | 17 | 9,55 |
| *Tetrapturus audax* | 14 | 2 | 14,29 | *Sphyraena* spp. | 15 | 1 | 6,67 |
| *Thunnus* spp. | 7 | 1 | 14,29 | *Alepisaurus ferox* | 340 | 20 | 5,88 |
| *Acanthocybium solandri* | 353 | 35 | 9,92 | *Thunnus alalunga* | 368 | 21 | 5,71 |
| *Thunnus alalunga* | 103 | 9 | 8,74 | *Lepidocybium flavobrunneum* | 2185 | 110 | 5,03 |
| *Lepidocybium flavobrunneum* | 448 | 35 | 7,81 | *Brama brama* | 80 | 4 | 5,00 |
| *Seriola dumerili* | 43 | 3 | 6,98 | *Tetrapturus audax* | 121 | 6 | 4,96 |
| *Istiophorus albicans* | 574 | 34 | 5,92 | *Lampris guttatus* | 21 | 1 | 4,76 |
| *Tetrapturus albidus* | 520 | 27 | 5,19 | *Xiphias gladius* | 11168 | 502 | 4,49 |
| *Thunnus obesus* | 1934 | 81 | 4,19 | *Thunnus obesus* | 1082 | 41 | 3,79 |
| *Tetrapturus pfluegeri* | 56 | 2 | 3,57 | *Tetrapturus angustirostris* | 107 | 4 | 3,74 |
| *Xiphias gladius* | 12337 | 382 | 3,10 | *Sphyrna zygaena* | 40 | 1 | 2,50 |
| *Makaira nigricans* | 424 | 13 | 3,07 | *Thunnus albacares* | 175 | 4 | 2,29 |
| *Coryphaena hippurus* | 1481 | 43 | 2,90 | *Coryphaena hippurus* | 2787 | 58 | 2,08 |
| *Ruvettus pretiosus* | 35 | 1 | 2,86 | *Carcharhinus falciformis* | 222 | 4 | 1,80 |
| *Thunnus albacares* | 868 | 24 | 2,76 | *Makaira nigricans* | 60 | 1 | 1,67 |
| *Alepisaurus ferox* | 230 | 6 | 2,61 | *Ruvettus pretiosus* | 212 | 3 | 1,42 |
| *Alopias superciliosus* | 626 | 15 | 2,40 | *Istiophorus platypterus* | 142 | 2 | 1,41 |
| *Gempylus serpens* | 60 | 1 | 1,67 | *Isurus oxyrinchus* | 1518 | 21 | 1,38 |
| *Isurus oxyrinchus* | 943 | 7 | 0,74 | *Alopias superciliosus* | 78 | 1 | 1,28 |
| *Pseudocarcharias kamoharai* | 1250 | 8 | 0,64 | *Thunnus maccoyii* | 86 | 1 | 1,16 |
| *Isurus paucus* | 360 | 1 | 0,28 | *Lamna nasus* | 161 | 1 | 0,62 |
| *Prionace glauca* | 30167 | 46 | 0,15 | *Prionace glauca* | 8568 | 48 | 0,56 |