Fisheries Research 278 (2024) 107093

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Full length article

Leader material and bait effects on target and bycatch species caught in an Atlantic Ocean pelagic longline fishery

Catarina C. Santos[a,b,*], Miguel N. Santos[a,1], Daniela Rosa[a,b], Rui Coelho[a,b]

[a] IPMA - Portuguese Institute for the Ocean and Atmosphere, Av. 5 de Outubro s/n, Olhão 8700-305, Portugal
[b] CCMAR - Centre of Marine Sciences. University of Algarve, Campus de Gambelas Ed 7, Faro 8005-139, Portugal

ARTICLE INFO

Handled by A.E. Punt

Keywords:
Pelagic longline fishery
Nylon monofilament *vs.* wire leaders
Squid *vs.* mackerel
Shark mortality
Bycatch mitigation

ABSTRACT

The influence of bait type and leader material on target and bycatch species was assessed through fishing experiments in the Portuguese shallow pelagic longline fishery in the Atlantic Ocean. Wire leaders were found to decrease catch rates of commercially valuable species such as bigeye tuna and yellowfin tuna, while increasing catch rates of elasmobranchs, including the blue shark and shortfin mako. The odds ratios of capture swordfish and tunas also decrease when using wire leaders, while elasmobranchs have higher odds ratios of capture and at-haulback mortality when using wire leaders. Squid bait led to higher catches of targeted tuna species, however it also resulted in higher catches of marine turtles. For most of the taxa caught at-haulback mortality risk was found to be higher on squid bait, which may be related with increased deep-hooking events. While bait type and leader material did not significantly affect size selectivity for most species, wire leaders were found to retain larger blue sharks and fish bait attracted smaller-sized swordfish. This study showed that banning wire leaders on pelagic longline fisheries is an effective measure for reducing the retention of pelagic shark species, particularly of large size blue sharks.

1. Introduction

Pelagic longline fishing is a commercial fishing technique that has historically been used to catch swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.) in both coastal and open-ocean waters. However, incidental mortality of non-targeted taxa has led to considerable concern over the ecological impacts of this fishery in marine ecosystems (e.g. Lewison and Crowder, 2007; Anderson et al., 2011; Coelho et al., 2012b). The pelagic longline fishing gear consists of a mainline suspended by floats with a series of baited hooks hanging vertically in branch lines, which can be set to fish at a variety of depths from near surface waters to depths down to 300 m, depending on target species (ICCAT Manual, 2006–2016). Shallow longliners target mostly swordfish between depths of 20–60 m, while deeper setting (between depths of 100–300 m) is used when targeting tunas [i.e. albacore (*Thunnus alalunga*) and bluefin tuna (*Thunnus thynnus*)](A. Domingo, *personal communication*). These depths overlap with the spatial distribution of several protected and vulnerable species, exposing them to a potential risk of capture. Some of the species' groups affected include billfishes, marine turtles, seabirds and mammals, as well as other fish species (e.g. Carranza et al., 2006; Garrison, 2007; Jiménez et al., 2010; Coelho et al., 2012b; Gallagher et al., 2014). The latter include several pelagic sharks that are particularly susceptible to overexploitation due to low potential for population recovery caused by a slow growth and low fecundity life history strategy (Cortés et al., 2010). Accordingly, fisheries bycatch - the unintended capture of non-target species during fishing operations - poses a serious threat for marine megafauna worldwide and its mitigation is key for the sustainability of marine resources (Hall et al., 2000; Soykan et al., 2008).

Over the past few decades, the consequences of longline fisheries bycatch have become the subject of intense scrutiny. This has led to a growing number of research initiatives that focused on developing and testing measures that could minimize the interactions of longline gear with non-target species and/or reduce their fishing mortality rates (Clarke et al., 2014; Swimmer et al., 2020). Bycatch in longline fisheries can be mitigated through the implementation of different types of measures, including spatial-temporal closures, or through changes in fishing practices and gear (e.g. reduction of longline soak time, use of circle hooks instead of J-hooks, use of fish bait instead of squid bait) (e.g. Hall, 1996; Watson et al., 2005; Ward et al., 2008; Gilman, 2011; Coelho

---

* Corresponding author at: IPMA - Portuguese Institute for the Ocean and Atmosphere, Av. 5 de Outubro s/n, Olhão 8700-305, Portugal.
E-mail address: catarina.ccns@gmail.com (C.C. Santos).

[1] Present address: International Commission for the Conservation of Atlantic Tunas (ICCAT), Calle Corazón de Maria 8, 6th floor, 28002 Madrid, Spain

https://doi.org/10.1016/j.fishres.2024.107093
Received 12 December 2023; Received in revised form 14 June 2024; Accepted 14 June 2024

et al., 2012b; Swimmer et al., 2020). When comparing both strategies, changes in fishing gear measures tend to generate better acceptance within the fishing community since they offer fishers the opportunity to maintain the fishing activity with no other substantial cost than the purchase of the gear modification (Favaro and Côte, 2015).

The use of different hook types has been widely tested and represents the most commonly evaluated strategy for mitigating longline fisheries bycatch and reducing overall mortality (e.g. Read et al., 2007; Serafy et al., 2009; Godin et al., 2012, Domingo et al., 2012, Santos et al., 2013); additionally, the benefits of using one leader material and/or bait species over the other, have also been tested with much less effort (Santos et al., 2023). However, the available results have often been inconsistent among studies, which has led to scepticism about the value of these measures and, in some cases, has prevented their implementation. For example, while most studies concluded that using fish bait instead of squid seems to be an effective measure to lower bycatch of marine turtles (Watson et al., 2005; Yokota et al., 2009; Foster et al., 2012; Santos et al., 2012; Coelho et al., 2015; Gilman et al., 2017; Swimmer et al., 2017), results on sharks have been mixed and often inconclusive. The currently available information on this topic was synthesized in a meta-analysis by Santos et al. (2023), with the authors noting that using fish instead of the traditional squid bait in shallow pelagic longlines does not result in lower catch rates for sharks. In contrast, a previous review by Gilman et al. (2020) reported a significant reduction in blue shark (*Prionace glauca*) catch rates with fish bait, although it was suggested that the effect of bait type on the catch risk of pelagic sharks is variable and species-specific. In Coelho et al. (2012b), the effect of bait in catch rates and at-haulback mortality was also suggested to vary depending on the species. Moreover, while several nations as well as tuna Regional Fishery Management Organizations (t-RFMOS), namely the Western and Central Pacific Fisheries Commission (WCPFC), have supported the ban of wire leaders in longline fisheries in an attempt to reduce shark retention, research on the effects of leader material on the catch and mortality rates of bycatch species remains scarce. Previous studies indicated that catch rates of pelagic sharks were lower when using nylon instead of the alternative wire leaders (Ward et al., 2008; Vega and Licandeo, 2009; Afonso et al., 2012; Santos et al., 2017; Scott et al., 2022), most likely because sharks would be able to sever nylon leaders and escape; nevertheless, sharks that manage to escape the gear but ultimately do not survive constitute a type of “discarded” bycatch that warrants assessment through post-release mortality studies. Santos et al. (2023) emphasized that findings on the effects of leader material should be interpreted with caution due to the small number of adequate references, adding that work with prior experimental design standardization should be seen as a research priority. In fact, the common conclusion between studies is that further investigation is required to confirm the effectiveness of such bycatch mitigation strategies.

This study aims to test the effect of bait type (fish vs squid) and material used on the terminal tackle of the branch lines (monofilament nylon leader vs multifilament wire leader) on the catches of the Portuguese shallow pelagic longline fishery targeting swordfish and blue shark in the Atlantic Ocean. Specifically, we analysed and compared catch composition and catch rates, at-haulback mortality rates, bite-off rates, hooking location and catch-at-size rates from both types of bait and leader material tested. Subsequently, we provide the expected effects in terms of odds ratios in the catches and at-haulback mortality, when changing between those different fishing gear configurations.

2. Materials and methods

2.1. Experimental design and data collection

For this study, a total of 105 longline sets (total effort of 92,225 hooks) were carried out along three experimental fishing trips in the north-eastern Tropical and Equatorial Atlantic Ocean, along wide latitudinal (3° to 14° N) and longitudinal (18° to 37° W) ranges (Fig. 1), between June 2013 and October 2014. A commercial fishing vessel from the Portuguese pelagic longline fleet participated in the experiments. The fishing gear consisted of a standard monofilament polyamide mainline of 3.6 mm in diameter, with five branch lines between floats. Each branch line was approximately 12.5 m in length, the first section consisting of 2.5 mm monofilament (9.85 m long) connected by a weighted (80 g) swivel to a second section. The latter, in the case of the control (nylon), consisted of a 2.5 mm nylon monofilament leader (2.65 m in length) with a hook in the terminal tackle; in the case of the treatment (wire), a 2.5 mm nylon monofilament gangion (1.9 m in length) connected by a weighted (60 g) swivel to a third section composed of a 1.4 mm multifilament stainless steel leader (3 strands, 0.75 m long) with a hook in the terminal tackle. A battery flashlight (colour green) was attached to the swivel connecting the first and second sections of the branch lines. Only one stainless steel 10° offset J hook style was used (EC-9/0-R, produced by WON YANG, Korea), corresponding to the traditional J-hook used by the fishery.

Two different bait types were used, mackerel (*Scomber* spp.) (whole fish) and squid (*Illex* spp.), but only one bait type was used in each set to avoid possible interaction effects, similar to Watson et al. (2005). Standardized bait size was used in all longline sets (squid 24.5±1.64 cm and mackerel 36.4±1.83 cm). All characteristics of the fishing gear and fishing practices (e.g. gear section placement, setting time, colour of the battery flashlight, bait size and hook) were standardized and maintained constant over the three trips. The total number of hooks per set ranged between 280 and 1345, fishing at depths of approximately 20–50 m. Gear deployment began traditionally at 17:00 h, with haulback starting the next day at about 06:00 h. Branch line type was alternated section by section of the longline to minimize the potential for confounding effects specific to a set (e.g. location, water temperature, fish density, etc.). Moreover, the branch line type of the first gear section in the water changed every set, following a fixed scheme (i.e. mono:wire:mono:wire, and so on).

Following Santos et al. (2017), power tests were carried out in order to estimate the experimental fishing effort required to detect a fishing method that has different degrees of effectiveness in catching swordfish and blue shark in comparison with the control fishing method. The control fishing method was assumed to be the combination of gear and bait most commonly used in the fishery, specifically monofilament nylon leaders and J hooks baited with squid. The power calculations were based on the necessary number of hooks required to detect a 25 % and 50 % change in the number of the two most caught species in the fishery (swordfish and blue shark).

A trained scientific fishery observer from the Portuguese Institute for Sea and Atmosphere (IPMA, IP) monitored the experimental protocols and collected the data on the vessel. Whenever a specimen was caught in the longline, the observer identified the species, recorded the leader line material, specimen’s fate (retained/discarded), condition at haulback (alive/dead) and condition if discarded (alive/dead), as well as the type of interaction (i.e. hooking location: *mouth/jaw* – when the hook was visible and located in the mouth; *deeply ingested* – when the hook was ingested and located in the throat or gut; *foul hooked* – when the hook was located externally anywhere else other than the mouth; *entangled* – when the specimen was entangled in the gangion line). In the case of marine turtles, when possible, these were boated with a large dip net. Further, and whenever possible, the observer and crew attempted to remove fishing gear using long-handled de-hookers and line cutters. Whenever possible the sex of the specimens was determined and the size was measured to the nearest lower 1 cm (lower jaw-fork length for billfishes; fork length for other fishes; carapace curved length for turtles). However, due to the size/weight of some species [i.e. manta rays (*Manta* spp.) and leatherback turtles (*Dermochelys coriacea*) and in order to increase their odds of survivorship, some specimens were not brought onboard, being immediately released by cutting-off the line. All branch lines which presented broken or absent hooks (i.e. bite-offs) were

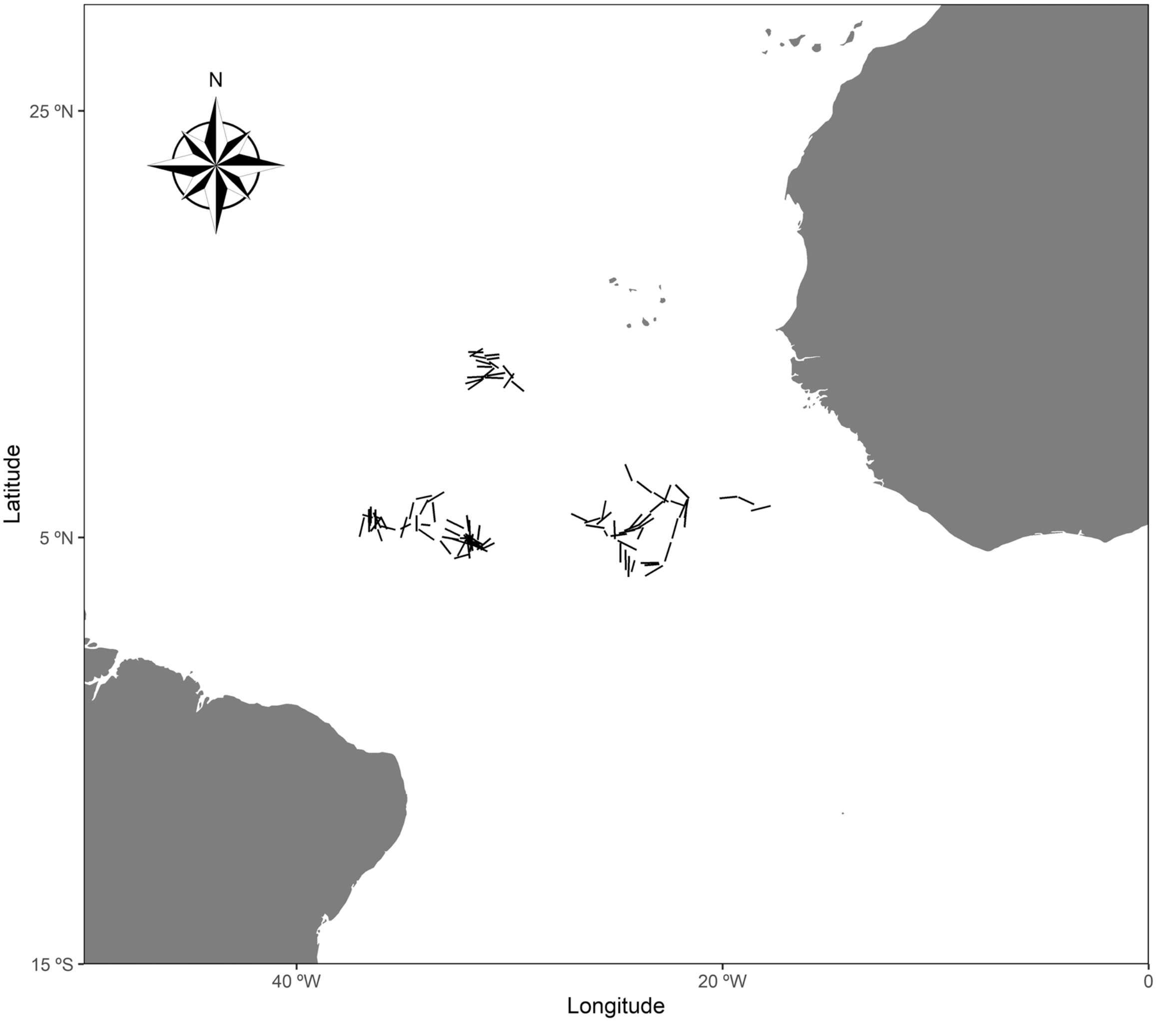

Fig. 1. Location of the experimental longline sets. Location of the experimental longline sets in the north-eastern Tropical and Equatorial Atlantic region.

identified. Only bite-offs inflicted on the leader were included in the analysis.

Five groups were established for the captured species: billfishes, which included swordfish, marlins and sailfishes, with the latter two considered a bycatch; tunas, belonging to the genus *Thunnus*; elasmobranchs, which included sharks, the pelagic stingray (*Pteroplatytrygon violacea*) and manta rays; other bony fishes, which accounted exclusively for other teleost bycatch species; and marine turtles (the complete list of species is described in detail in Table 1 of Supplementary material). Finally, all the species that were accidentally caught but not retained were considered discards, consisting mostly of teleost and elasmobranch species with low commercial value and/or shark species whose retention is forbidden by the International Commission for the Conservation of Atlantic Tunas (ICCAT) [i.e. bigeye thresher (*Alopias superciliosus*), hammerheads (*Sphyrna* spp.), silky (*Carcharhinus falciformis*) and oceanic whitetip (*C. longimanus*)].

2.2. Data analysis

Catch rates expressed as catch per unit of effort (CPUE) were estimated in number of individuals (CPUE) per 1000 hooks. At-haulback mortality rates (MPUE) were also calculated as the number of dead specimens at-haulback per 1000 hooks. For the retained species, catch per unit of effort was estimated in weight (kg) per 1000 hooks (CPUEb), using conversion equations, as the retained catches were processed and frozen onboard and weighing was difficult. For billfishes and tunas, these were calculated using the ICCAT conversion equations (ICCAT, 2006–2016). However, in the case of the remaining species ([i.e. blue shark, shortfin mako (*Isurus oxyrinchus)*, longfin mako (*Isurus paucus*) and other bony fishes)], conversion equations from IPMA (unpubl. data) were used.

Kolmogorov-Smirnov tests with Lilliefors correction (Lilliefors, 1967) were used for testing catch composition, CPUE and MPUE for normality, while Levene tests were used for testing the homogeneity of variances. Those tests were applied to the raw data collected. Due to the general lack of normality and homogeneity of variances, the differences between leader and bait types were tested with randomization tests, to determine if the observed differences between leader and bait types were significant or if they were occurring due to randomness in the sampling (Manly, 2007). Therefore, a Monte Carlo approach was used with the data randomized and resampled 9999 times to build the expected distribution of the differences under a random distribution, which was then compared and used to determine the significance of the differences observed in the sample.

The mean length and respective standard deviations were calculated for all species captured and brought on board. For the two most abundant species caught (i.e. swordfish and blue shark), the length frequency distributions were plotted with histograms. For those two species, the mean sizes were compared between both leader and bait types with randomization tests.

The bite-offs were calculated for each fishing set as the number of bite-offs per 1000 hooks within each of the leader material/bait

Table 1

Means and standard deviations (StD) for catch in number per unit of effort, by species and species groups caught using different leader materials (nylon and wire) and bait species (fish and squid). *P*-values refer to the results of permutation tests used to compare leader and bait effects.

			Mean standard catch per unit of effort (number/1000 hooks)									
			Nylon				**Wire**				**Permutation test**	
Species			**Fish**		**Squid**		**Fish**		**Squid**		**(*P* values)**	
Group	**Scientific name**	**FAO code**	**CPUE**	**± StD**	**CPUE**	**± StD**	**CPUE**	**± StD**	**CPUE**	**± StD**	**Bait**	**Leader**
Billfishes	*Makaira nigricans*	BUM	0.6	1.25	2.0	3.09	0.6	1.47	1.0	1.50	**0.0016**	0.069
	Istiophorus albicans	SAI	0.6	1.25	1.3	2.62	0.7	1.71	1.5	3.54	**0.0182**	0.705
	Tetrapturus pfluegeri	SPF	0.1	0.50	0.1	0.58	0.1	0.64	0.1	0.57	1.000	0.842
	Xiphias gladius	SWO	13.5	8.81	15.8	15.21	12.6	12.02	11.4	10.42	0.763	0.100
	Tetrapturus albidus	WHM	1.1	2.23	1.5	2.61	1.3	2.26	1.5	2.33	0.334	0.742
Total billfishes			15.9	8.67	20.8	15.00	15.4	11.81	15.5	11.77	0.131	0.081
Tunas	*Thunnus alalunga*	ALB	0.2	0.73	0.0	0.00	0.0	0.00	0.1	0.41	0.348	0.368
	Thunnus obesus	BET	1.2	3.92	7.6	11.19	0.7	2.11	3.8	4.65	**<0.001**	**0.015**
	Thunnus albacares	YFT	0.9	2.40	2.9	4.55	0.4	1.28	1.6	3.15	**<0.001**	**0.041**
Total tunas			2.3	5.79	10.6	14.60	1.1	1.64	5.5	5.25	<0.001	**0.008**
Other bony fishes	*Alepisaurus ferox*	ALX	0.0	0.00	0.2	0.67	0.2	0.87	0.2	0.75	0.448	0.326
	Seriola dumerili	AMB	0.1	0.50	0.0	0.32	0.1	0.50	0.2	0.67	0.701	0.475
	Coryphaena hippurus	DOL	1.1	3.50	3.4	17.01	0.3	0.97	2.7	8.91	**0.046**	0.727
	Gempylus serpens	GES	0.2	0.84	0.2	0.66	0.0	0.00	0.0	0.00	0.774	**0.031**
	Lepidocybium flavobrunneum	LEC	0.1	0.50	0.1	0.41	0.1	0.59	0.1	0.49	0.752	0.817
	Lobotes surinamensis	LOB	0.0	0.00	0.1	0.41	0.0	0.00	0.1	0.41	0.526	1.000
	Mola mola	MOX	0.1	0.50	0.2	0.66	0.0	0.00	0.1	0.41	0.381	0.250
	Ruvettus pretiosus	OIL	0.0	0.00	0.0	0.32	0.0	0.00	1.6	3.62	**<0.001**	**<0.001**
	Brama brama	POA	0.0	0.00	0.0	0.00	0.0	0.00	0.1	0.49	-	-
	Cubiceps capensis	UBP	0.0	0.00	0.1	0.41	0.0	0.00	0.0	0.00	-	-
	Acanthocybium solandri	WAH	0.2	0.68	0.2	0.72	0.5	1.14	0.5	1.39	0.657	**0.032**
Total other bony fishes			1.6	3.79	4.4	16.91	1.2	2.44	5.3	9.77	**<0.001**	0.896
Elasmobranchs	*Prionace glauca*	BSH	25.0	24.96	22.1	21.98	39.0	33.87	29.4	0.18	0.094	**0.004**
	Alopias superciliosus	BTH	0.3	0.96	0.4	1.23	0.4	1.64	0.2	0.75	0.801	0.756
	Carcharhinus falciformis	FAL	0.1	0.55	0.4	1.28	0.1	0.58	0.1	0.51	0.262	0.227
	Isurus paucus	LMA	0.2	0.76	0.1	0.58	0.3	1.07	0.4	1.02	1.000	0.175
	Mobulidae	MAN	0.1	0.64	0.3	1.23	0.2	0.82	0.3	1.30	0.279	0.683
	Carcharhinus longimanus	OCS	1.0	2.25	0.9	1.57	0.9	1.71	0.9	1.82	0.917	0.731
	Pteroplatytrygon violacea	PLS	1.6	3.04	3.2	5.49	0.3	0.78	0.0	0.00	0.169	**<0.001**
	Pseudocarcharias kamoharai	PSK	0.5	1.79	1.7	3.12	0.5	1.32	0.8	1.80	**0.012**	0.143
	Isurus oxyrinchus	SMA	0.1	0.69	0.0	0.32	0.4	1.03	0.4	1.45	0.921	**0.015**
	Sphyrna zygaena	SPZ	0.0	0.00	0.1	0.51	0.3	1.20	0.1	0.49	0.536	0.175
	Galeocerdo cuvier	TIG	0.1	0.52	0.1	0.41	0.3	0.81	0.0	0.00	0.052	0.594
Total elasmobranchs			29.0	24.96	29.3	21.43	42.7	34.50	32.6	25.20	0.197	**0.027**
Sea turtles	*Dermochelys coriacea*	DKK	0.7	1.89	0.6	2.21	0.4	1.08	0.9	2.03	0.329	0.955
	Lepidochelys olivacea	LKV	0.4	1.25	2.4	4.78	0.4	1.15	1.2	2.19	**<0.001**	0.176
	Caretta caretta	TTL	0.1	0.52	0.1	0.11	0.0	0.00	0.1	0.65	0.572	0.438
Total sea turtles			1.2	2.24	3.1	6.26	0.8	1.64	2.2	2.24	**0.001**	0.265

combinations. The mean and standard deviations for each combination were calculated and plotted, and the differences tested with randomization tests.

The relationship between hooking location and leader material/bait species was assessed with plots and with contingency table analysis and chi-square proportion tests. This analysis was performed only for species that numbered > 30.

Generalized linear models (GLM) with a binomial error distribution and a logit link function were used for determining the influence of changing between the two different leader materials and bait types in the various species or combined taxonomic groups. This was tested for both the catches in number and for the at-haulback mortality, and was only applied to species or other taxa with catches in number > 30. The response variable of the models was the proportion of catches (or dead specimens in the case of mortality models) in each longline set, calculated as the number of catches (or dead specimens in the case of mortality models) given the number of hooks used in each set. The explanatory variables included in the GLM were bait type and leader material. The baseline reference levels for the explanatory variables were monofilament nylon leader and squid bait (control), and the other levels of the variables were compared against this combination. Given that the log link function was used, the odds ratios of the parameters with their respective 95 % confidence intervals were calculated and used for interpretation as the exponential values of the estimated parameters. An odds ratio > 1.0 indicates higher values for treatment compared with the control.

Data analysis for this paper was carried out using the R Project for Statistical Computing version 4.2.0 (R Core Team, 2022). Most analyses used functions available in the core R program, and exceptions were the Levene test to compare homogeneity of variances using library "car" (Fox and Weisberg, 2011), the permutation tests that were carried out using library "perm" (Fay and Shaw, 2010), and the plots that were built using ggplot2 (Wickham, 2009).

3. Results

3.1. Power tests

A total of 92,225 hooks were used during the experimental fishing sets (105 fishing sets), corresponding to 46,290 hooks of monofilament leaders and 45,935 of wire leaders. Regarding the bait type, 50.3 % and 49.7 % of the hooks were baited with squid and fish, respectively. According to the power analysis conducted, the number of hooks deployed was larger than those necessary to detect a 25 % change in the catch rates (in number) of blue shark and swordfish, the main species targeted in the Portuguese pelagic longline fishery in the Atlantic. Specifically, the required number of hooks, within each of the tested combination, to detect such change was 12,061 for blue shark and 15,963 for swordfish, which were both exceeded.

3.2. Catch composition

A total of 33 taxa were caught during the study, specifically 11 species of elasmobranchs (including 9 species of shark), 5 species of billfishes, 3 species of tuna, 11 species of other bony fishes and 3 species of marine turtles (Table 2 of Supplementary material). The highest number of species was recorded when using monofilament leaders with squid bait (31 out of 33 species), while wire leaders with fish bait caught the lowest number of taxa (25 out of 33 species). However, catch composition was not significantly influenced by bait species (p-value=0.341) or leader material (p-value=0.680). Swordfish and blue shark were the most frequently caught species, occurring in more than 98 % of the fishing sets. These were followed by bigeye tuna and white marlin that were present in more than 50 % of the fishing sets. Species like blue marlin, yellowfin tuna, pelagic stingray, oceanic whitetip, olive ridley sea turtle, dolphin fish, sailfish and crocodile shark were also regularly caught (30–50 %), while the remaining species were less common in the catches (≤20 %). No significant differences in frequency of occurrence were observed between leader (permutation test: difference in means=0.606 specimens; p-value=0.791) and bait (permutation test: difference in means=-3.182 specimens; p-value=0.143) types.

A total of 4043 specimens were caught during this study, of which 570 were discarded either because they were non-commercial species, retention is prohibited by ICCAT, or there had been a depredation event (i.e. when a predator feeds on or damages the catch that are retained on the fishing gear). Of the 15 taxa retained, blue shark and swordfish were the most abundant species, together accounting for almost 80 % of the total retained specimens. In addition, 17 taxa were systematically discarded, specifically all three marine turtle species caught, eight elasmobranchs and six bony fishes (Table 2 of Supplementary material).

3.3. Catch rates

The effects of leader and bait type on the catch rates varied among species and species groups (Table 1). Significantly higher CPUEn of bigeye tuna, yellowfin tuna, pelagic stingray, snake mackerel and all tuna species combined were observed on nylon leaders compared to wire leaders. On the contrary, CPUEn of blue shark, shortfin mako, wahoo, oilfish and all elasmobranchs combined were higher on wire leaders. Bait species showed a significant effect on CPUEn of blue marlin, sailfish, bigeye tuna, yellowfin tuna, oilfish, dolphinfish, crocodile shark, olive ridley sea turtle, as well as for all turtle and other bony fish species combined, with squid bait producing higher CPUEn. Target species – swordfish and blue shark – had the highest overall CPUEn recorded in the study. The highest value of 39.0 individuals per 1000 hooks was recorded for blue shark when using wire leaders baited with squid, while swordfish had higher CPUEn on nylon leaders baited with fish (15.8 individuals per 1000 hooks). Monofilament nylon leaders baited with fish recorded the highest CPUEn for billfishes, tunas and sea turtles, while elasmobranchs and other bony fishes had greater CPUEn

Table 2

Means and standard deviations (StDs) for catch in weight (kg) per unit of effort (CPUEb/per 1000 hooks), by species and species groups caught using different leader materials (nylon and wire) and bait species (fish and squid). *P*-values refer to the results of permutation tests used to compare leader and bait effects.

			Mean standard catch per unit of effort (biomass in kg/1000 hooks)									
			Nylon				Wire				Permutation test	
Species			Fish		Squid		Fish		Squid		(*P* values)	
Group	Scientific name	FAO code	CPUEb	± StD	CPUEb	± StD	CPUEb	± StD	CPUEb	± StD	Bait	Leader
Billfishes	*Makaira nigricans*	BUM	36.5	104.14	147.7	226.64	52.3	143.99	92.6	169.31	<0.001	0.406
	Istiophorus albicans	SAI	10.9	26.61	28.0	55.55	16.3	43.22	29.2	64.35	0.027	0.655
	Tetrapturus pfluegeri	SPF	1.3	9.61	2.3	12.30	2.5	12.93	1.9	9.81	0.947	0.839
	Xiphias gladius	SWO	507.5	411.98	706.9	916.58	479.5	488.03	495.6	447.38	0.200	0.143
	Tetrapturus albidus	WHM	16.2	34.36	23.9	43.28	19.0	34.59	21.7	36.65	0.325	0.953
Total billfishes			572.4	434.35	908.8	875.68	569.6	494.25	640.8	463.56	0.010	0.095
Tunas	*Thunnus alalunga*	ALB	0.0	0.00	0.0	0.0	0.0	0.00	1.6	11.68	-	-
	Thunnus obesus	BET	64.8	210.50	333.5	491.93	31.0	98.94	152.4	221.57	<0.001	0.009
	Thunnus albacares	YFT	40.4	108.98	164.6	244.81	22.4	80.75	84.7	173.79	<0.001	0.036
Total tunas			105.2	284.21	498.0	677.61	53.3	164.69	238.7	246.35	<0.001	0.005
Other bony fishes	*Seriola dumerili*	AMB	0.0	0.00	0.4	3.02	0.0	0.00	0.6	2.91	0.243	0.969
	Coryphaena hippurus	DOL	9.6	35.95	29.6	143.06	3.6	11.07	21.8	71.15	0.052	0.666
	Lepidocybium flavobrunneum	LEC	1.2	8.40	1.0	7.05	0.3	1.49	0.4	3.24	1.000	0.486
	Ruvettus pretiosus	OIL	0.0	0.00	0.7	5.29	0.0	0.00	0.0	0.00	-	-
	Acanthocybium solandri	WAH	1.1	5.36	1.1	3.56	3.7	9.78	3.0	9.81	0.732	0.030
Total other bony fishes			11.9	36.66	32.8	142.89	7.5	15.27	25.8	71.01	0.043	0.726
Elasmobranchs	*Prionace glauca*	BSH	1372.2	1427.25	1242.5	1276.40	2368.4	2183.40	1760.9	1499.61	0.111	0.001
	Isurus paucus	LMA	4.4	18.74	2.2	11.50	15.8	66.29	10.5	34.14	0.491	0.065
	Isurus oxyrinchus	SMA	3.1	22.00	1.0	7.71	26.4	77.21	27.4	91.25	0.963	0.001
Total elasmobranchs			1379.6	1427.25	1245.8	1277.00	2410.6	2191.08	1798.8	1519.40	0.107	<0.001

on wire leaders baited with squid and fish, respectively (Table 1). On the other hand, catch in weight (CPUEb) for billfishes, tunas and other bony fishes was higher on nylon leaders baited with squid, and elasmobranchs showed higher CPUEb on wire leaders baited with fish, although results were not statistically significant (Table 2).

The odds ratios for the catches were significantly lower for the billfish and tuna groups and higher for elasmobranchs when using wire leaders compared to monofilament (Fig. 2A). At the species level, swordfish, bigeye tuna, yellowfin tuna and the pelagic stingray showed significantly lower odds of being captured with wire leaders, with odds ratios varying between reductions of 93 % (CI: 83–97 %) for pelagic stingray and 21 % (CI: 10–31 %) for swordfish (Fig. 2A). Blue shark was the only species showing significantly higher odds of being captured with wire leaders, specifically with the odds ratios increasing by 57 % (CI: 43–72 %) (Fig. 2A). Moreover, an increase in catches was verified for all taxa when using squid as bait, with the exception of elasmobranchs that showed the opposite trend although the reduction was not statistically significant (Fig. 2B). Percentages of increase in the odds ratios ranged from 73 % for pelagic stingray (CI:12–167 %) to 455 % for bigeye tuna (CI: 283–703 %) (Fig. 2B). Blue shark was the only species with a significant decrease in catches with squid bait (decrease of 15 % in the odds ratios; CI: 7–23 %) (Fig. 2B).

3.4. At-haulback mortality rates

Significantly lower MPUE of blue marlin and bigeye tuna were found on wire leaders, while no significant differences were found for the remaining species. Bait had a significant effect on MPUE of bigeye tuna, dolphinfish, all tuna species and other bony fishes combined. Specifically, squid bait was associated with higher MPUE (Table 3). Swordfish was the species with the highest overall value of MPUE, reaching the highest value of 14.8 dead individuals per 1000 hooks on nylon leaders baited with fish (Table 3). Monofilament nylon leaders baited with fish recorded the highest MPUE for billfishes, tunas and sea turtles, while MPUE of elasmobranchs and other bony fishes were higher on wire leaders baited with squid and fish, respectively (Table 3).

Similarly to what was described above, species exhibited varying trends of at-haulback mortality with the two different leader materials and bait species tested (Fig. 3). The mortality at-haulback was significantly lower for billfishes and tunas and higher for elasmobranchs when using wire leaders (Fig. 3A). Such trends were also observed for blue marlin (decrease in odds ratios of 50 %; CI:11–72 %), swordfish (decrease in odds ratios of 21 %; CI:10–31 %), bigeye tuna (decrease in odds ratios of 51 %; CI:30–65 %), yellowfin tuna (decrease in odds ratios of 44 %; CI:4–67 %) and blue shark (increase in odds ratios of 39 %; CI:15–67 %) (Fig. 3A). Results also indicated that squid bait was associated with a significantly higher at-haulback mortality for most species assessed, except for swordfish for which no significant differences were detected (Fig. 3B).

3.5. Bite-offs and hooking location

A total of 930 bite-offs were recorded resulting in a rate of 10 bite-offs per 1000 hooks. Significant differences in the number of bite-offs were found between leader materials and bait type, with most bite-offs occurring on nylon leaders (permutation test: difference in means=12.34 bite-offs/1000 hooks; p-value<0.001) and while using fish bait (permutation test: difference in means=4.29 bite-offs/1000 hooks; p-value=0.002) (Fig. 4). Specifically, results showed that bite-off rates decreased by 78 % when using wire leaders instead of nylon leaders (CI: 74–82 %). There was also a reduction in the order of 39 % when changing from fish bait to squid bait (CI: 30–46 %). Additionally, it is noteworthy that if bite-offs on nylon leaders were assumed to represent sharks that escaped, differences in catch rates between leader materials would be non-significant (permutation test: difference in means=1.994 sharks/1000 hooks; p-value=0.407).

Fifty-one percent of the specimens caught during this experiment were deeply hooked, however hooking location was highly variable

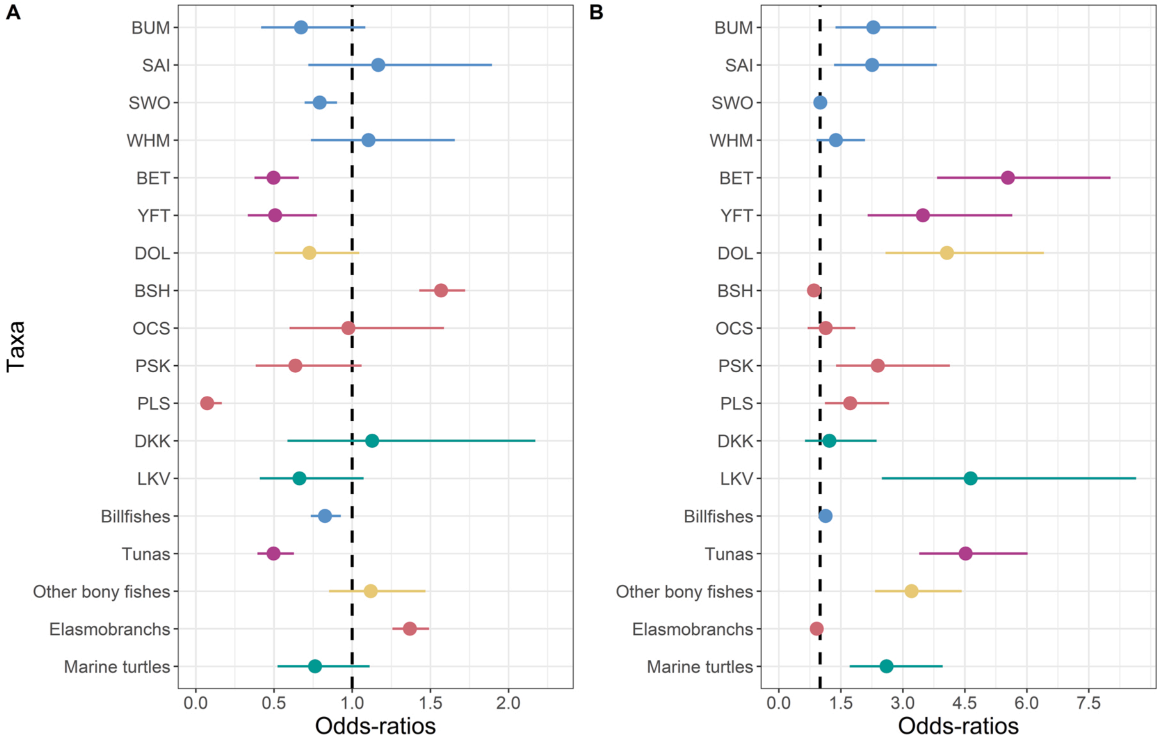

Fig. 2. Odds ratios for the catches. Odds ratios for the catches of species and species groups with catches > 30, when changing from nylon to wire leaders (A) and from fish bait to squid bait (B). Circles represent the point estimates and error bars represent the 95 % confidence intervals. (Note: nylon leaders/fish bait is considered the control and wire leaders/squid bait the experiment; an odds ratio >1 indicates that the odds of being capture is higher with wire leaders/squid bait).

Table 3
Means and standard deviations (StD) for at-haulback mortality in number per unit of effort, by species and species groups caught using different leader materials (nylon and wire) and bait species (fish and squid). *P*-values refer to the results of permutation tests used to compare leader and bait effects.

			Mean standard at-haulback mortality per unit of effort (number/1000 hooks)									
			Nylon				**Wire**				**Permutation test**	
Species			**Fish**		**Squid**		**Fish**		**Squid**		**(*P*-values)**	
Group	**Scientific name**	**FAO code**	**MPUE**	**± StD**	**MPUE**	**± StD**	**MPUE**	**± StD**	**MPUE**	**± StD**	**Bait**	**Leader**
Billfishes	*Makaira nigricans*	BUM	0.5	1.21	1.6	2.66	0.4	1.13	0.6	1.29	0.164	**0.022**
	Istiophorus albicans	SAI	0.3	0.97	1.1	2.39	0.6	1.57	1.2	3.08	0.054	0.379
	Tetrapturus pfluegeri	SPF	0.1	0.50	0.1	0.58	0.1	0.64	0.1	0.57	0.710	1.000
	Xiphias gladius	SWO	12.0	8.47	14.8	14.93	13.2	13.15	10.2	11.25	0.311	0.124
	Tetrapturus albidus	WHM	1.0	1.80	1.4	2.37	1.2	1.83	1.4	2.34	0.507	0.280
Total billfishes			13.9	8.34	19.0	14.73	15.6	12.80	13.6	12.86	0.112	0.143
Tunas	*Thunnus alalunga*	ALB	0.0	0.00	0.0	0.00	0.0	0.00	0.1	0.41	1.000	1.000
	Thunnus obesus	BET	0.9	3.02	4.9	7.60	0.5	1.57	2.1	3.00	**<0.001**	**0.027**
	Thunnus albacares	YFT	0.5	1.95	1.8	3.41	0.3	1.25	0.9	2.43	0.088	0.411
Total tunas			1.4	4.65	6.7	10.44	0.8	0.00	3.1	3.72	**0.001**	0.066
Other bony fishes	*Alepisaurus ferox*	ALX	0.1	0.55	0.2	0.67	0.2	0.87	0.2	0.75	0.981	0.498
	Seriola dumerili	AMB	0.1	0.50	0.0	0.00	0.1	0.50	0.1	0.49	0.968	0.992
	Coryphaena hippurus	DOL	0.5	2.28	1.9	10.23	0.1	0.46	2.0	6.94	**0.023**	0.818
	Gempylus serpens	GES	0.2	0.84	0.2	0.66	0.0	0.00	0.0	0.00	1.000	1.000
	Lepidocybium flavobrunneum	LEC	0.1	0.50	0.1	0.41	0.0	0.33	0.1	0.49	1.000	1.000
	Lobotes surinamensis	LOB	0.0	0.00	0.1	0.41	0.0	0.00	0.1	0.41	-	-
	Mola mola	MOX	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	-	-
	Ruvettus pretiosus	OIL	0.0	0.00	0.0	0.32	0.0	0.00	0.0	0.00	-	-
	Brama brama	POA	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	-	-
	Cubiceps capensis	UBP	0.0	0.00	0.1	0.41	0.0	0.00	0.0	0.00	-	-
	Acanthocybium solandri	WAH	0.2	0.68	0.2	0.72	0.6	1.46	0.5	1.39	0.125	0.924
Total other bony fishes			1.2	2.56	2.7	10.19	1.0	2.40	2.9	7.30	**0.019**	0.795
Elasmobranchs	*Prionace glauca*	BSH	5.8	7.31	6.5	6.69	8.9	11.63	8.4	0.07	0.757	0.908
	Alopias superciliosus	BTH	0.1	0.50	0.2	0.78	0.1	0.64	0.1	0.49	0.155	0.681
	Carcharhinus falciformis	FAL	0.1	0.55	0.2	0.88	0.1	0.58	0.1	0.51	0.506	0.488
	Isurus paucus	LMA	0.1	0.50	0.0	0.32	0.1	0.52	0.2	0.78	1.000	0.504
	Mobulidae	MAN	0.0	0.00	0.0	0.32	0.0	0.00	0.1	0.49	-	-
	Carcharhinus longimanus	OCS	0.4	1.28	0.5	1.12	0.4	1.13	0.7	1.77	0.911	0.806
	Pteroplatytrygon violacea	PLS	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	-	-
	Pseudocarcharias kamoharai	PSK	0.1	0.55	0.3	0.97	0.2	0.71	0.3	1.00	0.705	1.000
	Isurus oxyrinchus	SMA	0.1	0.50	0.0	0.32	0.3	0.88	0.2	0.80	1.000	1.000
	Sphyrna zygaena	SPZ	0.0	0.00	0.1	0.51	0.4	1.50	0.0	0.00	0.317	0.334
	Galeocerdo cuvier	TIG	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	-	-
Total elasmobranchs			6.6	7.31	8.0	6.86	10.5	12.03	10.1	9.65	0.854	0.838
Sea turtles	*Dermochelys coriacea*	DKK	0.1	0.50	0.1	0.97	0.0	0.00	0.0	0.00	1.000	0.493
	Lepidochelys olivacea	LKV	0.1	0.41	0.4	1.00	0.0	0.00	0.1	0.49	0.159	0.209
	Caretta caretta	TTL	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	-	-
Total sea turtles			0.1	0.64	0.5	1.35	0.0	0.00	0.1	0.49	0.214	0.054

among species. For example, while species like yellowfin tuna, crocodile shark and the pelagic stingray were predominantly hooked in the mouth (68 %, 71 % and 97 %, respectively), swordfish, dolphinfish and oceanic whitetip tended to be deeply hooked (67 %, 73 % and 67 %, respectively) (Fig. 5). In the case of leatherback sea turtle, 97 % of specimens were foul-hooked (Fig. 5). Deeply hooked specimens were mainly found when squid was used as bait. Additionally, chi-square analysis showed that hooking location was dependent on leader type for blue shark (chi-square=8.21; df=3; p-value=0.041) and yellowfin tuna (chi-square=4.28; df=1; p-value=0.038). Significant differences were also detected for blue shark when comparing hooking location between bait type (chi-square=18.45; df=3; p-value<0.001).

3.6. *Length composition of catches*

For most species, there were no major differences in size range, or in mean size for the different leader materials and bait types tested (Table 3 of Supplementary material). However, the results showed significant differences in the mean size between leader materials for blue shark (permutation test: difference in means=-1.66; p-value=0.036). Particularly, slightly larger individuals were captured with wire leaders (mean size= 202.58 cm FL; SD=± 16.53 cm FL) than with the traditional nylon leaders (mean size= 200.92 cm FL; SD= ± 16.72) (Fig. 6). For swordfish, significant differences were detected in the mean size captured with the two baits tested (permutation test: difference in means=-6.69; p-value<0.001), with hooks baited with fish capturing smaller specimens (mean size=138.63 cm FL; SD=± 29.51 cm FL) than when squid was used as bait (mean size= 145.31 cm FL; SD=± 31.54 cm FL) (Fig. 6).

4. Discussion

Over the last decade, several gear changes have been tested in longline fisheries worldwide trying to mitigate bycatch of non-target species and accidentally caught vulnerable fauna. Nevertheless, the cost and logistical challenges associated with large-scale experiments in the open ocean have resulted in relatively few studies that rigorously assess the efficiency of such measures in reducing bycatch. Similarly to hook shape, the choice of leader material as well as the type of bait used can significantly affect the financial yield of the fishery, however their

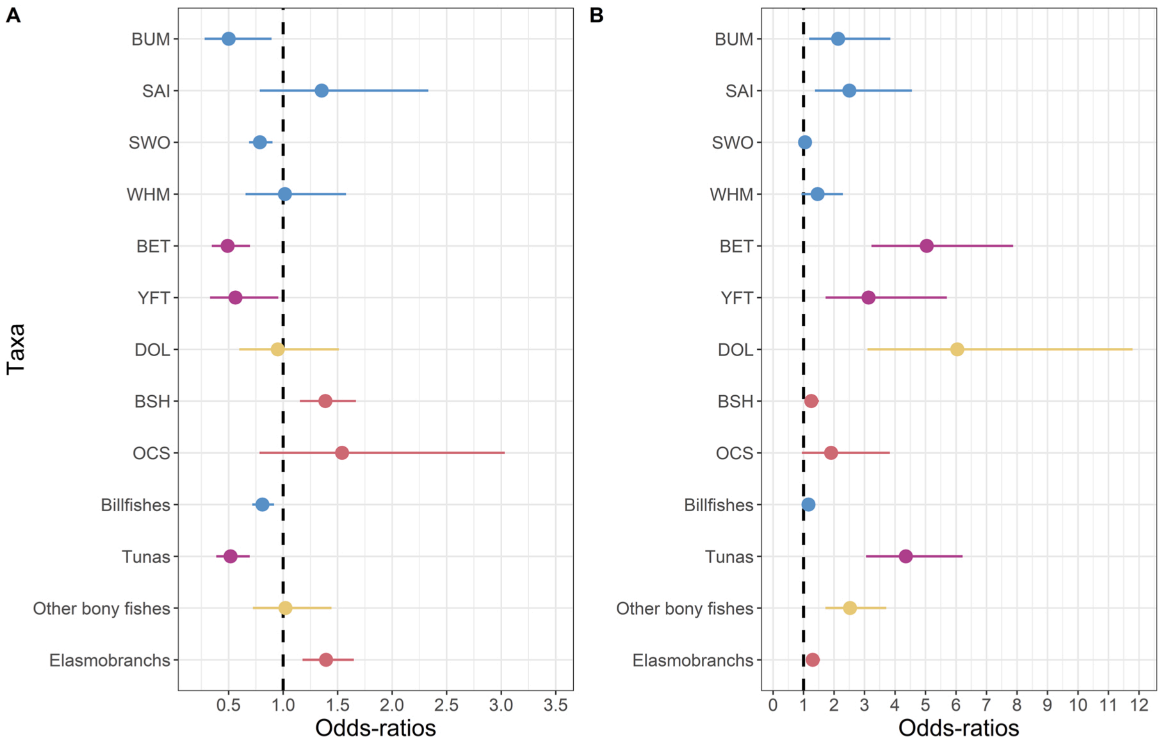

Fig. 3. Odds ratios for the mortality at-haulback. Odds ratios for mortality at-haulback of species and species groups with catches > 30, when changing from nylon to wire leaders (A) and from fish bait to squid bait (B). Circles represent the point estimates and error bars represent the 95 % confidence intervals. (Note: nylon leaders/fish bait is considered the control and wire leaders/squid bait the experiment; an odds ratio >1 indicates that the odds of being dead at-haulback is higher with wire leaders/squid bait).

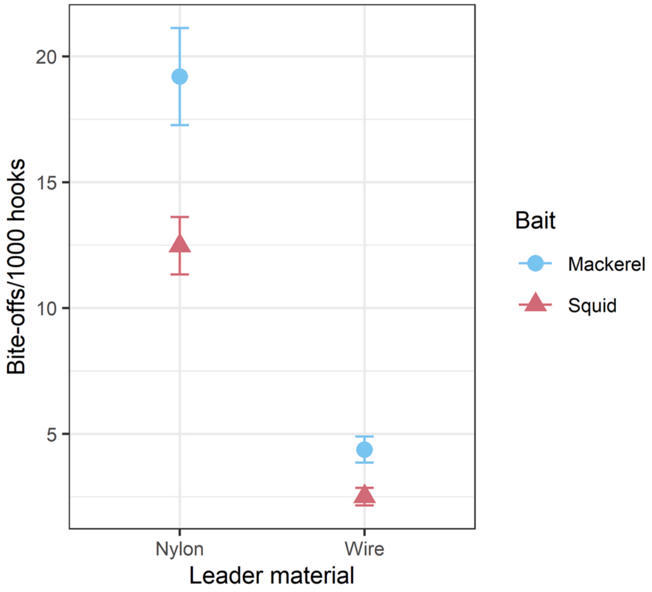

Fig. 4. Bite-offs rate on each leader material and bait species. Mean bite-offs per 1000 hooks on each leader material (nylon vs wire) and bait species (fish vs squid). Circles represent the point estimates and error bars represent the 95 % confidence intervals.

impacts on catch and mortality rates of species remain mostly understudied. As such, our study was specifically designed to test the influence of two different types of bait (fish vs squid) and materials used on the terminal tackle of the branch lines (monofilament nylon vs multifilament wire) on target and non-target species caught in shallow pelagic longline fisheries in the Atlantic Ocean.

Analyses showed that type of bait and leader material had no significant effect on the number of taxa caught, nor on the species frequency of occurrence for all taxa. On the other hand, leader material and bait species seemed to affect catch and at-haulback mortality rates of some of the species assessed. The use of wire leaders led to lower catch rates of some commercially valuable species, such as bigeye and yellowfin tunas, while increasing catch rates of elasmobranchs, including the blue shark and shortfin mako. Relative catchability was also influenced by leader material, with results pointing to lower odds ratios of capture of billfishes – including swordfish, the main target species of the shallow setting longline fishery – and tunas, and higher odds ratio of capture of elasmobranchs when using wire leaders. Similar results have been reported in the Atlantic (Afonso et al., 2012), Pacific (Ward et al., 2008; Vega and Licandeo, 2009; Scott et al., 2022) and Indian Oceans (Santos et al., 2017). Ward et al. (2008) found that catch rates of bigeye tuna on wire were lower than those on nylon. Afonso et al. (2012) and Vega and Licandeo (2009) indicated that target species – swordfish and tunas – were caught less frequently on gangions with wire leaders. One possible explanation for such trends may be related to these species' ability to detect wire leaders in the water and therefore avoid them (Ward et al., 2008). Tunas and billfishes are visual predators known to possess exceptional vision, capable of discerning small objects from a distance of 30 m (Brill et al., 2005). Some species exhibit a specialized heating system that specifically warms the eyes and brain, enhancing temporal resolution and thereby improving the detection of prey or lures (Fritsches et al., 2005). Moreover, evidence of two anatomically distinct cone cells with different spectral sensitivity suggests they may have the ability to perceive colour (Fritsches et al., 2000; Brill et al., 2005). By contrast, wire leaders were reported to have increased shark catches (Ward et al., 2008; Vega and Licandeo, 2009; 2022), including blue shark (Santos et al., 2017; Scott et al., 2022).

Theoretically, wire leaders are much more durable and resistant to cutting and biting than the traditional nylon leaders, which would

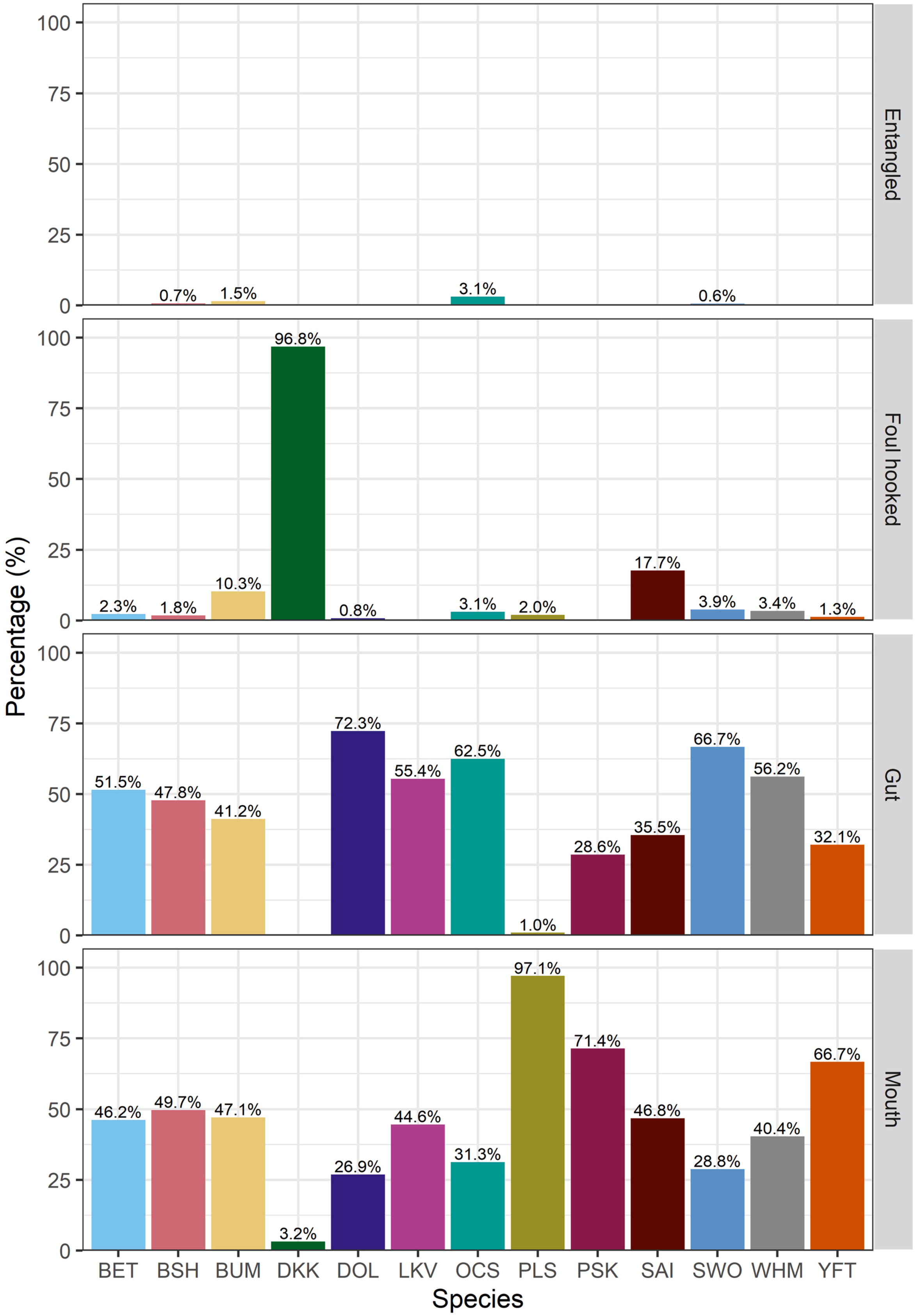

Fig. 5. Hooking location by species. Hooking location for the main species (n >30) captured during this study. The bars refer to the percentage of each hooking location for each species. (Note: FAO Species Codes were used to identify each species. Please see Table 1 of Supplementary material).

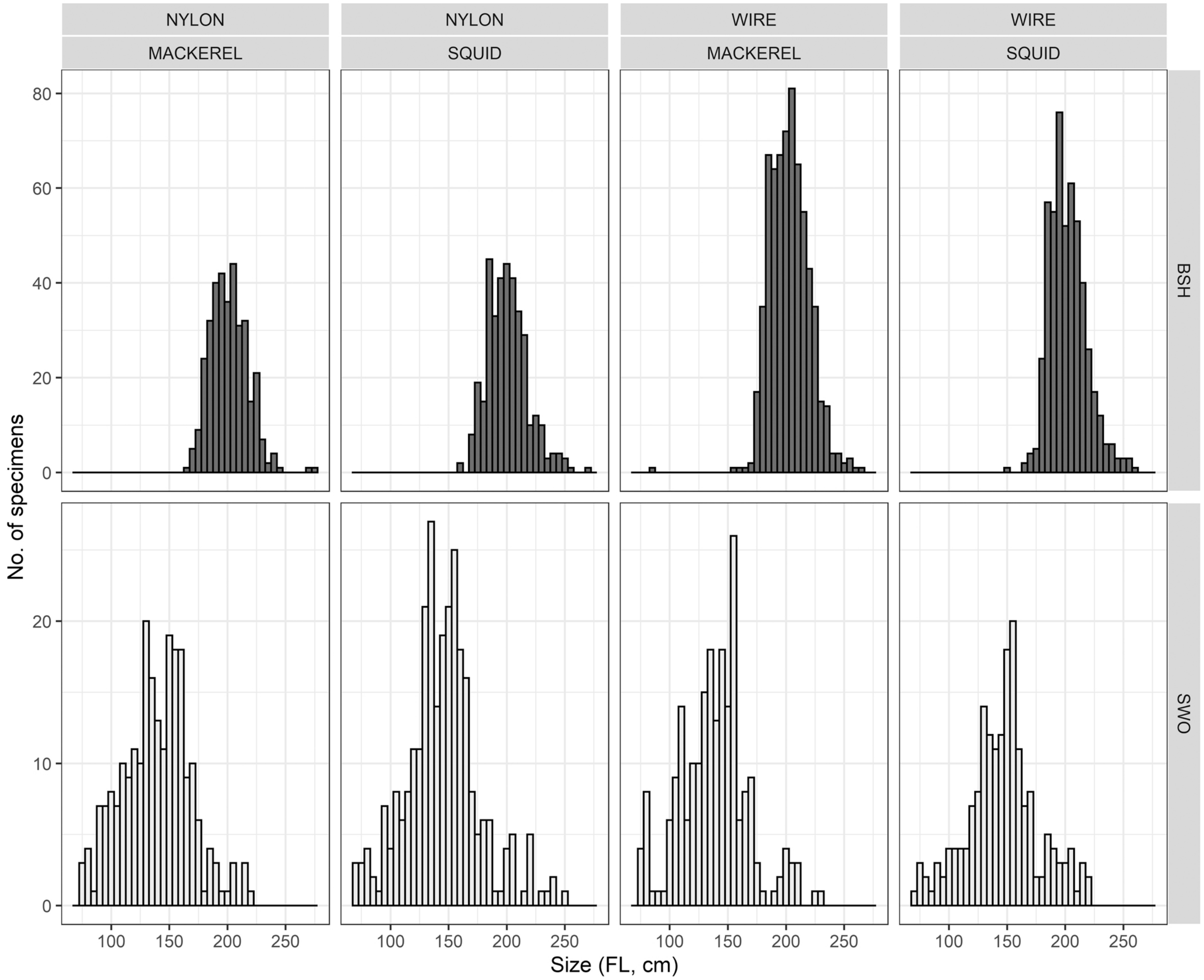

Fig. 6. Size distributions for blue shark and swordfish on each leader material and bait species. Size distributions for the 2 main species caught, blue shark and swordfish, on each leader material (nylon vs wire) and bait species (fish vs squid). Size measurements are given in centimetres: lower-jaw fork length for swordfish and fork length for blue shark.

prevent species with sharp teeth, such as sharks, from biting off the leader and escaping (Ward et al., 2008). However, this raises the question of whether shark catches on nylon leaders are under-reported. In our study, and since most bite-offs occurred on nylon leaders, if these were assumed to be sharks that severed the leader and escaped before gear retrieval, differences in catch rates between leader materials would be non-significant. Afonso et al. (2012) stated that differences in catch rates of sharks between leader materials were most likely caused by differing frequencies of bite-offs. Santos et al. (2017) suggested that deep hooking can result in leaders becoming more exposed to abrasion of teeth. Mortality risk was also influenced by leader material. In general, billfishes and tunas experienced lower at-haulback mortality rates and odds ratios of at-haulback mortality on wire leaders compared to nylon leaders. There is limited understanding of the effects of leader material on these species and we cannot explain such results, nevertheless other factors like soaking time, animal size and hooking location can be expected to influence mortality (Carruthers et al., 2009; Epperly et al., 2012). In contrast, wire leaders posed a greater threat for elasmobranchs. Similarly, Scott et al. (2022) found that using wire leaders in longline fisheries increased the potential for at-vessel mortality for sharks by up to 20 % compared to nylon leaders. Additionally, Bigelow and Carvalho (2021) concluded that banning wire leaders has the potential to reduce fishing mortality by 28.2 % and 35.8 % for silky shark and oceanic whitetip shark, respectively. However, mortality on nylon leaders might be higher than our estimates showed, since the fate of specimens that escape the gear remains largely unknown and there is a possibility of post-release mortality. Laboratory tests performed by Scott et al. (2022) suggested that sharks released with nylon trailing gear may carry it for at least a year, whereas copper crimps used with wire leaders began to break apart after ~60 days, potentially reducing the time animals carry trailing gear. Carrying trailing gear may impact swimming efficiency and poses a risk of injuries and infection (Parga et al., 2012; Adams et al., 2015), making these animals more likely to experience reduced survival rates. A study on post-release survival conducted by Hutchinson et al. (2021) demonstrated that survivorship can increase by up to 40 % when trailing gear is minimized, ideally by cutting the line and leaving less than 1 m in length.

Apart from leader material, bait constituted another relevant variable affecting both catches and at-haulback mortality of species. Our results showed that squid bait resulted in higher CPUE of some important target species, including bigeye and yellowfin tunas, as well as of all sea turtles and other bony fish species combined. The odds of capture were also significantly higher with squid bait for all taxa analysed, with the exception of elasmobranchs for which results were non-significant but revealed a reduction in odds of capture when squid bait was used. Previous studies have explored the effects of bait type on marine species and there is general agreement that sea turtles prefer squid over fish, leading to higher catches on squid bait. Nevertheless, mixed results have been described for sharks. For instance, in Foster et al. (2012), fish bait increased the catch of some vulnerable species including shortfin mako and porbeagle, while blue shark catch rates were found to be lower on fish bait. Conversely, Coelho et al. (2012a) reported higher catches of blue shark with fish bait relative to squid. In a recent literature review, Gilman et al. (2020) found that the use of squid would result in higher catch risk of marine turtles and blue shark, while results were non-significant for pelagic shark species combined. It was also suggested that catch rates of tunas and istiophorid billfishes may be higher on squid bait. Moreover, our results indicated that squid bait was responsible for higher at-haulback mortality rates of tunas and other bony fishes and higher odds ratios of at-haulback mortality for the majority of species assessed, nevertheless the current available information on this issue is very limited. Previous research has suggested a link between bait type, hooking location and subsequent likelihood of survival. Specifically, animals that were externally hooked have been observed to have higher at-haulback survival rates and may have higher odds of post-release survival in comparison to those that were deeply hooked, mainly due to reduced tissue damage and possible perforation of the internal organs (Cooke and Suski, 2004; Watson et al., 2005; Kerstetter and Graves, 2006; Campana et al., 2009). Moreover, Kiyota et al. (2004) studied hooking mechanisms associated with foraging behaviour of loggerhead sea turtles, indicating that while fish bait tends to be ingested in pieces, squid bait is usually swallowed whole and leads to deep-hooking. In Epperly et al. (2012), although hook type was one of the most important variables in predicting anatomical hooking location, baiting with squid rather than fish increased the probability of gut-hooking swordfish, but decreased the odds of gut-hooking blue shark and porbeagle. However, hooking location seems to depend on several variables other than bait and hook type, including hook offset, animal size (length), sea surface temperature and species (Epperly et al., 2012; Stokes et al., 2012; Parga et al., 2015). Here we found that most animals caught were deeply hooked and that this tendency was especially prevalent on squid baited hooks, nonetheless hooking location was species-specific.

Although leader material and bait type had no effect on size selectivity of most species, significant differences in mean size were found for blue shark and swordfish. In the case of blue shark, a larger mean size was observed with the use of wire leaders, which supports previous observations by Afonso et al. (2012) and Santos et al. (2017), which reported that wire leaders retain larger and more resilient animals. Moreover, the use of fish bait attracted smaller-sized swordfish, which agrees with the results reported by Amorim et al. (2015). Dominant prey items tend to shift with swordfish body length. Particularly, the diet of young swordfish is mainly composed of mesoplagic fish, while larger individuals have a diet focused on cephalopods (Hernandez-Garcia, 1995; Markaida and Hochberg, 2005; Young et al., 2006; Potier et al., 2007; Preti et al., 2023).

There is an ongoing discussion in several t-RFMOs regarding management measures (e.g. minimum size limits, maximum allowable catches and quotas, gear and spatial/temporal restrictions) that could maintain the sustainability of fish populations and balance the needs of fishers. Accordingly, the type of bait used, as well as the choice of leader material have been identified as key components in the success of the pelagic longline fisheries. Bait plays a critical role in attracting target species to longline gear, nevertheless its influence on catch and mortality rates of non-target species is complex and potential confounding factors, such as hook shape, need to be explored to further advance scientific knowledge in this field. Altering leader material is also seen as an option for mitigating bycatch of vulnerable fauna. Accordingly, several stakeholders have been advocating for the ban of wire leaders on longline fisheries to reduce retention and mortality of pelagic sharks, thereby safeguarding several vulnerable species from overfishing. Although catch and mortality rates of toothed species on monofilament nylon leaders may be underestimated, the present study showed banning wire leaders on longline fisheries to be an effective way of reducing shark at-haulback mortality. It is also important to recognize that the impact of bait and leader material on marine species is not solely determined by their individual characteristics. Other factors such as environmental conditions, soak time and animal handling are likely to play a significant role in the survival of species. Understanding these factors and their complex interactions is therefore critical, which emphasizes the urgent need for proper funding to be provided through the t-RFMOs for further study these matters and enhance the provision of scientific advice for fisheries management.

4.1. *Conclusions*

Our study sheds light on the trade-offs of using different bait species and leader materials in shallow pelagic longline fisheries. Although the intricacies of interactions in fisheries extend beyond gear characteristics, our work indicates that the use of wire leaders, as opposed to nylon leaders, significantly reduces catch rates of economically valuable tuna species, while elevating retention rates and the odds ratios of at-haulback mortality of sharks. Squid bait, as opposed to fish bait, while enhancing catches of tuna species, also leads to higher catches of marine turtles and causes higher odds ratios of at-haulback mortality for most taxa assessed. Given the findings highlighted above, we believe that the banning of wire leaders in longline fisheries could mitigate bycatch of pelagic shark species, namely of blue shark with a special emphasis on large size specimens, in pelagic longline fisheries. Ultimately, we encourage collaboration between scientists, fishers and policymakers, as we believe that it would enhance compliance and effective implementation of bycatch mitigation measures.

CRediT authorship contribution statement

Rui Coelho: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Daniela Rosa:** Writing – review & editing, Investigation. **Miguel N. Santos:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Catarina C. Santos:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Catarina C Santos reports financial support was provided by Foundation for Science and Technology (FCT). Daniela Rosa reports financial support was provided by Foundation for Science and Technology (FCT). Rui Coelho reports financial support was provided by Foundation for Science and Technology (FCT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

Acknowledgements

This study was funded by Project LL-SHARKs (Ref.: 31–03–05-FEP-

44) supported through Programa Operacional das Pescas (DGRM). C. C. Santos and D. Rosa were supported by FCT Doctoral grants (Ref.: SFRH/BD/139187/2018 and SFRH/BD/136074/2018) funded by National Funds and the European Social Fund. R. Coelho, C.C. Santos and D. Rosa (CCMAR) received partial support from FCT through projects UIDB/04326/2020, UIDP/04326/2020 and LA/P/0101/2020. We also thank scientific fishery observers for collecting the data and the skipper and crew of the participating fishing vessel for their cooperation and commitment during this study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.107093.

References

Adams, D.H., Borucinska, J.D., Maillett, K., Whitburn, K., Sander, T.E., 2015. Mortality due to a retained circle hook in a longfin mako shark *Isurus paucus* (Guitart-Manday). J. Fish. Dis. 38 (7), 621–628. https://doi.org/10.1111/jfd.12277.

Afonso, A.S., Santiago, R., Hazin, H., Hazin, F.H., 2012. Shark bycatch and mortality and hook bite-offs in pelagic longlines: interactions between hook types and leader materials. Fish. Res. 131, 9–14. https://doi.org/10.1016/j.fishres.2012.07.001.

Amorim, S., Santos, M.N., Coelho, R., Fernandez-Carvalho, J., 2015. Effects of 17/0 circle hooks and bait on fish catches in a southern Atlantic swordfish longline fishery. Aquat. Cons. 25 (4), 518–533. https://doi.org/10.1002/aqc.2443.

Anderson, O.R., Small, C.J., Croxall, J.P., Dunn, E.K., Sullivan, B.J., Yates, O., Black, A., 2011. Global seabird bycatch in longline fisheries. Endanger. Species Res. 14 (2), 91–106. https://doi.org/10.3354/esr00347.

Bigelow K., Carvalho F. 2021. Review of Potential Mitigation Measures to Reduce Fishing-related Mortality on Silky and Oceanic Whitetip Sharks (Project 101). WCPFC-SC17-2021/EB-WP-01. Report to the WCPFC Scientific Committee. Seventeenth Regular Session. 11–19 August 2021. Electronic meeting. https://doi.org/10.25923/10gt-as86.

Brill, R.W., Bigelow, K.A., Musyl, M.K., Fritsches, K.A., Warrant, E.J., 2005. Bigeye tuna (Thunnus obesus) behavior and physiology and their relevance to stock assessments and fishery biology. Col. Vol. Sci. Pap. 57 (2), 142–161.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks Prionace glauca assessed using archival satellite pop-up tags. Mar. Ecol. Prog. Ser. 387, 241–253. https://doi.org/10.3354/meps08109.

Carranza, A., Domingo, A., Estrades, A., 2006. Pelagic longlines: a threat to sea turtles in the Equatorial Eastern Atlantic. Biol. Conserv. 131 (1), 52–57. https://doi.org/10.1016/j.biocon.2006.02.003.

Carruthers, E.H., Schneider, D.C., Neilson, J.D., 2009. Estimating the odds of survival and identifying mitigation opportunities for common bycatch in pelagic longline fisheries. Biol. Conserv. 142 (11), 2620–2630. https://doi.org/10.1016/j.biocon.2009.06.010.

Clarke, S., Sato, M., Small, C., Sullivan, B., Inoue, Y., Ochi, D., 2014. Bycatch in longline fisheries for tuna and tuna-like species: a global review of status and mitigation measures. FAO Fish. Aquac. Tech. Pap. 588, 1–199.

Coelho, R., Fernandez-Carvalho, J., Lino, P.G., Santos, M.N., 2012. An overview of the hooking mortality of elasmobranchs caught in a swordfish pelagic longline fishery in the Atlantic Ocean. Aquat. Living Resour. 25 (4), 311–319. https://doi.org/10.1051/alr/2012030.

Coelho, R., Santos, M.N., Amorim, S., 2012. Effects of hook and bait on targeted and bycatch fishes in an equatorial Atlantic pelagic longline fishery. B Mar. Sci. 88 (3), 449–467. https://doi.org/10.5343/bms.2011.1064.

Coelho, R., Santos, M.N., Fernandez-Carvalho, J., Amorim, S., 2015. Effects of hook and bait in a tropical northeast Atlantic pelagic longline fishery: part I—incidental sea turtle bycatch. Fish. Res. 164, 302–311. https://doi.org/10.1016/j.fishres.2014.11.008.

Cooke, S., Suski, C., 2004. Are circular hooks and effective tool for conserving marine and freshwater recreational catch-and-release fisheries? Aquat. Conserv 14, 299–326. https://doi.org/10.1002/aqc.614.

Cortés, E., Arocha, F., Beerkircher, L., Carvalho, F., Domingo, A., Heupel, M., Holtzhausen, H., Santos, M.N., Ribera, M., Simpfendorfer, C., 2010. Ecological risk assessment of pelagic sharks caught in Atlantic pelagic longline fisheries. Aquat. Living Resour. 23 (1), 25–34. https://doi.org/10.1051/alr/2009044.

Domingo, A., Pons, M., Jiménez, S., Miller, P., Barceló, C., Swimmer, Y., 2012. Circle hook performance in the Uruguayan pelagic longline fishery. B. Mar. Sci. 88 (3), 499–511. https://doi.org/10.5343/bms.2011.1069.

Epperly, S.P., Watson, J.W., Foster, D.G., Shah, A.K., 2012. Anatomical hooking location and condition of animals captured with pelagic longlines: the grand banks experiments 2002–2003. B Mar. Sci. 88 (3), 513–527. https://doi.org/10.5343/bms.2011.1083.

Favaro, B., Côte, I.M., 2015. Do by-catch reduction devices in longline fisheries reduce capture of sharks and rays? A global meta-analysis. Fish Fish. 16 (2), 300–309. https://doi.org/10.1111/faf.12055.

Fay, M.P., Shaw, P.A., 2010. Exact and asymptotic weighted logrank tests for interval censored data: the interval R package. J. Stat. Softw. 36, 1–34 (Available from: https://CRAN.R-project.org/package=perm).

Foster, D.G., Epperly, S.P., Shah, A.K., Watson, J.W., 2012. Evaluation of hook and bait type on the catch rates in the western North Atlantic Ocean pelagic longline fishery. B Mar. Sci. 88 (3), 529–545. https://doi.org/10.5343/bms.2011.1081.

Fox, J., Weisberg, S., 2011. An R Companion to Applied Regression, 2nd ed. Sage, Thousand Oaks, CA (Available from: https://CRAN.R-project.org/package=car).

Fritsches, K.A., Brill, R.W., Warrant, E.J., 2005. Warm eyes provide superior vision in swordfishes. Curr. Biol. 15 (1), 55–58. https://doi.org/10.1016/j.cub.2004.12.064.

Fritsches, K.A., Partridge, J.C., Pettigrew, J.D., Marshall, N.J., 2000. Colour vision in billfish. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 355 (1401), 1253–1256. https://doi.org/10.1098/rstb.2000.0678.

Gallagher, A.J., Orbesen, E.S., Hammerschlag, N., Serafy, J.E., 2014. Vulnerability of oceanic sharks as pelagic longline bycatch. Glob. Ecol. Conserv. 1, 50–59. https://doi.org/10.1016/j.gecco.2014.06.003.

Garrison, L.P., 2007. Interactions between marine mammals and pelagic longline fishing gear in the US Atlantic Ocean between 1992 and 2004. Fish. Bull. 105, 408–417.

Gilman, E.L., 2011. Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar. Policy 35 (5), 590–609. https://doi.org/10.1016/j.marpol.2011.01.021.

Gilman, E., Chaloupka, M., Bach, P., Fennell, H., Hall, M., Musyl, M., Piovano, S., Poisson, F., Song, L., 2020. Effect of pelagic longline bait type on species selectivity: a global synthesis of evidence. Rev. Fish. Biol. Fish. 30 (3), 535–551. https://doi.org/10.1007/s11160-020-09612-0.

Gilman, E., Huang, H.W., 2017. Review of effects of pelagic longline hook and bait type on sea turtle catch rate, anatomical hooking position and at-vessel mortality rate. Rev. Fish. Biol. Fish. 27 (1), 43–52. https://doi.org/10.1007/s11160-016-9447-9.

Godin, A.C., Carlson, J.K., Burgener, V., 2012. The effect of circle hooks on shark catchability and at-vessel mortality rates in longlines fisheries. B Mar. Sci. 88 (3), 469–483. https://doi.org/10.5343/bms.2011.1054.

Hall, M.A., 1996. On bycatches. Rev. Fish. Biol. Fish. 6 (3), 319–352. https://doi.org/10.1007/BF00122585.

Hall, M.A., Alverson, D.L., Metuzals, K.I., 2000. By-catch: problems and solutions. Mar. Pollut. Bull. 41 (1-6), 204–219. https://doi.org/10.1016/S0025-326X(00)00111-9.

Hernandez-Garcia, V., 1995. The diet of the swordfish Xiphias gladius Linnaeus, 1758, in the central east Atlantic, with emphasis on the role of cephalopods. Fish. Bull. 93, 403–411.

Hutchinson M., Siders Z., Stahl J., Bigelow K. (2021). Quantitative Estimates of Post-Release Survival Rates of Sharks Captured in Pacific Tuna Longline Fisheries Reveal Handling and Discard Practices That Improve Survivorship. PIFSC Data Rep., DR-21-001. doi: 10.25923/0m3c-2577ICCAT. 2006-2016. ICCAT Manual. International Commission for the Conservation of Atlantic Tuna. In: ICCAT Publications [on-line]. Updated 2016. [Accessed 24 June 2023].

Jiménez, S., Abreu, M., Pons, M., Ortiz, M., Domingo, A., 2010. Assessing the impact of the pelagic longline fishery on albatrosses and petrels in the southwest Atlantic. Aquat. Living Resour. 23 (1), 49–64. https://doi.org/10.1051/alr/2010002.

Kerstetter, D.W., Graves, J.E., 2006. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fish. Res. 80 (2-3), 239–250. https://doi.org/10.1016/j.fishres.2006.03.032.

Kiyota, M., Yokota, K., Nobetsu, T., Minami, , Nakano, H. (2004). Assessment of Mitigation Measures to Reduce Interactions between Sea Turtles and Longline Fishery. Proceedings of the 5th SEASTAR2000 Workshop, pp 24–29.

Lewison, R.L., Crowder, L.B., 2007. Putting longline bycatch of sea turtles into perspective. Conserv. Biol. 21 (1), 79–86. ⟨https://www.jstor.org/stable/4124644⟩.

Lilliefors, H.W., 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J. Am. Stat. Assoc. 62 (318), 399–402. Jun 1.

Manly, B.F.J., 2007. Randomization, bootstrap and Monte Carlo methods in biology, 3rd ed. Chapman & Hall/CRC, New York.

Markaida, U., Hochberg, F.G., 2005. Cephalopods in the diet of swordfish (*Xiphias gladius*) caught off the West Coast of Baja California, Mexico. Pac. Sci. 59 (1), 25–41. https://doi.org/10.1353/psc.2005.0011.

Parga, M.L., 2012. Hooks and sea turtles: a veterinarian's perspective. Bul. Mar. Sci. 88 (3), 731–741. https://doi.org/10.5343/bms.2011.1063.

Parga, M.L., Pons, M., Andraka, S., Rendon, L., Mituhasi, T., Hall, M., Pacheco, L., Segura, A., Osmond, M., Vogel, N., 2015. Hooking locations in sea turtles incidentally captured by artisanal longline fisheries in the Eastern Pacific Ocean. Fis. Res. 164, 231–237. https://doi.org/10.1016/j.fishres.2014.11.012.

Potier, M., Marsac, F., Cherel, Y., Lucas, V., Sabatié, R., Maury, O., Ménard, F., 2007. Forage fauna in the diet of three large pelagic fishes (lancetfish, swordfish and yellowfin tuna) in the western equatorial Indian Ocean. Fis. Res. 83 (1), 60–72. https://doi.org/10.1016/j.fishres.2006.08.020.

Preti, A., Stohs, S.M., DiNardo, G.T., Saavedra, C., MacKenzie, K., Noble, L.R., Jones, C. S., Pierce, G.J., 2023. Feeding ecology of broadbill swordfish (*Xiphias gladius*) in the California current. PloS One 18 (2), e0258011. https://doi.org/10.1371/journal.pone.0258011.

R Core Team, 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (Available from: http://www.R-project.org/).

Read, A.J., 2007. Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. Biol. Conserv 135 (2), 155–169. https://doi.org/10.1016/j.biocon.2006.10.030.

Santos, M.N., Coelho, R., Fernandez-Carvalho, J., Amorim, S., 2012. Effects of hook and bait on sea turtle catches in an equatorial Atlantic pelagic longline fishery. B Mar. Sci. 88 (3), 683–701. https://doi.org/10.5343/bms.2011.1065.

Santos, M.N., Coelho, R., Fernandez-Carvalho, J., Amorim, S., 2013. Effects of 17/0 circle hooks and bait on sea turtles bycatch in a Southern Atlantic swordfish longline fishery. Aquat. Conserv. 23, 732–744. https://doi.org/10.1002/aqc.2324.

Santos, M., Lino, P., Coelho, R., 2017. Effects of leader material on catches of shallow pelagic longline fisheries in the southwest Indian Ocean. Fish. B-NOAA 115, 219–232. https://doi.org/10.7755/FB.115.2.9.

Santos, C.C., Rosa, D., Gonçalves, J.M., Coelho, R., 2023. A review of reported effects of pelagic longline fishing gear configurations on target, bycatch and vulnerable species. Aquat. Conserv. https://doi.org/10.1002/aqc.4027.

Scott, M., Cardona, E., Scidmore-Rossing, K., Royer, M., Stahl, J., Hutchinson, M., 2022. What's the catch? Examining optimal longline fishing gear configurations to minimize negative impacts on non-target species. Mar. Policy 143, 105186. https://doi.org/10.1016/j.marpol.2022.105186.

Serafy, J.E., Kerstetter, D.W., Rice, P.H., 2009. Can circle hook use benefit billfishes? Fish Fish. 10 (2), 132–142. https://doi.org/10.1111/j.1467-2979.2008.00298.x.

Soykan, C.U., Moore, J.E., Zydelis, R., Crowder, L.B., Safina, C., Lewison, R.L., 2008. Why study bycatch? An introduction to the Theme Section on fisheries bycatch. Endanger. Species Res. 5 (2-3)), 91–102. https://doi.org/10.3354/esr00175.

Stokes, L.W., Epperly, S.P., McCarthy, K.J., 2012. Relationship between hook type and hooking location in sea turtles incidentally captured in the United States Atlantic pelagic longline fishery. B. Mar. Sci. 88 (3), 703–718. https://doi.org/10.5343/bms.2011.1074.

Swimmer, Y., Gutierrez, A., Bigelow, K., Barceló, C., Schroeder, B., Keene, K., Shattenkirk, K., et al., 2017. Sea turtle bycatch mitigation in US longline fisheries. Front. Mar. Sci. 4, 260. https://doi.org/10.3389/fmars.2017.00260.

Swimmer, Y., Zollett, E., Gutierrez, A., 2020. Bycatch mitigation of protected and threatened species in tuna purse seine and longline fisheries. Endanger. Species Res. 43, 517–542. https://doi.org/10.3354/esr01069.

Vega, R., Licandeo, R., 2009. The effect of American and Spanish longline systems on target and non-target species in the eastern South Pacific swordfish fishery. Fish. Res. 98 (1-3), 22–32. https://doi.org/10.1016/j.fishres.2009.03.010.

Ward, P., Lawrence, E., Darbyshire, R., Hindmarsh, S., 2008. Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. Fish. Res. 90 (1-3), 100–108. https://doi.org/10.1016/j.fishres.2007.09.034.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can. J. Fish. Aquat. Sci. 981, 965–981. https://doi.org/10.1139/F05-004.

Wickham, H., 2009. ggplot2: elegant graphics for data analysis, 1st ed. Springer, New York. Available from: https://CRAN.R-project.org/package=ggplot2.

Yokota, K., Kiyota, M., Okamura, H., 2009. Effect of bait species and color on sea turtle bycatch and fish catch in a pelagic longline fishery. Fish. Res. 97 (1-2), 53–58. https://doi.org/10.1016/j.fishres.2009.01.003.

Young, J., Lansdell, M., Riddoch, S., Revill, A., 2006. Feeding ecology of broadbill swordfish, *Xiphias gladius*, off eastern Australia in relation to physical and environmental variables. B Mar. Sci. 79 (3), 793–809.