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Shark by-catch observed in the bottom longline fishery off the Kerguelen Islands in 2006–2016, with a focus on the traveller lantern shark (*Etmopterus viator*)

Charlotte Chazeau[1]✉, Samuel P. Iglésias[2], Clara Péron[1], Nicolas Gasco[1], Alexis Martin[1] and Guy Duhamel[1]

[1] Muséum national d'Histoire naturelle, Département Adaptations du vivant, UMR 7208 BOREA (MNHN, CNRS, IRD, Sorbonne Université, UCBN), CP 26, 43 rue Cuvier, 75231 Paris Cedex 05, France

[2] Institut Systématique Evolution Biodiversité (ISYEB), Muséum national d'Histoire naturelle, CNRS, Sorbonne Université, Station Marine de Concarneau, Place de la Croix, 29900 Concarneau, France

✉Corresponding author: charlotte.chazeau@mnhn.fr

Abstract

Data collected by fishery observers on board French fishing vessels targeting Patagonian toothfish (*Dissostichus eleginoides*), were examined to quantify and describe shark by-catch within the Kerguelen exclusive economic zone (EEZ). From 2006 to 2016, the fishing crews of longline vessels reported the total catches of the line and observers were asked to identify and count fish by-catch on 25% of the total fishing effort. A total of 26 203 longline hauls and more than 55 million hooks were checked by observers reporting 29 500 individual sharks caught as by-catch. Four shark species were identified (traveller lantern shark – *Etmopterus viator*, southern sleeper shark – *Somniosus antarcticus*, Portuguese dogfish – *Centroscymnus coelolepis* and porbeagle shark – *Lamna nasus*) among which *E. viator* was numerically largely dominant (99%). Relative abundance (number of shark per 1 000 hooks observed) calculated for sets with sharks present, was used to show bathymetric and geographical distributions and biological data were analysed. There were marked differences between distributions of the shark by-catch species and their relative abundance. This study is a major contribution to the ecological knowledge of *E. viator* with a detailed description of its distribution, the deepest record for the species (1 951 m) and the updated length at first maturity for female (48.5 cm). Length-frequency distribution (LFD) for *E. viator* showed a bimodal distribution typical for long-lived species and a sexual dimorphism with females significantly longer than males. Although the stability of LFD through years seems to rule out the possibility of *E. viator* to be at risk in the Kerguelen EEZ, further studies must be conducted to assess population size and mitigate shark by-catch in the French longline fisheries.

Prises accessoires de requins observées dans la pêcherie palangrière de fond au large des îles Kerguelen en 2006–2016, avec une attention particulière pour le sagre long nez (*Etmopterus viator*)

Résumé

Les données collectées par les contrôleurs de pêche à bord des navires de pêche français ciblant la légine australe (*Dissostichus eleginoides*), ont été examinées afin de quantifier et décrire les prises accessoires de requin dans la Zone Economique Exclusive (ZEE) de Kerguelen. Entre 2006 et 2016, les équipages des palangriers ont déclaré la capture totale sur les lignes et les contrôleurs de pêche ont identifié et compté toutes les espèces de prises accessoires sur 25% de chaque ligne. Au total 26 203 palangres et plus de 55 millions d'hameçons ont été contrôlés et 29 500 requins comptabilisés. Quatre espèces de requins ont été identifiées (*Etmopterus viator*, *Somniosus antarcticus*, *Centroscymnus coelolepis* et *Lamna nasus*) parmi lesquelles *E. viator* était numériquement prédominant (99%).

L'abondance relative (nombre d'individus pour 1 000 hameçons observés) calculée pour les lignes en présence de requin, a été utilisée pour montrer la distribution bathymétrique et géographique de ces prises accessoires et les données biologiques ont été analysées. Les résultats ont montré des différences marquées entre les distributions des différentes espèces de requins et leur abondance relative. Cette étude constitue une contribution majeure à la connaissance écologique d'*E. viator* avec une description détaillée de sa distribution, le record de profondeur pour l'espèce (1 951 m) et une longueur à première maturité actualisée pour les femelles (48,5 cm). L'analyse de la fréquence de taille chez *E. viator* a révélé une distribution bimodale typique d'une espèce longévive et un dimorphisme sexuel avec les femelles significativement plus grandes que les males. Bien que la stabilité de la fréquence de taille au cours du temps semble exclure la possibilité qu'*E. viator* soit menacé dans la ZEE de Kerguelen, des études supplémentaires doivent être menées pour évaluer la taille de la population et réduire les prises accessoires de requins dans les pêcheries palangrières françaises.

Keywords: Elasmobranchs, distribution, abundance, length frequency, Southern Ocean, longline fishery

Introduction

Sharks are distributed worldwide and can be either targeted or caught as by-catch in many shelf, pelagic or deep-sea commercial fisheries (Compagno, 2001; Fowler et al., 2004; Zhou and Fuller, 2011; Hanchet et al., 2013). When caught as by-catch, discarded or occasionally landed, sharks are often underestimated or misidentified. Moreover, they are often poorly recorded in fishery statistics (Kyne and Simpfendorfer, 2007). However, total catch and mortality of sharks worldwide, including reported and unreported landing, discards and shark finning, was estimated at 1.41 million tonnes for the year 2010 representing approximately 97 million individuals (Worm et al., 2013).

As chondrichthyans, sharks are generally considered to display K-strategy life-history traits such as slow growth, late maturity and low fecundity resulting in limited reproductive output which makes them particularly vulnerable to fishing pressure (Hoenig and Gruber, 1990; Kyne and Simpfendorfer, 2007). Studies showed that these life-history traits differ depending on broad-scale habitats (shelf, pelagic and deep water) (Garcia et al., 2008; Rigby and Simpfendorfer, 2015) but also within the deep habitat and across geographic regions (Rigby and Simpfendorfer, 2015). On average, deep-water species have later age at maturity, a higher longevity and a slower growth than shallow-water species (Garcia et al., 2008; Rigby and Simpfendorfer, 2015). Furthermore, within the deep habitat, chondrichthyans still tend to mature later, live longer and also have smaller litter size and breed less frequently, with increasing depths (Rigby and Simpfendorfer, 2015). Consequently, the capacity of the deep-water chondrichthyan populations to recover from exploitation decreases with increasing depth. Given that approximately half of the known chondrichthyan species live in the deep ocean (below 200 m) and that between 2009 and 2014 half of the new species described were deep-water species (Cotton and Grubbs, 2015), it is important to monitor exploitation rates and by-catch levels in fisheries operating in deep-water habitats. According to the Red List of the International Union for Conservation of Nature (IUCN), 5.2% of the chondrichthyan species living in deep-waters are considered to be threatened. However, this number is likely to be underestimated since 57.6% of deep-sea chondrichthyan species are data deficient (Dulvy et al., 2014). According to their life-history traits, these data-deficient species are likely to be threatened in areas where they are caught in fisheries and potentially under-reported.

Compared to other ocean basins, the Southern Ocean is not considered as a hotspot of threats for chondrichthyans (Dulvy et al., 2014), but little information is available on sharks in this region. Shark directed fishing is prohibited since 2006 by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR; c.f. Conservation Measure 32-18, CCAMLR, 2018), the international body in charge of fishery regulation within the Convention Area which covers most of the Southern Ocean. In the Southern Ocean, information on shark population is mostly derived from sharks caught as by-catch in commercial bottom trawl and longline fisheries and to a lesser extent from research surveys usually conducted over continental shelves. Previous work on biogeographic distribution of fish in the Southern Ocean showed that five species of sharks were found (Duhamel et al., 2014): four demersal species and one pelagic species. The four demersal species are Portuguese dogfish (*Centroscymnus coelolepis*), southern sleeper shark (*Somniosus antarcticus*), traveller lantern shark (*Etmopterus viator*), *Etmopterus* sp. and the last species porbeagle shark *Lamna nasus* is pelagic. These shark species were all mainly recorded in the northern part of the Southern Ocean, except a few records in the Ross Sea (Duhamel et al., 2014). Within the Southern Ocean, the three smaller species (*C. coelolepis*, *E. viator* and *Etmopterus* sp.) were recorded in localised areas whereas the two larger (*S. antarcticus* and *L. nasus*) displayed a larger distribution (Duhamel et al., 2014). *Centroscymnus coelolepis* is a cosmopolitan species with a wide bathymetric range also found in other ocean basins. In the Southern Ocean, it has only been reported around Crozet and Kerguelen Islands (Duhamel et al., 2005). *Etmopterus viator* is a wide-ranging species occurring in the Southern Hemisphere. It was found in New Zealand and South African waters (Straube et al., 2011) but also in few regions of the Southern Ocean. So far, it has been found only on the Kerguelen Plateau and possibly on the sub-Antarctic area of the Macquarie Ridge (Straube et al., 2011). Another species of genus *Etmopterus* was recorded in the Ross Sea but it was not identified at the species level (Hanchet et al., 2013). *Somniosus antarcticus* is also wide ranging in the Southern Hemisphere and in sub-Antarctic waters. It was mostly reported around South Georgia, Marion Island, Crozet Islands, Kerguelen Plateau and Macquarie Island (Duhamel et al., 2014) but also in the Ross Sea (Hanchet et al., 2013). Finally, *L. nasus*, which is widely distributed particularly in the North Atlantic and Southern Hemisphere (Compagno, 2001), was only reported around South Georgia, Crozet Islands and Kerguelen Plateau in the Southern Ocean (Duhamel et al., 2014).

In the Kerguelen exclusive economic zone (EEZ), in the Southern Indian Ocean, four species of sharks are caught in fishing gears. A demersal fishery started in 1970 with trawlers targeting several shelf species for 20 years. Soon after the creation of the EEZ in 1978, an observer program was established to collect biological data and monitor the fishery (Duhamel et al., 2011). Patagonian toothfish (*Dissostichus eleginoides*) became the exclusive target fish species during the 1990s (Duhamel et al., 2011). It was first fished using bottom trawls on the shelves and slopes and shifted to bottom longlines in 2001 to exploit deeper fishing grounds (500–2 300 m) (Duhamel and Williams, 2011). Since then, there were only four occurrences of bottom trawl fishing in the Kerguelen EEZ during the French biomass groundfish survey cruises named POKER limited to the shelf area (100–1 000 m) (Duhamel et al., 2019). These surveys provide fishery-independent biomass estimation of groundfish, specifically all species that are not true pelagic species (Duhamel and Hautecoeur, 2009). Few sharks were caught during these four surveys (n = 759 for *E. viator* and n = 4 for *S. antarcticus*) indicating that the shelf area of the Kerguelen Plateau is not a key habitat for demersal shark species in the region (Duhamel et al., 2019). In contrast, commercial bottom trawls indicated the occurrence of *L. nasus* as a regular by-catch between 170 m and 670 m (Duhamel et al., 2005). On the slope, the commercial longline fishery targeting Patagonian toothfish regularly catches sharks as by-catch.

The fishery observer program carried out on board fishing vessels enables the by-catch to be monitored (abundance and biological measurements) for the whole fishery (100% observer coverage on board vessels) at a precise geographic and bathymetric resolution. Although fishing vessels try to limit shark by-catch, biological information collected by observers on board fishing vessels represents a unique opportunity to gain scientific knowledge of sharks in the Southern Ocean. Within the three shark genera of *Etmopterus*, *Somniosus* and *Centroscymnus* all species live in deep waters (Cotton and Grubbs, 2015), where the deficit of information available on biological and life-history parameters is the highest (Kyne and Simpfendorfer, 2007). It is thus of considerable interest to analyse shark data collected in the bottom longline fishery of the Kerguelen Plateau.

Our study is the first one focusing on shark by-catch in the Kerguelen EEZ. The aim was to (i) quantify the by-catch rate of all shark species caught in the French bottom longline fishery, (ii) update the distribution map of these shark species, and (iii) improve our knowledge on the biological traits of the poorly documented *E. viator* which is the most-frequently caught shark species in the region.

Materials and methods

Description of the fishery and study area

The study area consists of the northwestern part of the Kerguelen Plateau in the French EEZ of CCAMLR Division 58.5.1 (Figure 1). Since the early 2000s, only French vessels are authorised to fish in the Kerguelen EEZ and they use exclusively bottom longlines with hooks (size 13/0–14/0 and mean total length 71 mm) attached by a snood to a self-weighted mainline ('Autoline' system) set on the bottom (Duhamel and Williams, 2011). Since 2006, lines are on average 10.4 km long and hooks spaced at 1.2 m. Lines are set at night-time and hauled generally after 24 hours. Fishing activity occurs on the slope from 500 to 2 000 m depth. Waters shallower than 500 m depth are prohibited for conservation reasons. A 'move on' rule applies on predominant by-catch species (grenadier *Macrourus* spp., blue antimora (*Antimora rostrata*), skates *Bathyraja* spp.) based on observer monitoring, so that if catch-per-unit-effort (CPUE) exceeds a certain level, then the master must set the next line at least two nautical miles from the previous haul. Description of this fishery can also be found in Duhamel et al., 1997 and Gasco, 2011.

Annual data were grouped on the basis of the French catch limit. The fishing season runs from 1 September of a year to 31 August the following year, with the reference year label consisting of the first year. From 2006 to 2016, a total of 226 commercial cruises were carried out in the area and an average of 2 651 longline sets were deployed per season by seven French longliners (eight during the 2015/16 season).

Observer coverage in the area is mandatory on every vessel and data are collected by fishery observers employed by the French administration (Terres Australes et Antarctiques Françaises, TAAF). All data are entered on board into an electronic logbook designed by the Muséum national d'Histoire naturelle (MNHN) and then uploaded in an 11G Oracle database named PECHEKER (Martin and Pruvost, 2007) hosted on the MNHN servers.

Data collection

By-catch data are collected by fishery observers on 25% of the hooks hauled for each line ('hauling observation period') while the crew register 100% of the catch. The number of fish (target and by-catch), whatever the fate (i.e. hauled on deck or cut off the line), are recorded and identified at species level (when possible) by fishery observers during the hauling observation period. Most hauls (98.8%) are observed by fishery observers. The few lines for which there were no hauling observations are explained by line damage stopping hauling and preventing observation. For our shark by-catch analyses, we used the counts made during the hauling observation period by fishery observers rather than the 100% observation by the crew, because observers are trained for by-catch identification and the depth and locations of the observed portion of the line (25%) is more accurate.

In instances where shark by-catch was hauled on deck, observers measured (total length, TL, to the nearest mm) and sexed sharks. For large sharks such as *S. antarcticus*, the line was often cut off by the crew and the animal returned to the sea (dead or alive). In these cases, observers had only rough size estimations. Despite observer data being available since the start of the longline fishery, we used the data collected from 2006 to 2016 because we consider the data to be more accurate during this period.

Data analysis

The observer data coverage was mapped using QGis (QGIS Development Team, 2009) to visualise the spatial distribution of the hauling observation effort. We used a 0.1° × 0.1° grid where we summed the total number of observed hooks per grid cells.

For every species, we calculated an abundance index, defined as the number of shark individuals caught per longline quarter standardised to 1 000 hooks. Since only 18.7% of the total hauls caught sharks, we decided to use relative abundance, calculated only for hauls with sharks present, to investigate the effects of depth and describe bathymetric and geographical distributions. Shark distribution maps were constructed in QGis (QGIS Development Team, 2009) by using the coordinates (longitude and latitude) of each portion of the line observed (25%) and colour-coded locations according to their relative abundance (individual/1 000 hooks in hauls where sharks were present). All statistical analyses were performed using the RStudio software 1.1.383 (RStudio Team,

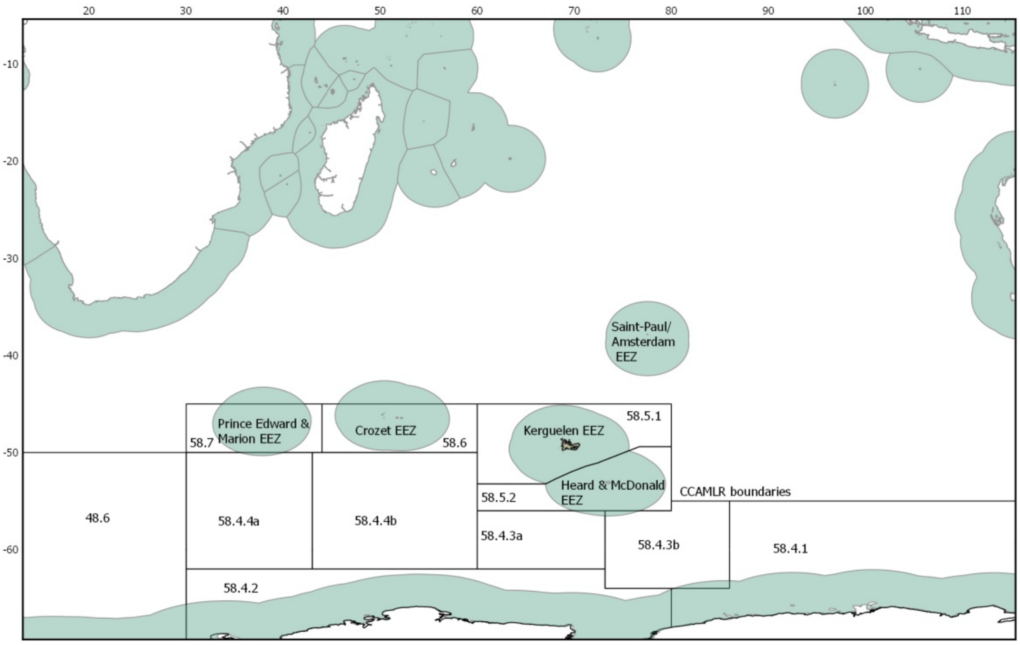

Figure 1: Location of the Kerguelen EEZ in the Southern Ocean.

2016). For the dominant shark species, *E. viator*, relative abundance was analysed to test for differences among years using analysis of variance (ANOVA); post-hoc identification of annual differences was determined by Tukey testing (Miller, 1981). Total length measurements data were also analysed using one-way ANOVA and Tukey testing (Miller, 1981) to determine if and when differences occurred between years.

Shark measurements were analysed using length frequency distribution (LFD) for the most-common species observed, *E. viator*. For this species, the length at maturity was taken from Duhamel et al. (2005) and was considered to be approximately 46 cm in males and 50 cm in females. We re-estimated the length at first maturity using data collected on gestating females noted by fishery observers. Likewise, sex ratio was only determined for this dominant species. Chi-square testing (Agresti, 2007) was used to analyse the sex ratio over the entire study period and over every year to detect any annual changes. Total length data were also analysed using Welch two sample *t*-test to test for differences among males and females.

Results

Hauling observation effort and shark species composition

Hauling observations were distributed uniformly throughout our study period, occurring in all years between 500 and 2 000 m depth (Figure 2). From 2006 to 2016, fishery observers monitored 26 203 hauls representing more than 55 million hooks (Table 1). Mean annual hauling observation effort was 2 620 hauls and 5 513 759 hooks. The highest values of hauling observation were observed in 2006 (6.5 million hooks) in the beginning of the hauling observation protocol and the minimum in 2015 (4.6 million hooks) in accordance with the annual catch limit (~ 5 000 tonnes) of the target species, *D. eleginoides*.

The target species *(D. eleginoides*) comprised 60% of the total observed catches in number and the sharks comprised almost 1% ranking at the fourth place of by-catch after ridge-scaled rattail (*Macrourus carinatus*), blue antimora (*Antimora rostrata*) and skates (Eaton's skate *Bathyraja eatonii* and Kerguelen sandpaper skate *Bathyraja irrasa*) (Figure 3). The other fish species occurred infrequently.

A total of 29 500 individual sharks were observed with one Lamniformes, *L. nasus* and

Table 1: Summary of hauling observation effort (in number of hooks and number of hauls) and shark observations in the bottom longline fishery off the Kerguelen Islands, between 2006/07 and 2015/16.

Observed effort	Years										
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
No. of hooks (in millions)	6.5	5.5	5.3	5.9	5.7	5.7	5.8	5.2	5.0	4.6	55.2
No. of hauls	2 794	2 367	2 330	2 555	2 574	2 577	2 939	2 659	2 804	2 604	26 203
No. of hauls with sharks	192	362	376	533	607	595	678	558	434	553	4 888
% of hauls with sharks	6.9	15.3	16.1	20.9	23.6	23.1	23.1	21.0	15.5	21.2	18.7

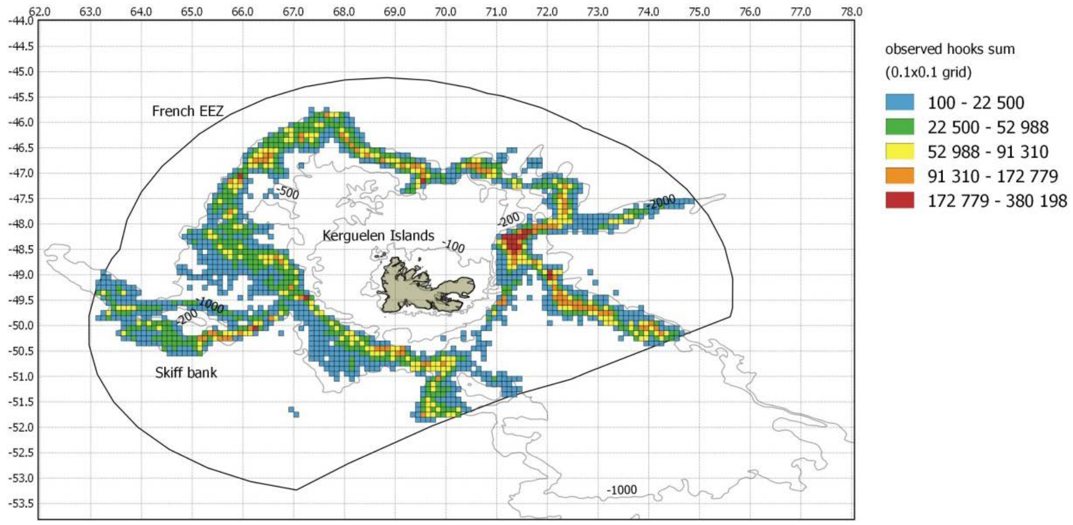

Figure 2: Spatial distribution of the hauling observation effort (total of observed hooks in a 0.1° × 0.1° grid) in the bottom longline fishery off the Kerguelen Islands, 2006/07–2015/16. The solid line represents the Kerguelen EEZ limit.

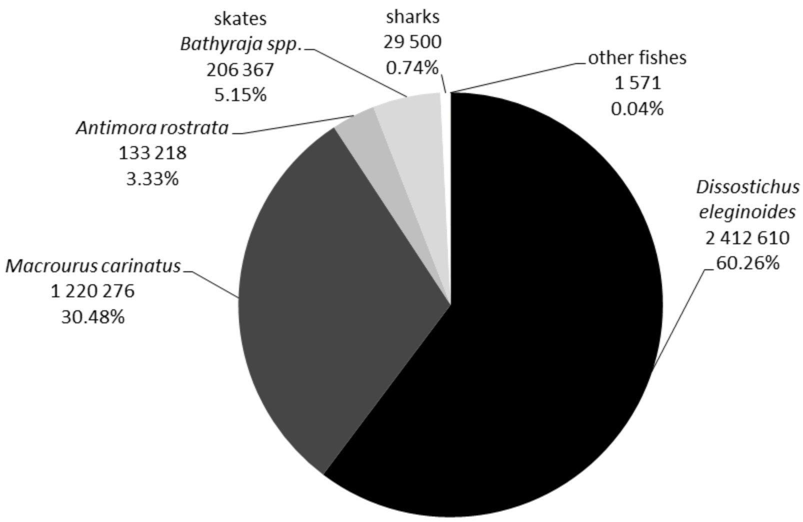

Figure 3: Composition of fish by-catch (in number and percentage of observed catch) from the bottom longline fishery off the Kerguelen Islands, 2006/07–2015/16.

three Squaliformes, *C. coelolepis*, *S. antarcticus* and *E. viator*. This last species represented 99% of shark catches (Table 2).

Relative abundance of shark species

Relative abundance (i.e. calculated for hauls with sharks present) showed substantial differences between shark species. Relative abundances for *E. viator* were the highest, with presence at a significant proportion of stations (4 838 stations with presence namely 18.5% of observed hauls). An increase in relative abundance with depth, from a minimum at 502 m (limit of authorised catches) to a peak around 1 200 m, was noted before a decreasing trend at the greatest depths with a maximum at 1 951 m (Figure 4). This species seemed to exhibit a depth preference with higher relative abundances between 750 m and 1 750 m. Relative abundance of *E. viator* was 2.54 individuals/1 000 hooks on average (range = 0.15–60 individuals/1 000 hooks). The other shark by-catch species were reported infrequently. *Somniosus antarcticus* occurred in 51 hauls at depths from 541 to 1 836 m with no variation in relative abundance between depths (in average 0.54 individuals/1 000 hooks) except a single haul with 4.80 individuals/1 000 hooks around 1 200 m (Figure 4). *Centroscymnus coelolepis* occurred in seven hauls at depths beyond 900 m (from 894 to 1 350 m) (Figure 4) with a mean relative abundance around 0.91 individuals/1 000 hooks. *Lamna nasus* occurred in five hauls at depths from 770 to 1 589 m (Figure 4) with a mean relative abundance around 0.48 individuals/1 000 hooks.

Regarding abundance index (i.e. abundance taking into account all hauls with or without shark occurrences), values were significantly lower than the previous ones because most hauls caught no sharks (81%). The abundance index was 0.53 individuals/1 000 hooks for *E. viator*, 0.001 for *S. antarcticus*, 2.2×10^{-4} for *C. coelolepis* and 9×10^{-5} for *L. nasus*.

For *E. viator* the highest relative abundance was in 2010 (3.17 individuals/1 000 hooks) and the lowest in 2006 (1.71 individuals/1 000 hooks). ANOVA results indicated significant relative abundance differences among years (F = 7.125; df = 9; P = 2.52×10^{-10}). Post-hoc tests indicated that significantly lower relative abundances were observed during 2006 compared to 2007, 2008, 2010 and 2011. Higher relative abundances were observed

Table 2: Temporal trend in shark species composition (in numbers) from hauling observations, from the bottom longline fishery off the Kerguelen Islands, between 2006/07 and 2015/16. * – Probable underestimation of *Etmopterus viator*.

Order	Family	Species	Years										Total	
			2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Number	%
Squaliformes	Etmopteridae	*Etmopterus viator*	857*	3 185	3 144	3 477	4 850	3 821	3 478	2 491	1 728	2 391	29 422	99.73
Squaliformes	Somniosidae	*Somniosus antarcticus*	9	3	1	4	7	5	2	18	2	10	61	0.21
Squaliformes	Somniosidae	*Centroscymnus coelolepis*	0	8	0	0	0	4	0	0	0	0	12	0.04
Lamniformes	Lamnidae	*Lamna nasus*	1	1	0	0	0	1	1	0	0	1	5	0.02
		Total	867	3 197	3 145	3 481	4 857	3 831	3 481	2 509	1 730	2 402	29 500	100

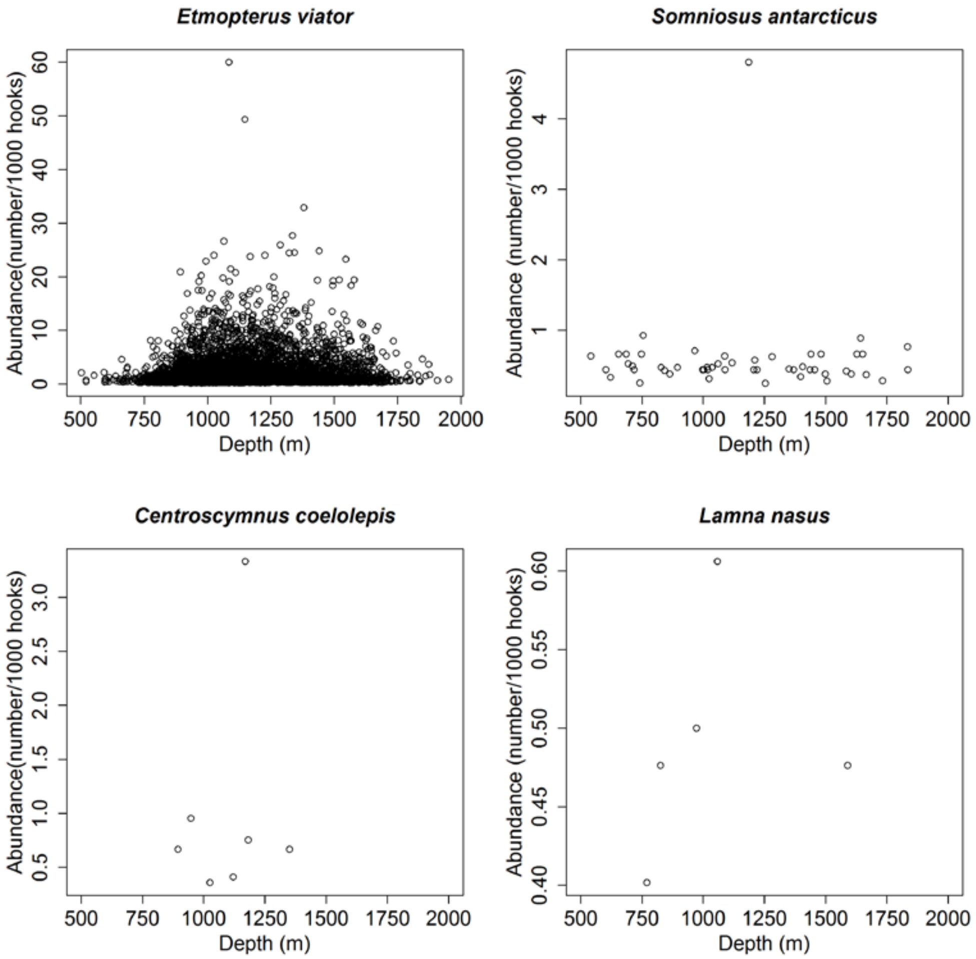

Figure 4: Relative abundance (number of individuals per 1 000 hooks in hauls where sharks were present) for the four shark species in relation to depth for all observed bottom longlines with presence of shark by-catch off the Kerguelen Islands, 2006/07–2015/16.

during 2010 compared to 2006, 2009, 2013, 2014 and 2015. However, there was no significant global increase or decrease in relative abundance over the studied period.

Species distribution

There were marked differences between distributions of the shark by-catch species and their relative abundance. *Etmopterus viator* was observed everywhere in the study area except in the south, the southwest and around the Skiff Bank where *E. viator* was scarce (present in few stations) or absent (Figure 5). The highest relative abundances were observed in the slope areas of the east part of the Plateau. *Somniosus antarcticus* was observed in 53 stations (0.2% of the total haul number) all along the slopes of the Kerguelen Plateau, including Skiff Bank (Figure 5). *Centroscymnus coelolepis* was only recorded from seven stations (five in the north, single ones in the west and on Skiff Bank) (Figure 5). *Lamna nasus* was only recorded in five stations in the northern part of the plateau and one on Skiff Bank (Figure 5).

Length-frequency distribution (LFD)

The large size of *L. nasus* and *S. antarcticus* (known to be up to 225 and 510 cm respectively in Kerguelen, Duhamel et al., 2005) makes them sometimes too difficult to haul aboard, thus measurements of this species were rarely available. Specimens of boarded *S. antarcticus* measured were in the range 134.8 to 179.0 cm (mean = 151.1 cm, n = 6). Two additional specimens, not boarded, were estimated at 280 and 400 cm. Specimens of *L. nasus* measured were in the range 123.0 to 193.0 cm (mean = 147.7 cm, n = 7). For *C. coelolepis* we did not have enough measurements to

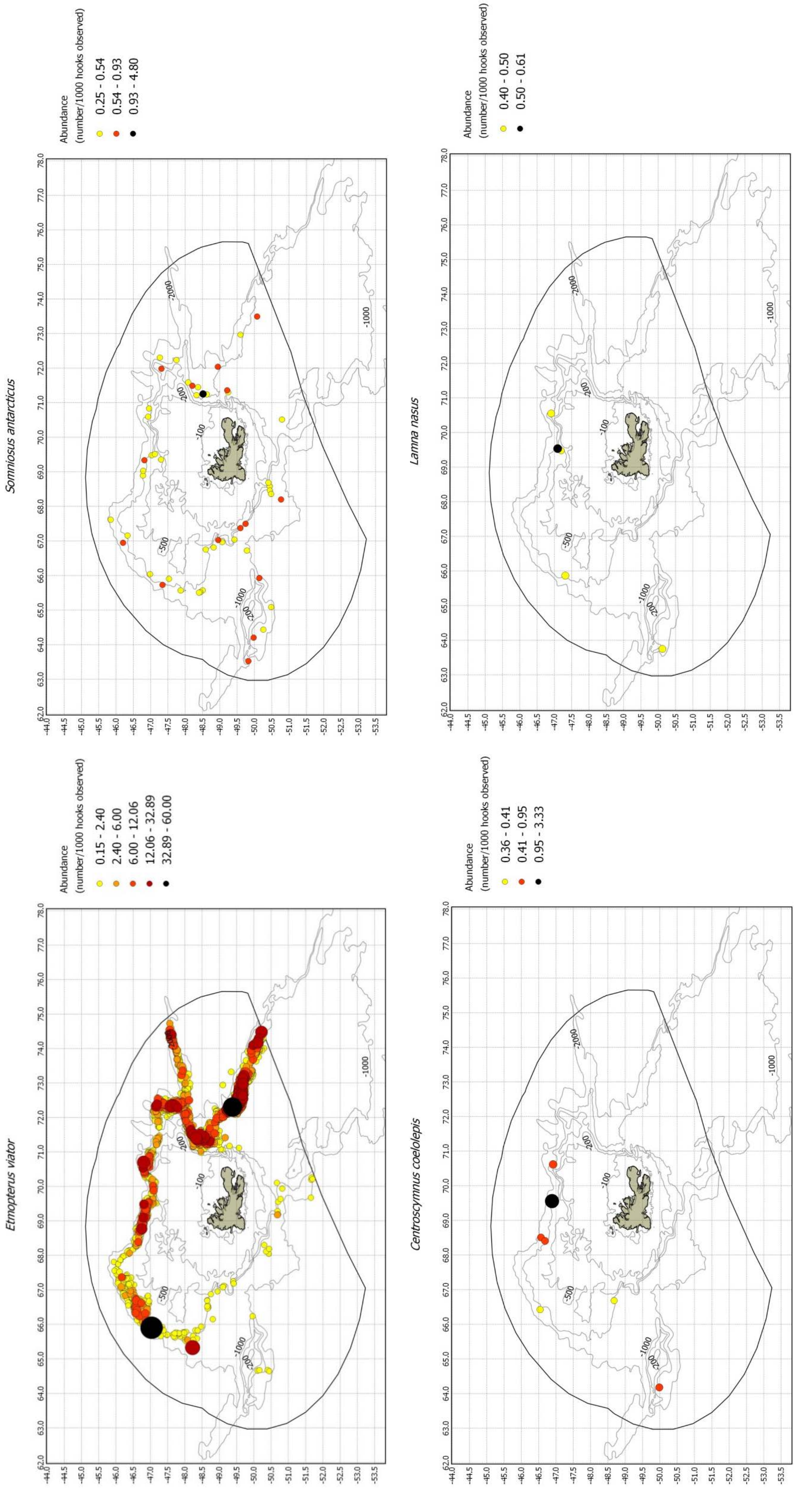

Figure 5: Distribution of shark occurrence and relative abundance (number of individuals per 1 000 hooks in hauls where sharks were present), for observed hauls with presence of *Etmopterus viator*, *Somniosus antarcticus*, *Centroscymnus coelolepis* and *Lamna nasus* caught in the bottom longline fishery off the Kerguelen Islands, 2006/07–2015/16.

establish an LFD. Specimens of *C. coelolepis* measured were in the range 36.0 to 107.0 cm (mean = 57.4 cm, n = 47).

Specimens of *E. viator* measured were in the range 15.0 to 59.5 cm (mean = 38.7 cm, n = 5 359). The length frequency of *E. viator* showed a marked bimodal distribution with a strong mode around 38 cm and a moderate mode around 52 cm (Figure 6). The first mode was mostly composed of immature individuals whereas the second mode was mostly composed of mature individuals. The very small additional mode around 17 cm could be viewed as an artefact and representing not individuals directly caught by hooks but neonates coming from caught gestating females giving birth on board. The smaller size of neonates, 15 cm, could be seen as the length class at birth.

The bimodal distribution was particularly marked for females and poorly visible for males (Figure 7). Sexual differences in length distribution of *E. viator* were also observed. Females were significantly longer than males (Welch Two Sample *t*-test: p-value < 0.05). For females, lengths were between 16.8 and 59.5 cm (with a mean length of 38.3 cm) and for males, lengths were between 15.0 and 57.0 cm (with a mean length of 37.9 cm). The information noted about the condition of gestating females revealed that the size of pregnant females ranged between 48.5 and 59.5 cm, with number of embryos counted between 3 and 13.

The bimodal distribution of *E. viator* was encountered each year. ANOVA results indicated significant length differences among years ($F = 4.022$; $df = 9$; $P = 3.81 \times 10^{-5}$). Post-hoc tests indicated that significantly larger individuals were observed during 2008 compared to several years (2015, 2012 and 2011) and during 2007 compared to 2012. But there was no significant global increase or decrease of mean length over the studied decade.

For *E. viator* there were no geographical distribution differences between individuals considered as immature and the ones considered as mature. There was also no spatial separation between males and females (Figure 8).

Sex ratio of *E. viator*

For *E. viator*, females dominated the catch with a sex ratio of 1.4 (Chi-squared test: $\chi 2 = 120.19$, $df = 1$, $P < 2.2 \times 10^{-16}$). Analysis of the sex ratio by years indicated that although female *E. viator* dominated in most years, a balanced sex ratio (1:1) was observed in 2013 and 2015.

Discussion

Data on shark by-catch are mostly documented in the Atlantic fisheries and are still very limited in the Southern Ocean (Compagno, 1990; Duhamel et al., 2005; Duhamel et al., 2014; Molina and Cooke, 2012; Oliver et al., 2015). Our analysis of a 10-year dataset of fishery observer data indicated the presence of at least four shark species in the deep-sea habitat of the Kerguelen Plateau (*E. viator*, *S. antarcticus*, *C. coelolepis* and *L. nasus*). Previous studies in the shallow and coastal waters of the Kerguelen Plateau reported the occurrence of very few picked dogfish (*Squalus acanthias*) but this species is thought to be very rare in the area, since it is the southern limit of its geographical range (Duhamel et al., 2005). Other shark species may occur on the pelagic domain but are not caught by current fishing gears.

Previously cited as the most common shark species in Kerguelen waters, our study showed that *S. antarcticus* now ranks at second place in number of shark by-catch from the French longline fishery. The smaller species, *E. viator*, was largely predominant in number with ~12 000 individuals caught every year as by-catch in average when extrapolated from the 25% hauling observation. This species was described as a new species (*E. viator* previously identified as *E*. cf. *granulosus* (Duhamel et al., 2005) or *?E. lucifer* (Compagno, 1990)) by Straube et al. (2011). It was thus separated from other species found in the Southern Hemisphere such as *E. granulosus*, *E*. sp. B., *E*. cf. *granulosus* and *E. litvinovi*.

On average, 18% of the observed hauls caught sharks over the 10 years period. The increase in this percentage during the first three years of our study period could be driven by the improvement in reporting rate for non-dominant by-catch species, such as sharks, by fishery observers.

Geographic and bathymetric distributions

The geographical and bathymetric distributions of deep-water sharks are influenced by depths (Clarke et al., 2005), temperature and by their

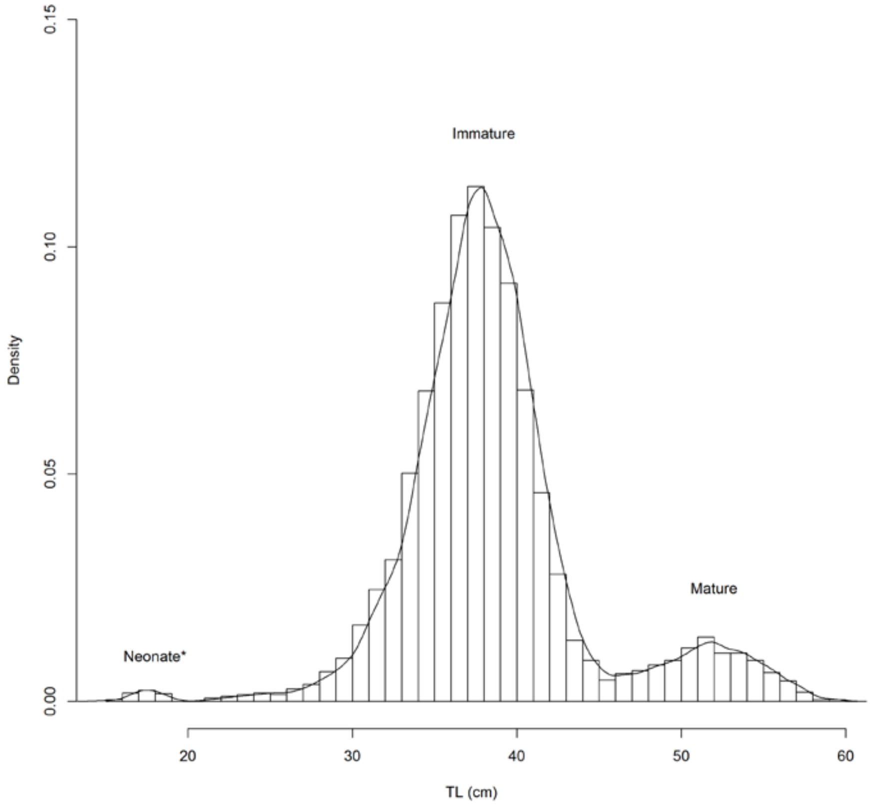

Figure 6: Length frequency distribution of *Etmopterus viator* (both males and females) caught during bottom longline fishery off the Kerguelen Islands, 2006/07–2015/16 (n = 5 359). *Not hooked specimens.

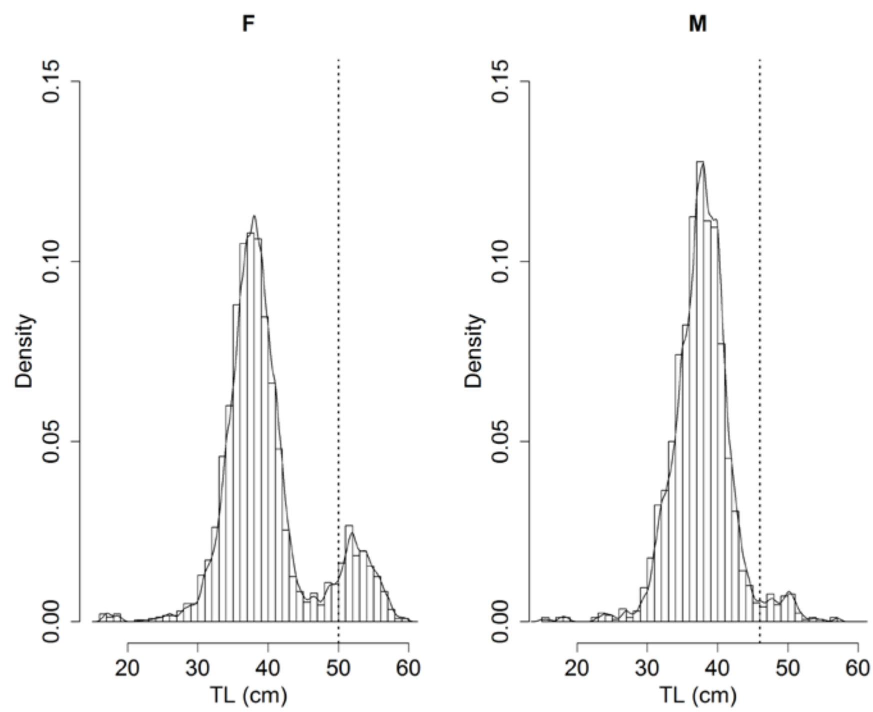

Figure 7: Female (F, n = 2 400) and male (M, n = 1 699) size distribution of *Etmopterus viator* caught during bottom longline fishery off the Kerguelen Islands, 2006/07–2015/16. The dotted line represents the approximate length at maturity according to Duhamel et al. (2005).

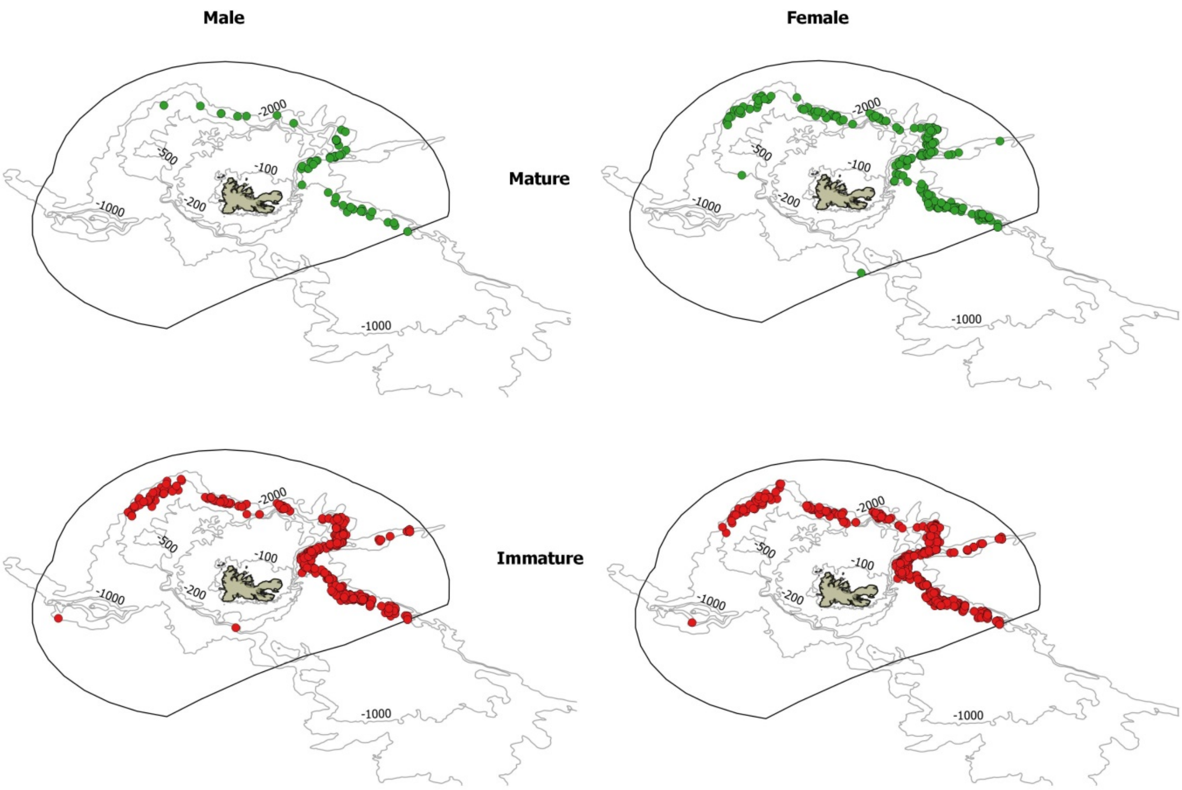

Figure 8: Distribution of mature and immature *Etmopterus viator* individuals separated by sex (length at maturity is considered at 46 cm for males and 50 cm for females, individuals shorter than 20 cm were excluded) caught during the bottom longline fishery off the Kerguelen Islands, 2006/06–2015/16.

feeding ecology. Our study showed that the geographical distribution of the four shark by-catch species varied between species both in term of occurrence and relative abundances. These differences can be explained by their preferred habitat types and/or food resources. Cherel and Duhamel (2004) showed that *S. antarcticus*, *E. viator* and *L. nasus*, have different feeding ecology in Kerguelen waters.

Lamna nasus is known to be an epipelagic species found in coastal waters and also offshore (Compagno, 2001; Semba et al., 2013) with a wide bathymetric range between 0 and 1 809 m (Weigmann, 2016). Even if *L. nasus* was hooked on the French bottom longlines in Kerguelen from 770 to 1 589 m, they could have been caught in the pelagic zone during setting or hauling operations. According to Duhamel et al. (2005), the distribution of *L. nasus* in Kerguelen also extends to shallow waters (<500 m) of the plateau and even in very coastal water. This species has never been caught during POKER bottom trawl surveys, but considering its active swimming ability, escapement is possible. Similarly, considering its size, this species could escape after being hooked in longlines but no evidence was found of snoods being severed. *Lamna nasus* is a known pelagic predator of mackerel icefish (*Champsocephalus gunnari* Lönnberg, 1905) in upper slope waters near the Kerguelen Islands but also of other different fish species and squids (Cherel and Duhamel, 2004; Duhamel et al., 2005).

Somniosus antarcticus, the largest shark of the area, was recorded sporadically all around the Kerguelen Plateau including Skiff Bank, in the same sector in which it was previously known to occur in trawl and longline catches (Duhamel et al., 2005). The species occurred at every depth range (541–1 836 m) from longline, but exhibited no depth preference. Juvenile *S. antarcticus* were also caught during POKER bottom trawl surveys confirming its presence at shallow depths (Duhamel et al., 2019). *Somniosus antarcticus* is a benthic top predator and scavenger, which preys upon larger items than *E. viator* and *L. nasus* (Cherel and Duhamel, 2004), and due to their sluggishness (Compagno, 1984), large size and heavy weight, they are often entangled on the line and cut off the line. Consequently, biological data such as length at maturity or sex are lacking.

Our study confirmed the scarcity of *C. coelolepis*, a medium-sized species, in the Kerguelen longline fisheries. This deep demersal species was found only occasionally on the slope at medium depths (894–1 350 m), a typical habitat for this species, commonly caught in deep-water longlines (>1 100 m) of the northeast Atlantic fisheries (Clarke et al., 2005). *Centroscymnus coelolepis* was absent from POKER trawl survey catches which confirmed its deep-water bathymetric range. Its low occurrence in the region could not be explained by poor gear selectivity since other studies showed that it was unable to escape trawls and longlines (Clarke et al., 2005) and *E. viator* of smaller sizes were caught in the Kerguelen longline fishery. These results may suggest that the Kerguelen EEZ is at the limit of the geographical distribution of this species.

Etmopterus viator is a deep demersal to benthopelagic shark (Duhamel et al., 2005), widely distributed around Kerguelen but not endemic (Straube et al., 2011). Our study showed a larger distribution than previously known in the Kerguelen EEZ and confirmed the scarcity of the species in the southwest (Duhamel et al., 2005). However, the distribution of *E. viator* probably extends in the southeast towards the Australian EEZ (Heard Island and McDonald Islands) of the Kerguelen Plateau. In the French longline fishery, *E. viator* was found in a very wide depth range (502–1 951 m). POKER trawl surveys also caught juveniles of *E. viator* at 324 m (Duhamel et al., 2019) confirming the presence of the species at a large bathyal scale. These minimum (324 m) and maximum (1 951 m) depth records in the Kerguelen waters extend the depth range of the species worldwide, since Weigmann (2016) reported a depth range between 830 and 1 610 m for *E. viator*. Based on relative abundance data, the species seems to exhibit a depth preference with higher values between 750 and 1 750 m. Interannual differences in depth range are more likely due to differences in the distribution of fishery effort in some concentrated local areas than changes in habitat preference of the species.

Deep-water sharks are known to segregate by sex and maturity classes as observed for *E. granulosus* in New Zealand waters (Finucci et al., 2018) or *C. coelolepis* in multiple areas (Moura et al., 2014) but in the present study no geographical differences seem to exist between juvenile and mature individuals or between males and females of *E. viator*. Little is known about the diet of *E. viator*. Cherel and Duhamel (2004) have observed stomach contents of specimens caught in a single trawl in Kerguelen and showed that *E. viator* prey upon squids and, to a lesser extent upon mesopelagic lantern fishes (myctophids).

Size- and sex-composition of *E. viator* in the bottom longline fishery

The French toothfish fishery caught the largest specimen of *E. viator* ever recorded in Kerguelen (59.5 cm, female specimen) and probably for the species since the maximum size reported was 57.7 cm (Weigmann, 2016). Considering that *E. viator* was sampled in wide geographical, bathyal and temporal ranges over the Kerguelen Plateau and that longlines selected both immature and adult individuals, it is assumed the length-frequency distribution obtained may reflect the whole catchable population. Gear selectivity excluded small individuals from birth (~15 cm) to ~30 cm, which were not, or less frequently, caught by the large hooks used in the fishery.

The observed bimodal distribution is typical for long-lived species for which growth rate decreases markedly with increasing body size (Klimley, 2013) or stops after the maturity is reached as suggested by Iglésias et al. (2010). The shape of this bimodal distribution also reflects species with late maturity, relatively high fecundity (a maximum of 13 young per batch presently observed) and relatively high mortality of juveniles.

In contrast to a study by Finucci et al. (2018) which showed that *E. granulosus* trawl catches were dominated by adults and, in particular, adult females, our study showed that *E. viator* catches were dominated by juvenile individuals in the Kerguelen bottom longline fishery.

Size classes in the overlapping zone of the two total length modes represent the length at first maturity and these size classes are probably composed of immature, close to mature and newly mature individuals. Since the minimum size of a pregnant female observed during this study is in accordance with the LFD result, we propose to redefine the length at first maturity for females at least to 48.5 cm (instead of 50 cm). Nevertheless, studies on specimens belonging to this overlapping zone are still needed to improve our knowledge on length at maturity.

The typical bimodal distribution of length frequency observed for long-lived species with slow growth at adult size is commonly confused in the literature and erroneously interpreted as an under-representation of pre-adult sizes in sampling. This bimodal representation is observed for Elasmobranchs and confirms that growth slows not long after attaining maturity and that adult life is long.

The increase in mortality of a species due to fishing, particularly of larger sizes, may impacts the shape of the bimodal distribution (Iglésias et al., 2010). The adult mode may decrease proportionally with the increase of fishing effort. Observation of the bimodal distribution over time is a good way to estimate the impact of the fishery on adults, particularly when the state of the virgin population is known, as it is probably the case for *E. viator* in the Kerguelen area. In this study, the bimodal distribution has been observed every year with no significant increase or decrease of the second mode suggesting that there were no significant effects of fishing activities on survival rates of mature fish.

Elasmobranchs are known to have sexual dimorphism in size, with female reaching larger maximum size than males (Compagno, 2001). This is confirmed, but not very marked, for *E. viator* with females and males attaining 59.5 and 57.0 cm maximum TL respectively. The relatively smaller adult mode for males compared to females and the sex ratio biased in favour of females could reflect a lower longevity of males or a higher mortality of adult males. A higher avoidance of hooks by adult males appears unlikely.

Elasmobranchs are gonochoric species known to present a mixed sex ratio at species level with possible local bias due to reproductive segregation. A lower proportion of adult males in the area appears unlikely according to the wide geographical, bathyal and temporal ranges covered by the fishery or it suggests a sex segregation at a larger geographical scale than the Kerguelen EEZ. *Etmopterus viator* claspers are small and could be missed by fishery observers during sex determination, particularly on younger individuals, creating a bias in sex ratio, but it could not explain the lower proportion of adult males.

Potential impacts of the French bottom longline fisheries on shark population status and management advices

Fishing for the valuable meat of *L. nasus* (either targeted or by-catch) has been a major threat to populations in many fisheries during the last century, especially in the North Atlantic (Fowler et al., 2004) and this subpopulation is now on the IUCN Red List and considered as vulnerable (IUCN, 2018). Fishing for sharks is prohibited in the CCAMLR area and in Kerguelen waters and by-catch of *L. nasus* is very scarce and never landed in ports for commercial purposes. Considering that 11 individuals were caught in 10 years, the impact of the Kerguelen longline fishery on the *L. nasus* population is likely to be small.

Somniosus antarcticus is registered as data deficient in the IUCN Red List so data are still needed globally and locally (IUCN, 2018). In the Kerguelen bottom longline fishery, the total number of *S. antarcticus* documented by the crew was 226 individuals between 2006 and 2016. The main management action to preserve the species in the area is to favour the release of the specimen alive when entangled in the line avoiding cutting the caudal.

Centroscymnus coelolepis is globally registered as near-threatened in the IUCN Red List (IUCN, 2018) but its regional IUCN status is unknown. In the Kerguelen EEZ, the threat to the population does not seem to be of concern given the low catch rate and the species distribution. Nevertheless, as recommended for *S. antarcticus*, the management advice is to maximise the post-capture survival rate.

Within chondrichthyans, Etmopteridae are considered as one of the least-threatened families (Dulvy et al., 2014) but *E. viator* is registered as not assessed in the IUCN Red List (IUCN, 2018). *Etmopterus viator* is the main shark by-catch in the French bottom longline fishery in the Kerguelen EEZ and is never landed in port and sold. Considering the by-catch rate (on average 2.4 tonnes per year), and its life-history traits and habitat, it is important to keep monitoring this species to manage shark by-catch. The management recommendation is to maximise the post-capture survival rate, but the viability state of *E. viator* is difficult to assess on board. Further investigations will be conducted to assess population size and post-capture survival rate through mark-recapture experiment, viability test or genetic studies. Post-capture survival rate is largely undocumented in sharks (Molina and Cooke, 2012; Oliver et al., 2015), and more information are needed to improve management and conservation of shark species (Braccini et al., 2012). In the Canadian pelagic longline fishery, Campana et al. (2016) stated that for fisheries with significant discards, post-release mortality has to be seriously taken into account in the fishery management to avoid risking overexploitation.

Conclusion

The wide depth range and geographical distribution covered by the commercial toothfish fisheries in Kerguelen (500–2 000 m) present an opportunity to expand our knowledge of deep-sea species. Data collected by trained observers on board are very valuable and essential to study by-catch, especially for less common species. The very high quality of the observer program must be maintained as it provides crucial data for fisheries management. Further studies must be conducted to assess population size and mitigate shark by-catch in the French longline fisheries.

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