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# Indicators of depredation impacting Reunion Island pelagic longline fishery

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**ABSTRACT.** Depredation is defined as the damage or removal of fish from fishing gear by predators. Depredation raises concerns about the conservation of marine protected species involved, fisheries yield and profitability, as well as stock assessment of target species. There is an obvious lack of knowledge about depredation impacting pelagic longline fisheries, especially in the southwest Indian Ocean. Thus, there is a real need for the development of accurate indicators to assess its impact in a given fishery. In Reunion Island, pelagic longliners targeting swordfish (*Xiphias gladius*) and tuna (*Thunnus spp.*) are affected by depredation from short-finned pilot whale (*Globicephala macrorhynchus*), false killer whale (*Pseudorca crassidens*) and various pelagic sharks. Catch and depredation data collected during self-reporting, commercial and experimental cruises between 2007 and 2015 were used to calculate depredation indicators such as the depredation occurrence (Interaction Rate), the proportion of fish depredated among the overall catch (Gross Depredation Rate), the average proportion of fish depredated per depredated set (Damage Rate) and the number of fish depredated per 1000 hooks (Depredation Per Unit Effort). Here we show that shark depredation impacted more fishing sets (IRs=31%) than toothed whale depredation (IRc=14%), but when depredation occurred, toothed whale depredation impact was higher: the number of fish damaged per 1000 hooks and the average proportion of fish damaged per set were greater for toothed whale depredated sets (DPUEc*=2.7 fish and DRc*=16.8%) than for shark depredated ones (DPUEs*=1.2 fish and DRs*=6.4%). Since 2011, when the pelagic fleet concentrated its fishing effort around the Reunion EEZ and the east coast of Madagascar, the gross depredation rate increased and ranged from 4 to 6.3%. These are minimum depredation estimates, since several uncertainties could not be taken into account: total depredation leaving no trace on the hook, bait depredation by small delphinids indirectly leading to catch loss, toothed whale presence scaring fish away or additional running costs when leaving a fishing area to avoid predators. Thus, combined with marginal profits, increased running costs and low fish prices, toothed whale depredation is likely to induce disastrous effects on Reunion pelagic longline fishery. Therefore, direct and indirect costs linked to depredation are being assessed in an on-going study.

**Keywords:** Southwest Indian Ocean | Shark | Toothed whale | Swordfish | Tuna | Depredation rate

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# 1 Introduction

Interactions with fisheries and human activities represent one of the most significant threats to various groups of marine populations worldwide (Northridge and Hofman, 1999; Stevens et al., 2000). Depredation is part of those interactions and defined as the damage or removal of bait or fish caught from the fishing gear by marine predators (bird, squid, toothed whale or shark). It reflects an opportunistic feeding behaviour of certain cetacean species that may have adverse consequences on their conservation and ecology. For instance, it may induce a diet shift of toothed whales, as it gives them easy access to prey remotely accessible in natural conditions alternating, therefore, their natural foraging behaviour (Donoghue et al., 2002; IOTC, 2007). Interacting with fishing gears, predators are exposed to higher injury or mortality risks due to eventual hooking or entanglement (Baird and Gorgone, 2005; Garrison, 2007; Kiszka et al., 2009; Forney et al., 2011). Depredation also affects harvested fish stocks, as the Catch Per Unit Effort (CPUE) used in stock assessment process is biased by the amount of fish depredated that are caught but not included in landed catch reports (Bach et al., 2011). In addition, depredation may lead to an increased fishing effort to compensate for fish loss, resulting in extra fishing pressure on exploited stocks (Donoghue et al., 2002). Finally, depredation affects the economics of fisheries.

In long-distance fisheries, spatial displacement of fleet from a fishing area where depredation has occurred is efficient in reducing toothed whale depredation (Tixier et al., 2010). However, for small semi-industrial vessels, this strategy may result in high running costs and heavy operational losses. Thus, depredation is more detrimental to small-scale fisheries operating with short fishing trips (lasting from few days to three weeks). Moreover, small semi-industrial vessels are usually 'fresh-fish boats' using ice to preserve their catch. If vessel operators extend fishing trip duration to compensate depredation losses, they may have to discard their catches from earlier operations due to quality deterioration ("high-grading" process).

Depredation by sperm whales (*Physeter macrocephalus*) and killer whales (*Orcinus orca*) on demersal longline fisheries has been broadly documented in sub Antarctic areas (Donoghue et al., 2002; Roche et al., 2007; Peterson et al., 2014; Guinet et al., 2015; Tixier et al., 2015b; Werner et al., 2015). Toothed whale and pelagic shark depredation impacting pelagic longline fisheries and occurring in tropical areas demonstrates little progress both in description and quantification of the depredation phenomenon (Poisson et al., 2001; Kock et al., 2006; Gilman et al., 2007; Varghese et al., 2007; IOTC, 2007; Nishida and Shiba, 2007; Ramos-Cartelle and Mejuto, 2007; Romanov et al., 2007; Rabearisoa, 2013; Romanov et al., 2013). Then, while facts of depredation were largely documented for the tropical Indian Ocean, systematically collected detailed information is still scarce for the area. Thus, there is a real need for the development of accurate indicators to assess the extent of depredation, which still remains a largely misunderstood phenomenon, especially in poorly studied areas such as the southwest Indian Ocean. 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 (Hamer et al., 2012; Rabearisoa et al., 2012; Hamer et al., 2015; McLellan et al., 2015; O'Connell et al., 2015; Rabearisoa et al., 2015; Straley et al., 2015; Thode et al., 2015; Tixier et al., 2015b,a; Werner et al., 2015).

The goal of this study is to assess the levels of interactions between the Reunion pelagic longline fishery, toothed whales and sharks by using indicators of depredation: depredation occurrence, gross depredation rate, damage rate, damage intensity and depredation per unit effort. Our report is based on information collected from observer, scientific and self-reporting programs.

# 2 Material and methods

## 2.1 The Reunion pelagic longline fishery

The pelagic longline fishery activity started in Reunion Island in 1991 (Bourjea et al., 2009). The fleet grew fast (up to 38 vessels in 2000), but due to tough operational conditions (increased fuel and bait prices, low CPUE, depredation, decreased offboard tuna and swordfish prices), the fleet size slightly decreased. In mid-2015, 32 vessels, ranging from 8 to 25 m in size, are still active. Reunion pelagic longliners are regularly subject to depredation by toothed whales and pelagic sharks (Poisson et al., 2001; Romanov et al., 2013).

The local pelagic longline fleet mainly targets swordfish (*Xiphias gladius*) and deploys night and shallow sets, with ligthsticks-equipped branchlines and squid (or a mix of squid and fish) bait. Lines are set at depths ranging from 20 to 100 m and hauled at sunrise. For the Reunion fleet, they can vary in length from 5 km to 100 km and hold from 300 to 2000 hooks. Even if swordfish is the main target species, some changes in the fishing strategy were experienced during recent years in order to capture tuna as well (e.g. by increasing the soaking time to overlap the tuna feeding activity at the surface). Therefore, bigeye (*Thunnus obesus*), albacore (*Thunnus alalunga*) and yellowfin tuna (*Thunnus albacares*) are also important commercial species (Romanov et al., 2013).

## 2.2 Depredation identification and quantification

Depredation is believed to be an important issue for the local longline fishery, and from the fishermen point of view, ”globis” (i.e. *Globicephala macrorhynchus*) seem to be the main responsible species. However, the local longline fleet also experiences catch depredation by false killer whales (*Pseudorca crassidens*) and pelagic sharks. Bait depredation by Risso’s dolphins (*Grampus griseus*) and bottlenose dolphins (*Tursiops aduncus*), and catch depredation by small predators such as cookie cutter shark (*Isistius brasiliensis*), squids, seabirds, crustaceans, that produces minor damage on target species were not considered in this paper.

Depredation was quantified using the number of fish damaged by toothed whales and/or sharks. However, a complete removal of the fish could not be taken into account except when the depredation event was observed while hauling the fish on board. Otherwise, the discrimination between toothed whale and shark attacks was done based on post-mortem analysis of the shape, size and bites pattern on the fish carcasses. Sharks generally leave crescent-shaped cuts with clean-cut edges of wounds, overall damage to the fish caught often represented by few single bites. Toothed whales leave torn off pieces of flesh, ragged edges of wounds with traces of conical widely spaced teeth. Heavy damage to individual fish is a characteristic of toothed whale attacks: they destroy the whole fish leaving only hard parts of the head or up to the position of the hook in the fish body (Secchi and Vaske, 1998; Romanov et al., 2007, 2009b).

Fish depredated by toothed whales are generally discarded, while fish depredated by sharks can be kept for fishermen self consumption if not heavily damaged.

## 2.3 Data of interest

Catch and fishing tactics data related to the Reunion pelagic longline fishery were extracted from IRD's ObServe database that contains data collected onboard French longliners operating in the Indian Ocean and purse seiners operating in the Indian and Atlantic Oceans. The longline fishery data used to perform this analysis were collected in the frame of various programs (Cauquil et al., 2015).

### 2.3.1 Observer program

The observer program of longliners based in La Reunion was initiated in March 2007 and was developed in the frame of the European Data Collection Framework (Bach et al., 2008). Data collected by sea-going observers include rigging (bait species and hook type used, floatlines and branchlines length, detailed gear configuration, line type) and fishing strategy (date, time and location at the beginning and at the end of each setting and hauling operation, setting shape, maximum fishing depth obtained from time depth recorders (TDR) deployed on the mainline). Catch and depredation data are reported by individual (species, capture status, fate, depredation and predator group when identification was possible, position on the longline). Whenever possible, biometry data was collected as well (length, sex, stomach fullness). A total of 69 trips (representing 560 fishing operations and 735969 hooks set) were analysed in this study. Observer trips were mainly carried out in the Reunion and Madagascar EEZs, from 2007 to 2015 (Figure 1a).

### 2.3.2 Scientific surveys

Fishery data collected during those surveys are more detailed than observer data (supplementary data such as hooking time, hook position on the capture, additional measurement data can also be collected). A total of 10 trips (representing 87 fishing operations and 51206 hooks set) were analysed in this study. Those surveys were carried out in the frame the Ecological-Based Artificial Bait (EBAB), PROSpection and habitat of large PElagic fish in the EEZ of Reunion Island (PROSPER) and Mitigating Adverse Ecological Impacts of Open Ocean Fisheries (MADE) projects. Scientific trips were carried out in the Mozambique Channel and in the Reunion and Tromelin EEZs from 2008 to 2012 (Figure 1b).

### 2.3.3 Self-reporting program

The self-reporting (SRP) program, monitored by IRD and CAP RUN, was developed in the frame of the European Data Collection Framework and is on-going since April 2011 (Bach et al., 2013). In Reunion Island, the size of the small and medium longliners (from 8 to 12 m LOA) does not allow them to get an observer on board. Therefore, the SRP program aims at monitoring their activities. As a result, captains of the longliners involved in this project are required to collect data related to fishing operations (location, date, time, gear configuration), catch composition (total, sold, depredated and discarded catch per species) and interactions with marine mammals, seabirds and sea turtles. Catch and depredation data are reported per species, by lot and by set. A total of 265 SRP trips (representing 1260 fishing operations and 1585662 hooks set) were analysed in this study. Self-reporting trips were mainly carried out around Reunion Island (Reunion EEZ) and along the east coast of Madagascar from 2011 to 2015 (Figure 1c).

## 2.4 Catch and depredation indicators

### 2.4.1 Catch

The nominal CPUE (Catch Per Unit Effort), defined as the total number of fish caught (damaged and intact) per 1000 hooks was assessed by using quarterly and yearly pooled catch and fishing effort data.

$$\text{CPUEt} = \frac{\text{Number of fish caught}}{\text{Number of hooks}} * 1000 \text{ and CPUEc} = \frac{\text{Number of fish commercialised}}{\text{Number of hooks}} * 1000$$

### 2.4.2 Depredation

Four indicators were used in this analysis to characterize depredation.

- Interaction Rate (Nishida and Tanio, 2001; Romanov et al., 2007, 2013)

The Interaction Rate (IR) is the proportion of longline sets depredated by sharks (IRs) or toothed whales (IRc). IR was calculated using the whole dataset 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.

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

- Gross Depredation Rate (Donoghue et al., 2002; Romanov et al., 2007, 2013)

The Gross Depredation Rate (GDR) was defined as the total number of fish depredated by toothed whales and/or sharks divided by the total number of fish caught. All fishing sets were considered to assess toothed whale Gross Depredation Rate (GDRc) and shark Gross Depredation Rate (GDRs). Quarterly and yearly values of GDR were computed on the quarterly or yearly pooled catch.

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

- Depredation Per Unit Effort (Ramos-Cartelle and Mejuto, 2007; Romanov et al., 2007, 2013)

The Depredation Per Unit Effort (DPUE), was calculated per set and per predator group, and was defined as the number of fish depredated per 1000 hooks. DPUE was assessed by quarter by using quarterly pooled catch and fishing effort data. Only fishing sets affected by toothed whales and/or sharks depredation were considered to assess DPUEc* and DPUEs* respectively.

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

- Damage Rate (Rabearisoa, 2013)

The Damage Rate (DR) was calculated per set and per predator group, and was defined as the proportion of fish depredated among the total catch at the scale of a fishing operation. Quarterly and yearly values of DR were calculated as the mean of the DR values calculated for a given quarter or year. Only fishing sets affected by toothed whales and/or sharks depredation were considered to assess DRc* and DRs* respectively.

$$\text{DR} = \frac{\text{Number of fish depredated}}{\text{Number of fish caught}}$$

# 3 Results

## 3.1 Summary of fishing effort

The overall study area extended between latitudes 30 S and 13 S and longitudes 39 E and 71 E and covered the 2007-04 to 2015-03 period (Figure 1). From 2007 to mid-2011, only scientific and observer data were available, and the spatial coverage sporadically spread in the Mozambique Channel, around La Reunion and along the east coast of Madagascar. Since the beginning of the self-reporting program in May 2011, data coverage significantly increased and is now mainly concentrated from the Reunion EEZ westward to the east coast of Madagascar (Figure 2, page 22). Monthly total CPUE (in number of individuals/1000 hooks) was highly variable and depicted a strong seasonality (Figure 3, page 23). A total of 1907 fishing operations with a total effort of 2372837 were considered (Table 1). The fishing effort per set averaged 1244 hooks and ranged from 135 to 1864 hooks. Data were collected from a total of 37 vessels (38% less than 13 m LOA (length over all), 24% about 13 m LOA, 19% between 16 m and 18 m LOA, and 19% between 20 m and 25 m LOA).

## 3.2 Depredation indicators

Depredation indicators were computed by quarter between 2007 and 2015 to assess the seasonality and interannual variations of depredation impact of both shark and toothed whale depredation.

### 3.2.1 Interaction rate

A total of 790 fishing operations were depredated (IR=41%), 165 were depredated by toothed whales (IRc=9%), 523 were depredated by sharks (IRs=27%) and 102 were depredated by both groups (IRb=5%).

The main toothed whale depredation hotspots were located around Reunion and along the east coast of Madagascar. The southern part of the Madagascar EEZ seemed to be depredation free (Figure 4, page 24). In contrast, shark depredation occurred all over the whole study area and all year long, and no particular shark depredation hot-spot could be identified (Figure 5, page 25).

### 3.2.2 Gross Depredation Rate

The overall gross depredation rate was defined as the percentage of fish depredated among the whole catch. The yearly values of the gross depredation rate (including both shark and toothed whale depredation) varied between 1.4% and 6.3% (Table 3 and Figure 6).

A total of 45989 commercial species fish were caught (29% of swordfish, 43% of tuna, 2% of billfish and 26% of dolphinfish). Even if not the main target species, tuna represented more than half of the total number of fish depredated (58.5%). Swordfish represented 33% of the total number of fish depredated (Table 2).

***Toothed whale GDR***

Similarly to interaction rate, quarterly values of toothed whale gross depredation rate (GDRc) were low before 2011 (from 0 to 4.4%, median = 0.3%). Since 2011, GDRc increased (range = 0.3-6.3%, median = 2.3%). Most of the highest GDRc values were observed during the first quarter (3.8% in 2011, 4% in 2013, 4.4% in 2014 and 6.3% in 2015) (Table 3).

***Shark GDR***

Shark gross depredation rate (GDRs) values were quite similar before and after 2011 and low variability was observed over time (range: 0.2-8%, median = 2.5%).

#### 3.2.3 Depredation per unit effort

***Toothed whale DPUE***

When toothed whale depredation was observed, quarterly values of DPUEc* ranged from 0.31 to 6.88 fish (median = 2.69). Since mid-2012, DPUEc* values tend to stabilize around an average value of 3.41 (Table 3 and Figure 6).

***Shark DPUE***

Quarterly values of DPUEs* ranged from 0.46 to 2.38, showing low variability (median = 1.21) (Table 3 and Figure 6).

#### 3.2.4 Damage rate

***Toothed whale DR***

For toothed whale depredated sets, quarterly DRc* was highly variable (range = 1.4-38.1%, median = 16.8%) with lower values prior to 2011 (range: 0-25.2%, median = 1.6%). Since 2011, DRc* values significantly increased (range: 1.4-38.1%, median = 22%), with particularly high values during the first and the third quarters, where 22% to 38% of the catch were lost to depredation. It should be noted that the yearly values of DRc*, calculated as the mean of the quarterly values of DRc* increased over time: from 7.8% in 2009 to 24.1% in 2014 (Table 3 and Figure 6).

***Shark DR***

For shark depredated sets, DRs* showed low variability, except for a peak during the first quarter of 2010 compared to DRc* (Table 3 and Figure 6). DRs* values ranged from 3.2 to 25% (median = 6.45%), suggesting that shark depredation is less detrimental than toothed whale depredation when it occurs.

## 3.3 Depredation impact on commercial CPUE

### 3.3.1 Toothed whale depredation

Toothed whale depredation impact was lower impact when fishing operations were monitored in the south of Madagascar before 2011 (Table 3). On the contrary, toothed whale depredation displays higher rates since 2011, when the fishing effort was concentrated between the east coast of Madagascar and Reunion and when data from coastal smaller longliners became available from the self-reporting program. For both fishing grounds (east Madagascar and Reunion (latitude>25°S) /south Madagascar (latitude<25°S)), catch and depredation data were pooled to compare the overall total and commercial CPUE, DPUE and damage rate. For non impacted sets, the total CPUE (in number of fish caught per 1000 hooks) was 15.7/27.7 and the commercial CPUE (in number of fish sold per 1000 hooks deployed) was 15.1/26.7. For toothed whale depredated sets, the total CPUE was 17.7/39.4, the commercial CPUE was 13.8/34, the DPUE (in number of fish depredated per 1000 hooks deployed) was 3.2/1.8, the damage rate (in % of fish depredated per fishing operation) was 18/4.6 and the interaction rate (in % of depredated sets) was 14/11% (Table 4).

A slight decrease of the total and commercial CPUE is observed, either for depredated or non-depredated sets. This suggests a general CPUE decrease over the years, due to the reallocation of the fishing effort from the south of Madagascar to Reunion/east Madagascar (Table 3). This CPUE decrease, combined to a slight increase of toothed whale DPUEc* (Figure 6), results in a deleterious impact on the commercial CPUE for toothed depredated-sets and in an increased DRc*: since 2012, the amount of commercialized fish is lower on toothed whale depredated-sets than on non-depredated ones (Figure 7).

### 3.3.2 Shark depredation

On the other hand, shark DPUE is quite stable over the quarters. No period of high or low shark depredation was identified. For sets impacted by shark depredation, DRs* ranged from 0.4% and 6.3% (median DRs* = 2.2) and DPUEs* ranged from 0.1 and 1.1 (median DPUEs* = 0.4). Compared to toothed whale depredation, its impact on the commercial CPUE was low, and for 22 quarters out of 28, the commercial CPUE was even higher for shark depredated sets than for non-depredated ones (Figure 7).

# 4 Discussion

## 4.1 Accuracy of self-reported data

The overall depredation occurrence (considering shark and/or toothed whale depredation) was significantly higher for observer (35.6%) than for self-reporting data (52.9%). Toothed whale interaction rate was fairly similar for both data type (9.7% for self-reporting data and 6.8% for observer data). On the other hand, shark interaction rates significantly differed (21.9% for self-reporting data, 38.3% for observer data) suggesting that shark depredation may be underreported in self-reported data. Sometimes, fishermen may not take small losses into account (for instance, when only one or two fish are lost per fishing operation, or if the fish depredated suffered minor damage and was still marketable), resulting in an underestimation of the accurate occurrence frequency of shark depredation. Also, the self-reporting data were partly provided by coastal smaller longliners that may be less affected by shark depredatation than bigger longliners, but this assumption should be checked in a further work. Similarly to the toothed whale depredation frequency, the toothed whale gross depredation rates observed for both self-reporting and observer data were fairly alike (2.1% for self-reporting data and 1.7% for observer data). Shark gross depredation rate was lower for self-reporting data (1.7% versus 2.4%). It should be noted that a higher proportion of damages were attributed to depredation by both predators (0.6%) for self-reporting data. Before 2014, self-reporting forms were less detailed than the actual ones. Fishermen reported a gross number of fish depredated (without predator distinction) per fishing operation and ticked a box if the set was depredated by toothed whales and/or sharks. If depredation by both predators occurred during the fishing operation, we had to consider that the reported depredation resulted from double depredation. Since 2014, more detailed forms were provided to fishermen and more accurate depredation report was obtained: the proportion of catch impacted by double depredation dropped to 0. Similar levels of yearly depredation rates were observed for both observer and self-reported data, justifying the reliability of depredation reports provided by fishermen (Figure 8). Moreover, the overall gross depredation rate (GDRc+GDRs+GDRb) was similar for both data types: 4.4% for self-reporting data and 4.1% for observer data (Table 5). When considering the sets exclusively depredated by sharks or toothed whales, DRc* and DRs* were similar for both data types: when shark or toothed whale depredation is reported by fishermen, the information can be considered as reliable as well (Table 5).

## 4.2 Comparative impact of toothed whale and shark depredation

The frequency of depredation events by sharks was three times higher than by toothed whales. Nonetheless, the loss induced by cetaceans was twice to four times higher when it occurred. Results found in this study are fully consistent with a study carried out on the subset of self-reporting operations for the 2011-2013 period (Romanov et al., 2013), and other studies worldwide. For instance, in Brazil, in comparison with shark depredation, average killer whale depredation rate was twice higher but less frequent (Monteiro et al., 2006; Dalla Rosa and Secchi, 2007). First studies undertaken in the Indian Ocean reported an average depredation rate by killer whales of 55% (Sivasubramanian, 1964). Shark depredation rate was four times lower, but shark depredation events were also more frequent. Depredation data from a Soviet historical database assessed that on average in the Indian Ocean, cetacean damages per set were twice higher than shark ones (Romanov et al., 2007). Similarly, in the waters off Brazil and the Azores archipelago, even if the proportion of sets depredated by toothed whales compared to sharks was low, catch loss was higher (Hernandez-Milian et al., 2008). A recent depredation study involving Seychelles semi-industrial longline fishery assessed that 19% of the overall swordfish catch was lost to depredation (GDRc=9% and GDRs=10.5%). Toothed whale depredation was three times less frequent than shark depredation (IRc=16% and IRs=50%). Nevertheless, the average damage per depredated set was higher when toothed whale depredation occurs (DRc*=53% and DRs*=13%, DPUEc*=19.3 fish and DPUEs*=4.8 fish). Therefore, shark and toothed whale depredation impacting Seychelles and Reunion longline fisheries displayed a similar pattern. However, depredation affects the overall catch more heavily in Seychelles, which appears to be a depredation hot-spot (Rabearisoa, 2013).

Differences in depredation rates and frequencies between sharks and toothed whales can be explained by the fact that shark attacks are done by isolated individuals, whereas toothed whale attacks are

generally done by several individuals as it was sometimes observed by fishermen, observers on board and during scientific surveys with pelagic longlines. These collective attacks may lead to high depredation rates at the level of the set. When depredation occurs, isolated sharks seem to attack fish randomly (and take only a few of them) whereas toothed whale groups seem to depredate longlines in a methodical way, attacking fish one after the other along the line (Sivasubramanian, 1964; Forney et al., 2011).
Furthermore, in comparison with sets not impacted by depredation, the amount of marketable fish was significantly lower when toothed whale depredation occurred, while shark depredation did not seem to affect this variable. Similarly, depredation by toothed whales on demersal longline fisheries significantly reduced the number of intact fish in Alaska and in South Georgia (Hill et al., 1999; Straley et al., 2002; Purves et al., 2004).

### 4.3 Why implementing depredation indicators?

Several depredation indicators were implemented in this study. They allowed to assess depredation impact at various levels: in terms of proportion of impacted fishing sets, proportion of catch depredated (globally or on depredated sets), amount of fish lost per 1000 hooks or per fishing operation, proportion of fish lost among the total catch. The review of available literature shows that several measures of depredation are used and no standard index of depredation has been implemented. Also, the definition of depredation can also be different. Thus, depredation can be defined and quantified as the percentage of damaged fish (in weight or in number) among the overall catch, the percentage of damaged fish in sets impacted by depredation exclusively, the percentage of sets or trips affected by depredation or the induced monetary loss to industry. Those estimates were obtained from various methods that did not allow appropriate comparisons between fisheries. Therefore, a standard depredation index should be defined. Since information about the fishing effort or the number of operated fishing operations or trips are not always available, the most appropriate depredation index should be the percentage of damaged fish, in weight or in number, among the overall catch (namely GDR in our study). When working on fishery-dependant data (especially if data are provided by fishermen reports or logbooks), catch data is the most relevant and generally available information in every fishery.
Other indicators can also be considered. For instance, the interaction rate could be a relevant index, as it depicts depredation occurrence. It allowed us to compare, for instance, shark and toothed whale depredation frequency, shark depredation being twice to three times more frequent. If additional and more detailed information are available (such as fishing effort or catch and depredation data per fishing operation), the percentage of damaged fish per damaged fishing operation and the number of fish lost per unit effort (1000 hooks for instance) can also be relevant depredation descriptors (respectively DR* and DPUE* in our study). They allowed us to show that, when depredation occurs, toothed whale damages are much more deleterious.

### 4.4 Relative comparison of Reunion and other fisheries depredation rates

Sporadic estimates of shark and/or toothed whale depredation in pelagic longline fisheries can be found in both scientific reports and scientific literature (Table 6). Despite the fact that those figures were obtained from various methods, we attempted to review the available literature providing some depredation rate estimates (Sivasubramanian, 1964; Hirayama, 1976; Lawson, 2001; Poisson et al., 2001; Nishida and Shiba, 2003; Monteiro et al., 2006; Ariz et al., 2007; Clark et al., 2007; Dai et al., 2007; Dalla Rosa and Secchi, 2007; de Fries et al., 2007; Ramos-Cartelle and Mejuto, 2007; Romanov et al., 2007; Varghese et al., 2007; Hernandez-Milian et al., 2008; Oleson et al., 2010; Rabearisoa, 2013; Romanov et al., 2013). For the Reunion pelagic longline fishery, we showed that shark damage rate (DRs*) median was 6.45% while it reached 16.8% for toothed whales depredated sets. Our results are slightly lower than the ones found in the literature: 11 to 21% for shark depredation and from 18 to 55% for toothed whale depredation. The yearly gross depredation rate (between 4 to 6.3%) sustained by Reunion longliners is similar to the values observed in other regions of the world where GDR ranged from 0.2 to 15% . Those results suggest that comparatively to other fishing grounds, shark and toothed whale depredation apparently induce lesser fish loss. However, interaction rates found in Reunion (IRc=9% and IRs=27%) are higher than the ones assessed in other areas, where IRs ranged from 20 to 25.6% and IRc ranged from 1.6 to 4.8%. Given the high depredation rates also found in Seychelles, the southwest Indian Ocean is likely to be a fishing area frequently affected by both toothed whale and shark depredation. Actually, based on the comparative values of depredation indicators calculated for the Seychelles pelagic longline fishery (Rabearisoa, 2013) and for our fleet of interest, there might be a southward decreasing toothed whale depredation gradient in the southwest Indian Ocean.

### 4.5 Study limits and biases of the depredation indicators

Data considered in the study are fishery-dependent, even if several sources where investigated: self-reported data, scientific trips and observer-monitored trips. For instance, available fishery data did not take into account the hooks that no longer have a bait or capture at hauling. Two hypotheses can be considered: (i) invertebrates (e.g. squids), toothed whales (such as dolphins) or an escaped fish could have eaten the bait, and (ii) the fish caught could also have been totally depredated (Etienne et al., 2010). Based on those uncertainties, vacant hooks may represent a part of unseen depredation though we cannot estimate it for now. Shark depredation can also be underestimated: if a fish is not heavily depredated, or if only a few fish are lost on the longline, this may not be reported. But shark depredation may also be overestimated: based on the observer data, 34% of the shark-fish depredated can still be kept onboard, while almost all toothed whale-fish depredated are discarded. Depredation by multiple predators can also occur on a fish, leading to inaccurate or multiple attribution of fish damage to predator categories. A bias might also arise from the uncertainty on predator group identification, discrimination between shark and toothed whales depredation from fish carcasses not being always obvious. Indeed, a possible misidentification might occur when fishermen report depredation events. Those biases could not be quantified and may likely lead to an underestimation of the real depredation impacting Reunion-based pelagic longliners. Results presented here are estimates for depredation rates for what could actually be observed, hence minimum depredation estimations for Reunion Island longline fishery.

# 5 Conclusion and perspectives

Given the disastrous consequences of depredation impacting fishermen, predators and target fish, it is crucial to monitor this phenomenon. However, this is a challenging issue, given the obvious lack of knowledge of the ecology and migration patterns of the involved species. Depredation monitoring should involve both scientists and fishermen, and include the development of standard data sheets (Romanov et al., 2009a), the use of a standard depredation index and appropriate quantification methods. Depredation impacting pelagic longline is a poorly understood phenomenon, especially in the southwest Indian Ocean. Improvement of the knowledge about depredation should give us valuable insights for the development of efficient depredation mitigation measures to reduce their impacts, in accordance with an ecosystemic approach to fisheries (EAF). The overall profitability of Reunion pelagic longline fisheries is low due to increased running costs and low fish prices. Consequently, even the slightest loss is likely to induce disastrous effects on fisheries (Romanov et al., 2013). It is now necessary to carry out a study to assess the economic impact of depredation by taking into account direct costs linked to depredation (amount of fish depredated) and indirect ones (additional running costs incurred by fishermen when leaving a depredated area, bait loss, etc).

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## Tables and figures

| Year | Tot. fishing effort | SRP effort | Obs. effort | Sci. effort | SRP coverage | Obs coverage |
|---|---|---|---|---|---|---|
| 2007 | 4273000 | 0 | 21499 | 0 | 0 | 0.5 |
| 2008 | 3128234 | 0 | 16500 | 8280 | 0 | 0.53 |
| 2009 | 3631503 | 0 | 94429 | 0 | 0 | 2.6 |
| 2010 | 3781552 | 0 | 71694 | 13575 | 0 | 1.9 |
| 2011 | 3769249 | 132678 | 114268 | 19159 | 3.52 | 3.03 |
| 2012 | 3367938 | 505735 | 119750 | 10192 | 15.02 | 3.56 |
| 2013 | 4042075 | 511584 | 131577 | 0 | 12.66 | 3.26 |
| 2014 | 3573445 | 371199 | 141786 | 0 | 10.39 | 3.97 |
| 2015 | - | 64466 | 24466 | 0 | - | - |

Table 1: Fishing effort covered per year and per program (SRP: self-reporting trips, Obs: observer-monitored trips, Sci: scientific trips). NB: For 2015, only data collected during the first quarter were considered.

| Group | Nb_Capt | Nb_Dep | Prop_Dep |
|---|---|---|---|
| Swordfish | 13121 | 655 | 33.0 |
| Tuna | 19612 | 1161 | 58.5 |
| Billfish | 1070 | 25 | 1.3 |
| Dolphinfish | 12186 | 144 | 7.3 |

Table 2: Capture and depredation (in number and in percent of fish depredated) per fish group.

| Quarter | Nsets | CPUEt_intact | CPUEs_intact | CPUEt_c* | CPUEs_c* | CPUEt_s* | CPUEs_s* | IR | IRc+IRb | IRs+IRb | GDR | GDRc+ GDRb | GDRs+ GDRs | DRc* | DRs* | DPUEc* | DPUEs* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007-1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2007-2 | 6 | 11.7 | 10.3 | 19 | 19 | 14.9 | 14.1 | 66.7 | 16.7 | 50 | 4.4 | 1.5 | 2.9 | 4.5 | 7.5 | 0.86 | 0.98 |
| 2007-3 | 7 | 6.1 | 6.1 | 0 | 0 | 6.1 | 6.1 | 71.4 | 0 | 71.4 | 2.5 | 0 | 2.5 | 0 | 3.2 | 0 | 0.46 |
| 2007-4 | 7 | 40.9 | 40.9 | 74.5 | 70.8 | 49.3 | 48.4 | 57.1 | 14.3 | 42.9 | 3.2 | 1.3 | 1.9 | 4.9 | 5.8 | 3.64 | 1.82 |
| Annual-2007 | 20 | 22.8 | 22.5 | 46 | 44.3 | 28.2 | 27.6 | **65.1** | **10.3** | **54.8** | **3.4** | **0.9** | **2.4** | **3.1** | **5.5** | **1.5** | **1.1** |
| 2008-1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2008-2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2008-3 | 12 | 32.3 | 31.7 | 0 | 0 | 32.3 | 31.7 | 8.3 | 0 | 8.3 | 0.2 | 0 | 0.2 | 0 | 4.3 | 0 | 0.74 |
| 2008-4 | 14 | 22.2 | 21.5 | 0 | 0 | 22.2 | 21.5 | 35.7 | 0 | 35.7 | 2.6 | 0 | 2.6 | 0 | 5 | 0 | 1.64 |
| Annual-2008 | 26 | 29.4 | 28.8 | 0 | 0 | 29.4 | 28.8 | 22 | 0 | 22 | 1.4 | 0 | 1.4 | 0 | 4.7 | 0 | 1.2 |
| 2009-1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2009-2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2009-3 | 33 | 18.5 | 17.9 | 20 | 18.6 | 18.9 | 18.1 | 57.6 | 21.2 | 54.6 | 3.4 | 0.3 | 3.1 | 1.6 | 5.1 | 0.31 | 1.25 |
| 2009-4 | 38 | 25 | 23.7 | 34.6 | 27 | 25.3 | 21.2 | 63.2 | 26.3 | 52.6 | 6.5 | 4.4 | 2.1 | 14 | 4 | 5.04 | 1.18 |
| Annual-2009 | 71 | 21.7 | 20.7 | 28.3 | 23.4 | 22.3 | 19.7 | 60.4 | 23.8 | 53.6 | 5 | 2.4 | 2.6 | 7.8 | 4.5 | 2.7 | 1.2 |
| 2010-1 | 12 | 5 | 4.7 | 0 | 0 | 5 | 4.7 | 25 | 0 | 25 | 5.3 | 0 | 5.3 | 0 | 25 | 0 | 1.53 |
| 2010-2 | 46 | 23.9 | 22.1 | 29.4 | 22.2 | 25.2 | 23 | 69.6 | 23.9 | 58.7 | 4.7 | 1.8 | 3.1 | 25.2 | 6.3 | 2.51 | 1.62 |
| 2010-3 | 22 | 26 | 24.7 | 0 | 0 | 26 | 24.7 | 54.5 | 0 | 54.5 | 2.5 | 0 | 2.5 | 0 | 4.8 | 0 | 1.12 |
| 2010-4 | 8 | 14.5 | 0 | 11.6 | 0 | 14.5 | 0 | 50 | 12.5 | 50 | 6 | 2 | 4 | 16.7 | 9.2 | 1.94 | 1.06 |
| Annual-2010 | 88 | 22.4 | 20.2 | 28.6 | 21.1 | 23.3 | 20.9 | 49.8 | 9.1 | 47 | 4.6 | 1 | 3.7 | 10.5 | 11.3 | 1.1 | 1.3 |
| 2011-1 | 33 | 10.3 | 7.8 | 30.7 | 21.1 | 10 | 7.2 | 57.6 | 12.1 | 54.6 | 11.8 | 3.8 | 8 | 38.1 | 11.4 | 4.59 | 2.38 |
| 2011-2 | 43 | 19.3 | 15.5 | 20.1 | 16.2 | 18.3 | 14.4 | 48.8 | 28 | 34.9 | 8.2 | 4.5 | 3.7 | 20.6 | 7.9 | 2.74 | 1.55 |
| 2011-3 | 76 | 19.8 | 18.7 | 47 | 44.4 | 20.2 | 19.1 | 35.5 | 9.2 | 34.2 | 2 | 0.3 | 1.7 | 1.4 | 6.1 | 0.69 | 1.23 |
| 2011-4 | 90 | 31.3 | 30.8 | 28 | 23.4 | 29.1 | 27.6 | 57.8 | 21.1 | 43.4 | 3.3 | 2.3 | 1.6 | 14.8 | 4.3 | 4.11 | 1.37 |
| Annual-2011 | 242 | 22.9 | 21.6 | 29.5 | 25 | 22.7 | 20.9 | 49.9 | 17.6 | 41.8 | 6.3 | 2.7 | 3.8 | 18.7 | 7.4 | 3 | 1.6 |
| 2012-1 | 33 | 18.6 | 18.4 | 5 | 2.5 | 18.6 | 18.4 | 48.5 | 3 | 48.5 | 4.5 | 0.3 | 4.2 | 33.3 | 9.9 | 1.67 | 1.47 |
| 2012-2 | 85 | 11.8 | 11.2 | 9.6 | 7.9 | 10.9 | 10.1 | 47.1 | 20 | 34.2 | 3 | 1.4 | 2.3 | 8.6 | 6 | 0.81 | 0.76 |
| 2012-3 | 230 | 16.1 | 15.6 | 12.6 | 9.6 | 15.7 | 15 | 35.7 | 8.2 | 29.1 | 3.5 | 1.3 | 2.5 | 22 | 8.1 | 2.69 | 1.42 |
| 2012-4 | 144 | 21.9 | 21.6 | 24.8 | 21.4 | 22 | 21.2 | 58.3 | 19.4 | 50 | 5 | 2.8 | 3.8 | 15.2 | 8 | 3.25 | 1.78 |
| Annual-2012 | 492 | 16.9 | 16.4 | 17.1 | 14.3 | 16.5 | 15.8 | 47.4 | 12.6 | 40.5 | 4 | 1.4 | 3.2 | 19.8 | 8 | 2.1 | 1.4 |
| 2013-1 | 127 | 11.3 | 11 | 9.5 | 5.5 | 10.7 | 10 | 36.2 | 12.6 | 28.3 | 6.6 | 4 | 4.5 | 35.4 | 11 | 3.76 | 1.9 |
| 2013-2 | 93 | 12.2 | 10.7 | 13.9 | 9.5 | 12 | 10.1 | 34.4 | 20.5 | 19.4 | 6.6 | 4.5 | 2.5 | 14.6 | 10.7 | 2.66 | 1.59 |
| 2013-3 | 153 | 12.8 | 12.5 | 15.6 | 11.4 | 12.9 | 12.2 | 23.5 | 9.1 | 17 | 4.1 | 3 | 1.2 | 26.1 | 6.6 | 3.98 | 0.87 |
| 2013-4 | 121 | 23.3 | 23.1 | 26.8 | 22.9 | 23.4 | 23.1 | 43 | 15.7 | 34.7 | 3.5 | 2.2 | 1.3 | 13.6 | 3.3 | 3.51 | 0.91 |
| Annual-2013 | 494 | 14.6 | 14.1 | 16.9 | 12.8 | 14.5 | 13.6 | 34.3 | 14.5 | 24.9 | 5.2 | 3.4 | 2.4 | 22.4 | 7.9 | 3.5 | 1.3 |
| 2014-1 | 110 | 11.4 | 10.8 | 12.8 | 8.1 | 11.5 | 10.4 | 33.6 | 12.7 | 22.7 | 6.5 | 4.4 | 2.1 | 33.5 | 7 | 4.27 | 1 |
| 2014-2 | 90 | 15.7 | 14.2 | 18.4 | 14.1 | 16.2 | 14.3 | 35.6 | 13.3 | 24.4 | 3.6 | 1.8 | 1.8 | 16.8 | 8.7 | 2.07 | 1 |
| 2014-3 | 68 | 15.8 | 15.1 | 12.3 | 9.2 | 15.4 | 14.2 | 35.3 | 13.3 | 23.6 | 3.7 | 1.7 | 1.9 | 22 | 5.4 | 2.07 | 1.06 |
| 2014-4 | 124 | 21.3 | 21.1 | 12 | 9.5 | 20.1 | 19.6 | 39.5 | 12.9 | 29.8 | 2.8 | 1.2 | 1.7 | 24.2 | 4.7 | 2.33 | 1.02 |
| Annual-2014 | 392 | 16 | 15.3 | 13.7 | 10 | 15.6 | 14.5 | 36 | 13.1 | 25.1 | 4.2 | 2.3 | 1.9 | 24.1 | 6.5 | 2.7 | 1 |
| 2015-1 | 82 | 12.4 | 11.4 | 14 | 6.4 | 12.7 | 10.7 | 34.1 | 12.2 | 24.4 | 8.1 | 6.3 | 1.8 | 35.8 | 6.8 | 6.88 | 0.84 |

Table 3: Catch and depredation indicators per quarter (c: toothed whale; s: shark; b: double depredation). CPUEtot is the number of fish caught per 1000 hooks. CPUEsold is the number of fish sold per 1000 hooks. CPUEt and CPUEs were computed on the subsets of non-depredated sets (intact), toothed whale-depredated sets (c*) and shark-depredated sets (s*). IR is the proportion of depredated sets. GDR is the percentage of fish depredated among the whole catch. DR is the percentage of fish depredated per fishing operation. DPUE is the number of fish depredated per 1000 hooks. *: the indicator was computed on depredated sets only.

| | CPUEt_nodep | CPUEc_nodep | CPUEt* | CPUEc* | DPUEc* | DRc* | IRc |
|---|---|---|---|---|---|---|---|
| Reu./East Mad. | 15.70 | 15.10 | 17.70 | 13.80 | 3.20 | 18.00 | 14.00 |
| South Mad | 27.70 | 26.70 | 39.40 | 34.00 | 1.80 | 4.60 | 11.00 |

Table 4: Comparison of total and commercial CPUE, DPUE, DR and IC for non depredated and toothed whale depredated sets in Reu./East Mad. (N sets=1700) and South Mad. (N sets= 207)

| | IRc | IRs | IRb | IR | GDRc | GDRs | GDRb | DRc* | DRs* |
|---|---|---|---|---|---|---|---|---|---|
| Self-reporting (n=1262) | 9.70 | 21.90 | 4.00 | 35.60 | 2.10 | 1.70 | 0.60 | 23.20 | 6.50 |
| Observer (n=648) | 6.80 | 38.30 | 8.20 | 52.90 | 1.70 | 2.40 | 0.00 | 24.50 | 6.00 |

Table 5: Interaction, Gross Depredation and Damage Rates per predator (c: toothed whale, s: shark) and data source. DR* is calculated on depredated sets only.

| Reference | Country (area) | Target species | Predator | Interaction rate (%) | Damage rate (%) | | Metric |
|---|---|---|---|---|---|---|---|
| | | | | | Depredated sets | All sets | |
| Sivasubramaniam, 1964 | Indian Ocean in general | TUN | KW | | 55 | 4 | W |
| | | | SHK | | 11 | | |
| Hirayama, 1976 | Pacific (Eastern Pacific, South China Sea, Japan, Coral Sea) | TUN | SHK | | | 5-14 | |
| Lawson, 2001 | South Pacific in general | TUN, SWO | TW | | | 0.8 | Nb |
| | | | SHK | | | 2.1 | Nb |
| Poisson et al., 2001 | La Reunion (Southwest Indian Ocean) | SWO | FKW, SFPW | | | 4 | W |
| | | | SHK | | | 3 | W |
| Nishida and Shiba, 2003 | Japan (Indian Ocean ) | TUN | KW, FKW, SHK | | 37 | 15 | Nb |
| Monteiro et al, 2006 | Brasil (Atlantic Ocean) | TUN, SWO | KW, FKW | 4.8 | | 0.48 | |
| | | | SHK | 20 | | 1 | |
| de Fries et al., 2007 | Australia (East coast) | TUN, SWO | TW, SHK, others | | | 0-15 | Nb |
| Dai et al., 2007 | China (Tropical, Pacific Ocean) | TUN, BIL | TW, SHK | 10.9 | | | |
| Varghese et al., 2007 | India (Andaman and Nicobar Islands, Arabian Sea, Indian EEZ) | TUN, SWO | TW, SHK | | 16.28 | | W |
| Romanov et al., 2007 | USSR (Indian Ocean) | TUN | TW | 1.6 | 44-56 | 0.8 | W |
| | | | SHK | 25.6 | 13-16 | 6.0 | W |
| Ramos-Cartele and Mejuto, 2007 | Spain (Atlantic, Indian, Pacific) | SWO | FKW | | | 0.5-2.6 | Nb |
| Ariz et al., 2007 | Spain (Indian Ocean) | SWO | TW, SHK, others | | | 2.3 | Nb |
| Moir Clark et al., 2007 | UK (British Indian Ocean Territory) | TUN, SWO | KW, FKW, SFPW, SHK | | | 2.6 | Nb |
| Dalla Rosa and Secchi, 2007 | Brasil (Southern Atlantic Ocean) | TUN, SWO | KW | | 45 | | Nb |
| | | | SHK | | 21 | | Nb |
| Hernandez-Milian et al., 2008 | Brazil and Azores (Atlantic Ocean) | SHK, TUN, SWO | TW | 1-9 | | 0.2-0.9 | Nb |
| Oleson et al, 2010 | Hawaii (Pacific Ocean) | TUN, SWO | FKW | | 18* | 0.8* | Nb |
| Rabearisoa, 2013 | Seychelles (Indian Ocean) | SWO | TW | 15.9 | 53 | 10.5 | Nb |
| | | | SHK | 49.5 | 13 | 8.8 | Nb |
| Romanov et al. 2013 | Reunion (Indian Ocean) | SWO | TW | 9-14 | 15-36 | 3.3-6.1 | Nb |
| | | | SHK | 22.6-27-1 | 3-9 | | Nb |

Target species abbreviations
BIL: Billfish
SWO: Sworfish (Xiphias gladius)
SHK: Unidentified shark species
TUN: Tuna species (Tuna spp.)

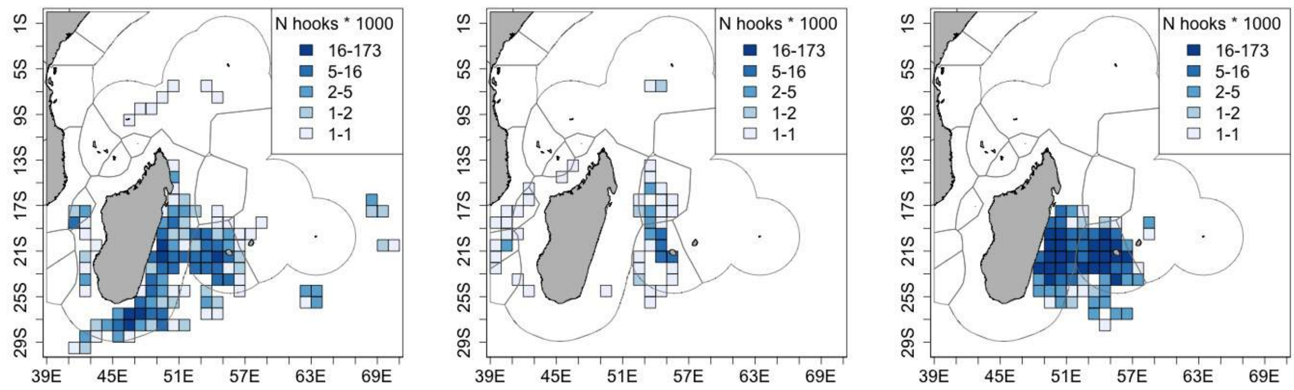
Predator species abbreviations
KW: Killer whale (Orcinus orca)
SFPW: Short-finned pilot whale (Globicephala macrorhynchus)
SHK: Unidentified shark species
TW: Unidentified toothed whale species (Odontoceti)

Metric
Nb: Depredation rate calculated as the proportion of fish lost in number
W: Depredation rate calculated as the proportion of fish lost in weight

* recalculated from swordfish and tuna caught and depredated data (Tab 4-2)

Interaction rate = depredated fishing sets/total number of fishing sets
Damage rate = fish damaged / total number of fish caught (including damaged)
Depredated sets: depredation rate calculated on depredated sets
All sets: depredation rate calculated on all sets (including non affected sets)

Table 6: Review of the available literature about depredation impacting pelagic longline fisheries




(a) Observer cruises

(b) Scientific cruises

(c) Self-reporting cruises

Figure 1: Distribution of fishing effort per trip type

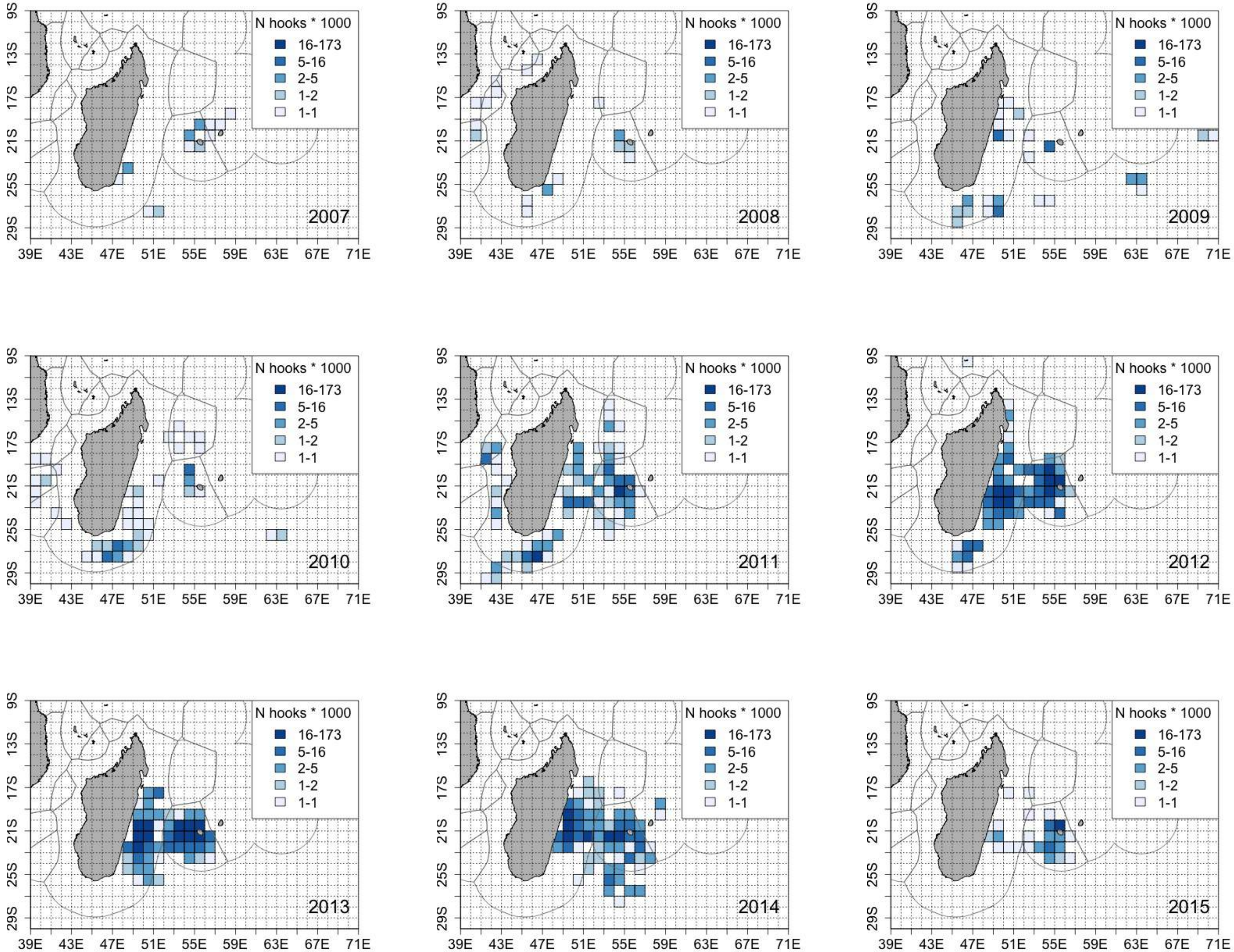



Figure 2: Distribution of fishing effort per year

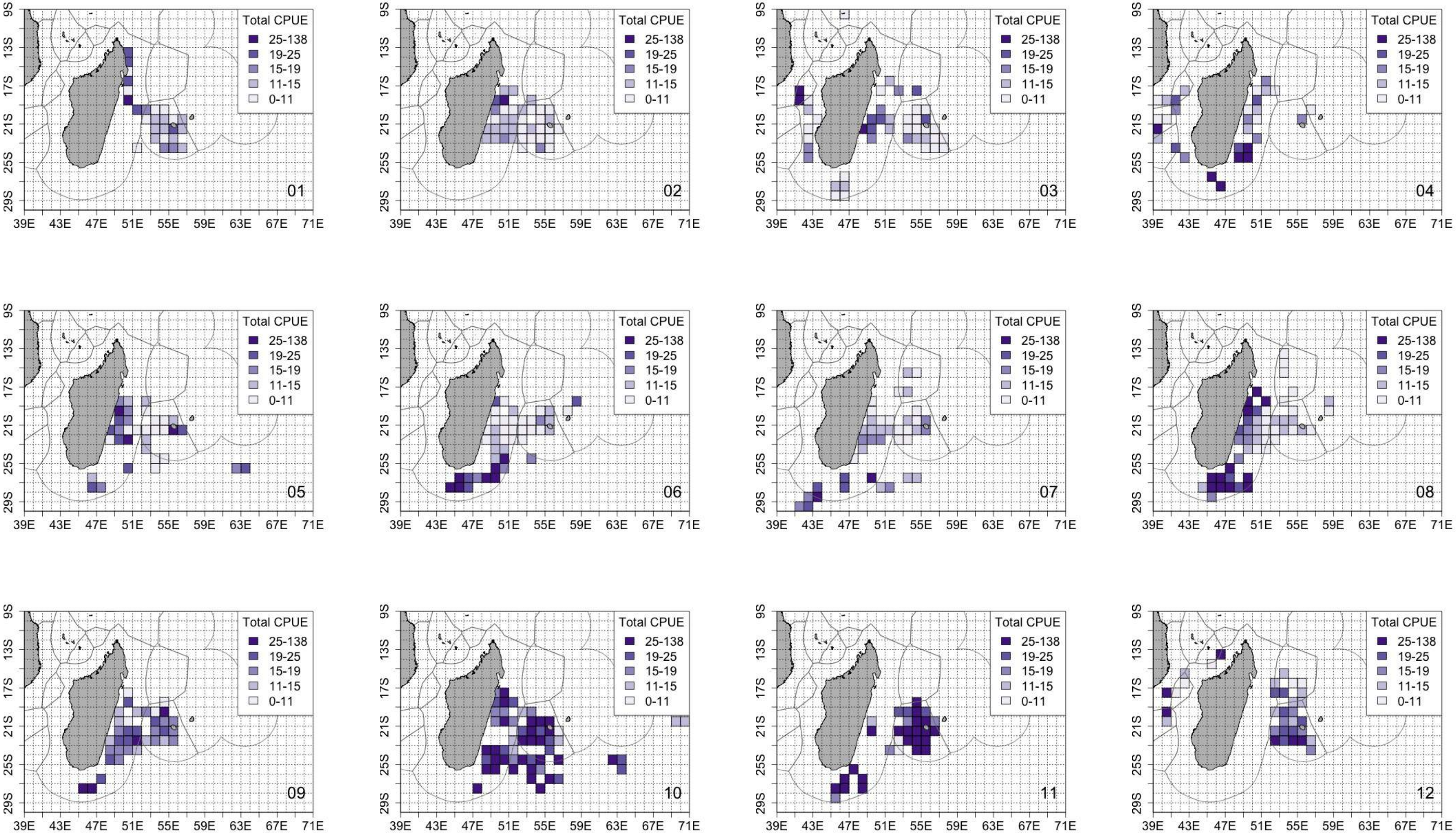



Figure 3: Distribution of total CPUE per month

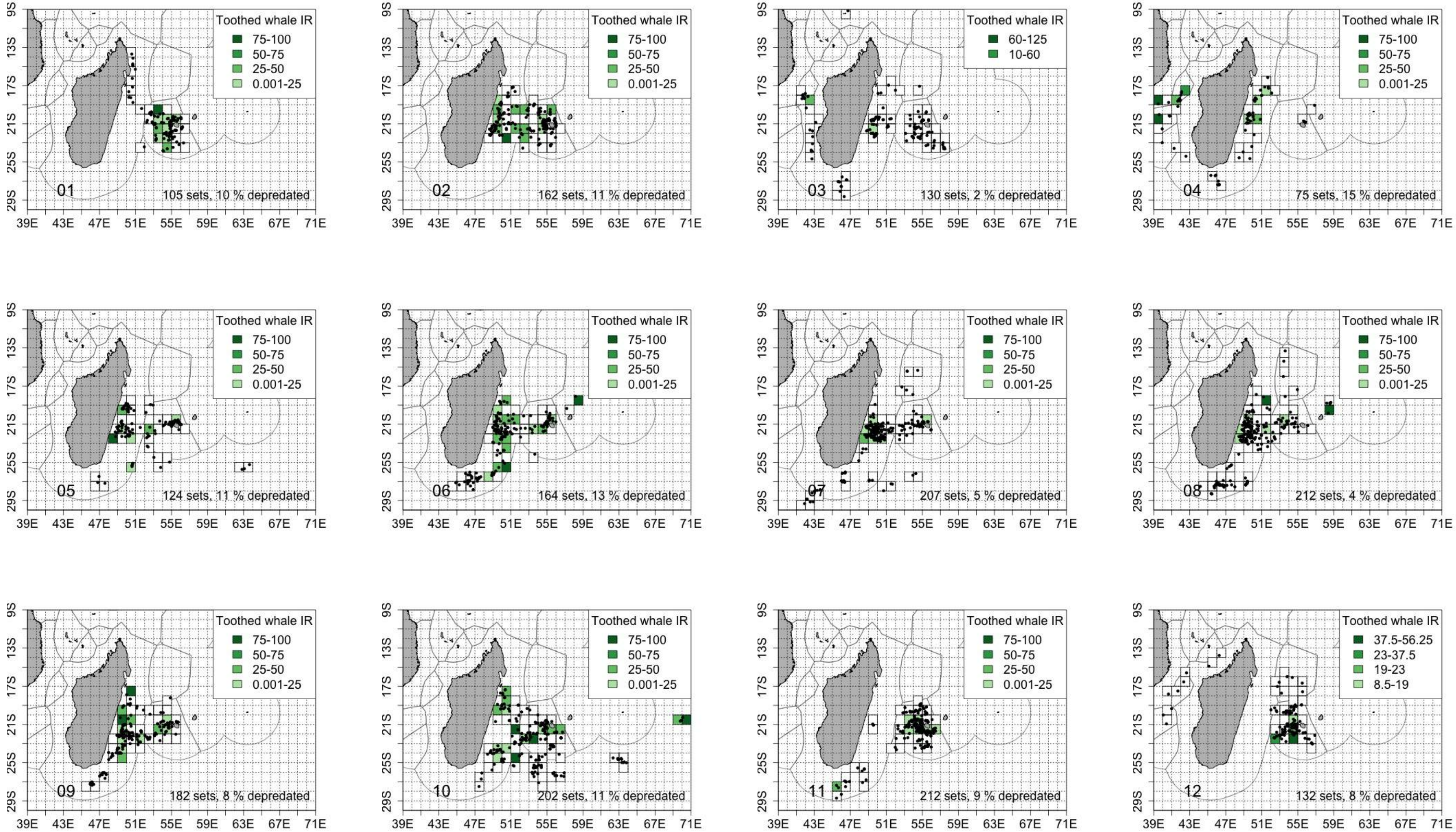



Figure 4: Distribution of toothed whale Interaction Rate per month

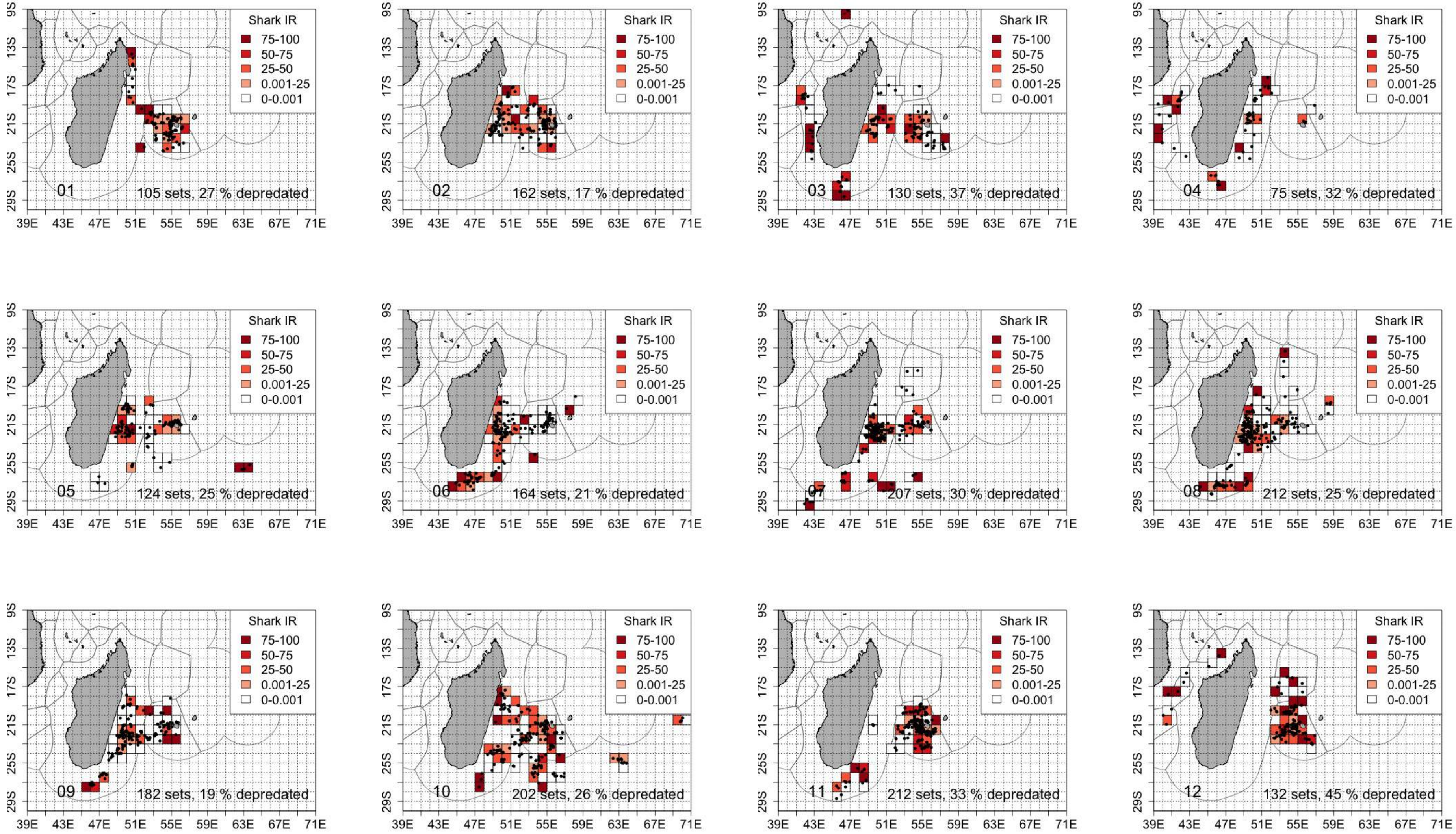



Figure 5: Distribution of shark Interaction Rate per month

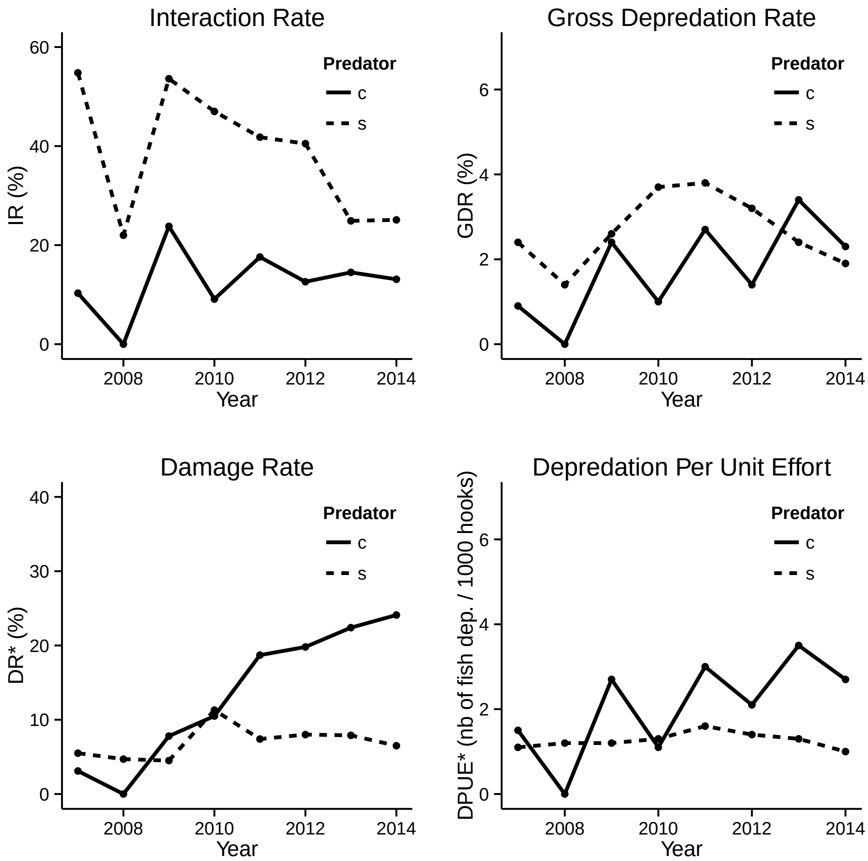



Figure 6: Depredation indicators evolution per year

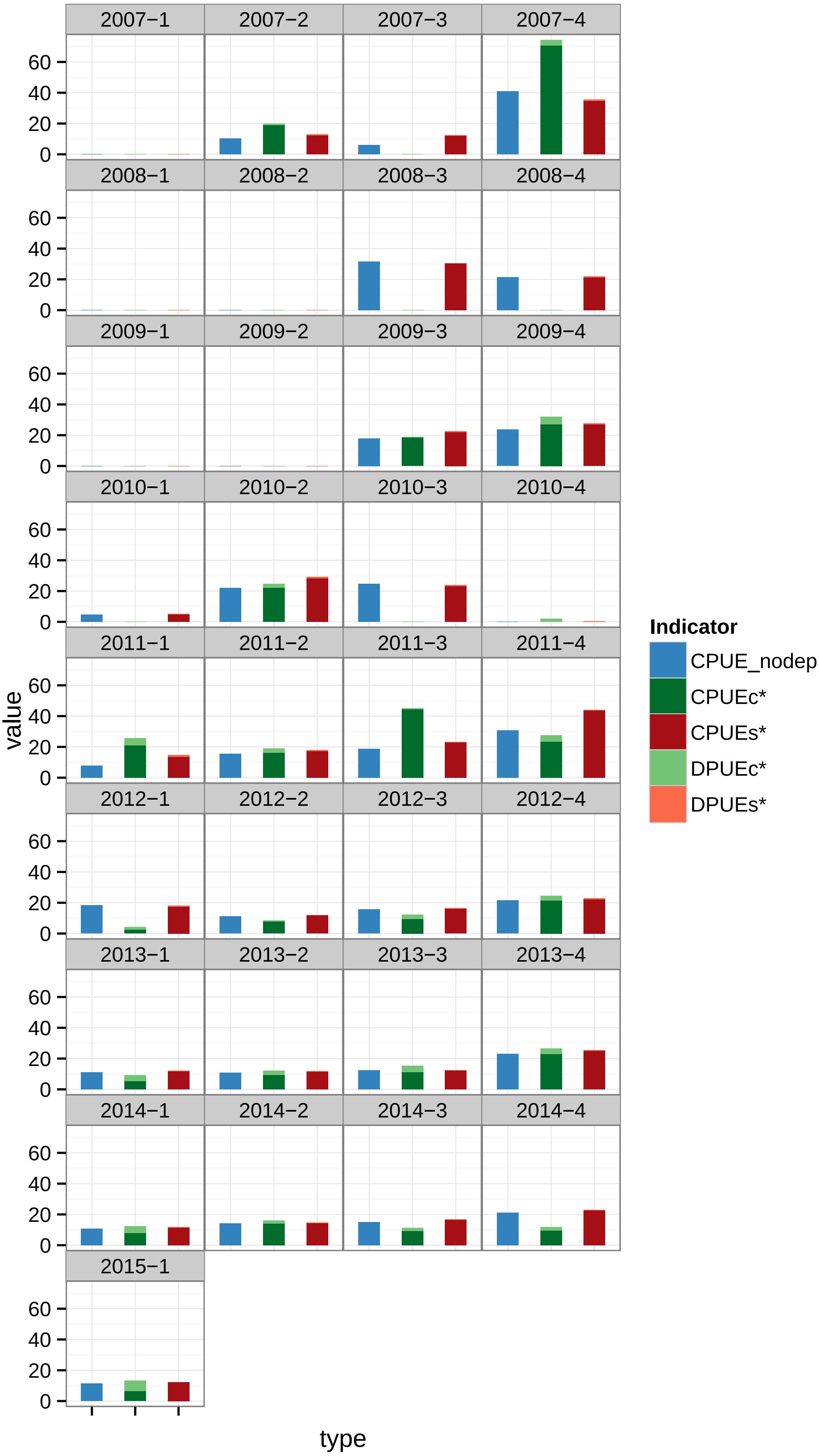



Figure 7: Commercial CPUE and DPUE for non depredated, toothed whale depredated and shark depredated sets per quarter

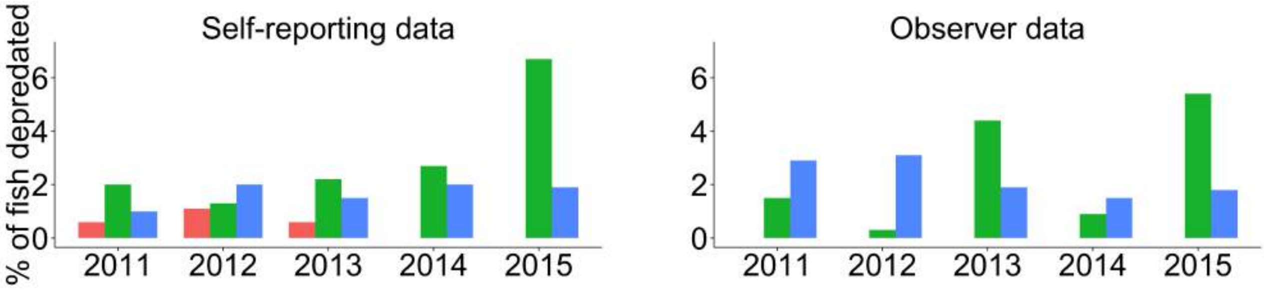



Figure 8: Proportion of fish depredated per year and per predator. Double depredation (pink); toothed whale depredation (green); shark depredation (blue)