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Short Communication

First assessment of circle hooks as bycatch mitigation measure for deep-water sharks on longline fisheries

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ABSTRACT

The recognition that deep-water sharks are among the most vulnerable marine species to fisheries exploitation led to the implementation of fishing prohibition regulations in European waters. Reducing unwanted bycatch and mortality are key fisheries mitigation measure for the conservation of these species. Yet, few studies have investigated how to mitigate the common bycatch of these sharks on deep-water longline fisheries. Specifically, the potential of hook type as such a measure has never been investigated. Here, we conducted fishing experiments to test how circle hooks affect the catchability, the hooking position, and the overall condition of deep-water sharks, in comparison to the commonly used J-hooks in the Azores bottom longline fishery. We found that circle hooks did not significantly reduce deep hooking (throat or gut hooked), nor improve the overall condition of captured sharks, while the catchability of deep-water sharks on circle hooks was greater than on the J-hooks currently used in the local fishery. As such, circle hooks do not appear as a suitable measure to reduce deep-water shark bycatch and increase survival potential in deep-water longlining. Despite deep hooking being rare for the deep-water sharks caught with both hook types in the experiments, at-vessel mortality was still substantial (around 40%). Post-release survival remains mostly unquantified but preliminary results suggest it could also be high. This study highlights the urgent need for continued research addressing bycatch mitigation measures for deep-water sharks and identifying efficient strategies to reduce bycatch and increase survival.

1. Introduction

Deep-water elasmobranchs, that live mostly below 200 m, are characterized by life-history traits, such as slow growth, late maturity, and low fecundity which exacerbate their vulnerability to fishing even at low mortality levels (Frisk et al., 2001; Garcia et al., 2008). Deep-water sharks are considered to be among the marine species most sensitive to exploitation (Rigby and Simpfendorfer, 2015; Simpfendorfer and Kyne, 2009), but are regularly caught, either directly or indirectly as bycatch in deep-water fisheries worldwide (e.g. Akhilesh et al., 2011; Finucci et al., 2019; Rigby et al., 2016; Rincon et al., 2017). In European waters, despite the fishing prohibitions imposed for several species of deep-water sharks in recent years (EU 2018/2025), deep-water sharks remain a common bycatch (Fauconnet et al., 2019b; Machete et al., 2011; Moura et al., 2018; Ramos et al., 2013). This bycatch raises serious concerns for management and conservation, creating an urgent demand for bycatch mitigation measures for these vulnerable and, in some cases, endangered species.

The fishing mortality of bycatch species may be mitigated by decreasing bycatch rates and increasing survival upon capture (Kerstetter and Graves, 2006). One way to decrease bycatch rates is by improving gear selectivity (O'Neill et al., 2019; Uhlmann et al., 2019). While longlines offer higher selectivity over gillnets or bottom trawls (Connolly and Kelly, 1996), as a passive gear it attracts individuals responding to bait stimulus; i.e., larger-bodied individuals of carnivorous species (Løkkeborg and Bjordal, 1992). As a result, sharks are one of the main bycatch on longlines, including in deep-water (Fauconnet et al., 2019b; Machete et al., 2011), and are often deemed difficult to avoid by fishers (Fauconnet et al., 2019a). Numerous selectivity experiments have been conducted on longline fisheries, testing different devices to reduce bycatch of unwanted species including pelagic (Gilman et al., 2016, 2008) and coastal demersal elasmobranchs (Afonso et al.,

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2011; Favaro and Côté, 2013; Hannan et al., 2013). In comparison, only few preliminary studies have addressed bycatch avoidance of deep-water sharks in longline fisheries. One tested the effect of distance of the gear above seafloor (Coelho et al., 2003), and the other, the use of steel vs nylon leaders (Ramos et al., 2013). Both studies showed inconclusive results. Similarly, few studies have addressed fishing mortality of deep-water sharks, yet an essential information to assess bycatch impacts on these species. Rodríguez-Cabello and Sánchez (2017) found that at-vessel mortality of deep-water sharks was lower compared to other deep-water teleost fish species, due to the lack of swim bladders and less visible signs of barotrauma in sharks, even if strong differences existed between species. However, sharks are still likely to be subject to barotrauma and their post-release mortality could be high, suggesting sub-lethal effects of capture impede their long-term survival (Rodríguez-Cabello and Sánchez, 2017; Talwar et al., 2017). Factors related to the capture process and fishing practice such as gear type, hooking position, tissue lesions, soak time, catch depth, and handling practices are deemed important in influencing fishing mortality on deep-water sharks, as for other shark species (Rodríguez-Cabello and Sánchez, 2017), yet little is known about how such factors affect survival potential. There is, therefore, an urgent need for more insights on bycatch mitigation through both increased selectivity and survival in deep-water longlines.

Circle hooks have been widely tested on pelagic longlines as bycatch mitigation strategies for pelagic sharks and sea turtles, with promising but species-dependent results (Godin et al., 2012; Read, 2007; Reinhardt et al., 2018). The catchability of circle hooks was found to differ among species, with lower catch rates for sea turtles and some species of billfishes, but higher catch rates for tunas, pelagic sharks and other species of billfishes (Reinhardt et al., 2018). The closed gape of circle hooks contributes to shallower and less internal hooking for most species, compared to the widely used J-hooks (Carruthers et al., 2009; Godin et al., 2012; Pacheco et al., 2011), improving the likelihood of survival upon release (Kerstetter and Graves, 2006). Circle hooks may thus offer a promising cost-effective measure to reduce the mortality of elasmobranchs caught on longlines, even though they might not reduce the probability of capture for all species. These hooks have been used in studies of deep-water shark mortality by Rodríguez-Cabello and Sánchez (2017) and Talwar et al. (2017), but these studies did not perform any comparison with alternative hook type. To our knowledge, the effects of circle hooks as a potential bycatch mitigation measure on deep-water shark catchability and mortality has not been tested before this study.

Twenty-five species of deep-water sharks are known to occur in the Azores region, northern Mid-Atlantic Ridge (Das and Afonso, 2017; Fauconnet et al., 2020), of which seven are listed as threatened in the European IUCN Red List assessment (Nieto et al., 2015). In spite of the fishing prohibition in place for several of these sharks (EU 2018/2025), they are still caught incidentally in the local bottom longline fishery (Fauconnet et al., 2019b), the most important local fishery when considering fleet size, number of fishers and landed value (Carvalho et al., 2011). This context provides an opportune setting to test how hook type (circle versus J-hooks) affects the catchability and the survival potential (measured by the hooking position, and the overall condition) of deep-water sharks bycaught in bottom longline fisheries.

2. Materials and methods

Fishing experiments using both circle and J-hooks were conducted onboard a commercial bottom longline fishing vessel in the Azores. Six fishing sets were performed off Faial and Pico Islands, in January and February 2018 (Table 1). A bottom longline, set on the bottom but raised above the seafloor, modified with steel leaders instead of the commonly used nylon leaders, was used for the experiments, as we aimed to 1) reduce the number of lost (bite-off) hooks, and 2) extend the usefulness of this experiment to the drifting longline fishery targeting black scabbardfish, which uses a similar fishing gear with steel leaders and has also high incidental catches of deep-water sharks (Freitas et al., 2018; Machete et al., 2011; Pajuelo et al., 2010; Ramos et al., 2013). We alternated the commercially used J-hooks size 9 with circle hooks of equivalent gape length (size 11), i.e., one J-hook followed by one circle hook, repeatedly along the whole longline and random selection of the type of the first hook of the longline, baited with squid, for a total 977–1201 hooks per set. The gear was deployed at night and hauled by early morning, with an average soak time of 4h46 (Table 1), similarly to the fishing hours commonly practiced in the commercial fishery. Three sets were done north of Faial Island, and three south of Pico Island over bottom depths ranging from 880 m to 1370 m, deeper than the depths most fished by the commercial fishery (200–700 m in average, but that can occasionally reach up to 1500 m depth) but selected to maximise the number of deep-water sharks caught in the experiments.

During the fishing experiments, we collected data on the condition of each hook at hauling (classified as: with or without bait, lost hook, or hook with catch). The number of lost hooks was used as a proxy for the number of bite-offs, i.e., leaders cut by the hooked individuals. The "escaped" individuals, i.e., those that released from the hooks just before being brought back onboard, were counted as part of the catch, even if it was not always possible to recapture them. We further collected data on each captured individual, including species, hooking position, vitality, lesions, and handling by the crew. Hooking position was classified as: mouth, oesophagus (gutted), body and eye. Vitality was classified as: 0 = dead, without reflexes; 1 = moribund, only opercular movements, spasms, etc. but unable to swim; 2 = stunned, with fin movements but disoriented and difficulty sinking; 3 = vigorous, swimming strongly in direction of the bottom. All deep-water sharks caught were measured and sexed. DNA samples were taken whenever species identification was uncertain.

Table 1
Characteristics of the fishing experiments using both circle and J-hooks onboard a commercial bottom longline fishing vessel in the Azores. Total number of hooks deployed in each fishing set, with circle and J-hooks in similar numbers alternated along the longline. Total catch in number of individuals from all fish species caught in each fishing set, including the number (no.) of individuals of deep-water sharks in parenthesis.

Date	Fishing area	Total number of hooks deployed	Deployment (start – end times)	Retrieval (start – end times)	Depth range (m)	Total catch (incl. no. of sharks)
30/01/2018	North Faial - Ponta dos Cedros	1007	04:30 – 05:00	09:24 – 14:41	[1085 – 1120]	74 (11)
02/02/2018	North Faial - Ponta dos Cedros	1201	04:10–04:45	09:28 – 17:20	[1170 – 1260]	179 (68)
04/02/2018	North Faial - Ponta dos Cedros	1025	03:30–04:00	08:45 – 13:33	[1287 – 1332]	150 (25)
05/02/2018	South Pico - Off São Mateus	977	03:40–04:10	08:40 – 13:08	[882 – 990]	133 (30)
07/02/2018	South Pico - Off São Mateus	1000	03:25–04:00	08:30 – 12:31	[1139 – 1183]	157 (47)
08/02/2018	South Pico – Off São João	998	03:14–03:43	09:30 – 14:08	[1186 – 1368]	154 (86)

The catchability of deep-water sharks by hook type was evaluated by comparing the Catch per Unit Effort (CPUE, defined as number of individuals per 1000 hooks) per fishing set and hook type. The difference in CPUE per hook type was tested using a paired Student's t-test after testing for normality with a Shapiro-Wilk test. The hooking position was tested by the proportion of deep (gut) vs. mouth hooked individuals for each hook type, and differences tested using a Pearson's Chi-squared test with Yates' continuity correction to account for small sample size. The overall condition of deep-water sharks was evaluated by the proportion of individuals in each vitality state and the difference between circle and J-hooks was tested using Pearson's Chi-squared test. All analyses were performed using R (R Core Team, 2020).

Results from these fishing experiments were additionally compared with results from a dedicated onboard observer programme that collected detailed data on catch vitality and handling (n = 21 longline sets), additionally to the regular data on fishing operation and catch composition (n = 138 longline sets) (Machete et al., 2020). The commercial fishery used set bottom longlines (with different settings from all hooks on the bottom to hooks raised above the seafloor) and mostly used J-hooks size 9, as in our experiments, but could also use larger hooks (from size 5–8), or combinations of several hook sizes. As hook size and fishing depths can influence catchability, the CPUEs of deep-water sharks from observer data were calculated for the sets exclusively using hook size 9 and at fished depths equal or greater than 800 m (n = 11 longline sets). The CPUE of J-hooks from observer data and from the fishing experiments conformed the assumption of normality. The difference between both data sets was tested with a Welch t-test, suitable to test difference between two samples of different sizes and variances (West, 2021). The proportion of deep-hooking and the proportion of individuals in each vitality state for the J-hooks used in the commercial fisheries were also calculated from observer data. The differences in both proportions with the J-hooks used in the fishing experiments were tested using Pearson's Chi-squared tests. All analyses were performed using R (R Core Team, 2020).

3. Results and discussion

In total, 263 sharks from 10 different deep-water species were caught during the fishing experiments, with almost double the sharks caught on circle- (n = 174) than J-hooks (n = 89). The catch was dominated by birdbeak dogfish *Deania calcea* (93 individuals, 35.4%), Portuguese dogfish *Centroscymnus coelolepis* (62 individuals, 23.6%) and longnose velvet dogfish *C. crepidater* (34 individuals, 12.9%). Leafscale gulper shark *Centrophorus squamosus*, roughskin dogfish *C. owstonii*, arrowhead dogfish *D. profundorum* and four other species were caught in lower numbers (Fig. 1). Species-wise, a higher number of individuals of *C. owstonii*, *C. squamosus*, *C. coelolepis,* and *C. crepidater* were caught on circle hooks than on J-hooks, while the opposite was observed for the lanternsharks *Etmopterus spp.* (1 out of 6, 16.7%, caught on circle hooks) and *D. profundorum* (5 out of 12, 41.7%, Fig. 1). A total of 575 teleosts from 6 different species were also caught during the fishing experiments; mainly black scabbardfish *Aphanopus* spp. (56.5%) and common mora *Mora moro* (39.2%), with catches evenly distributed among hook type (Fig. 1). The number of hooks remaining with bait was high but tended to be lower with circle hooks (81.2%) compared to J-hooks (85.3%), while the number of hooks without bait was slightly higher (3.1% vs 2.1% for circle and J-hooks respectively). The number of lost hooks/bite-offs was low with 4–21 hooks lost per fishing set, i.e., 0.82% of the hooks deployed on average per fishing set, in similar numbers between circle and J-hooks.

CPUEs were highly variable among species and fishing sets, but overall deep-water sharks were caught in significantly higher numbers

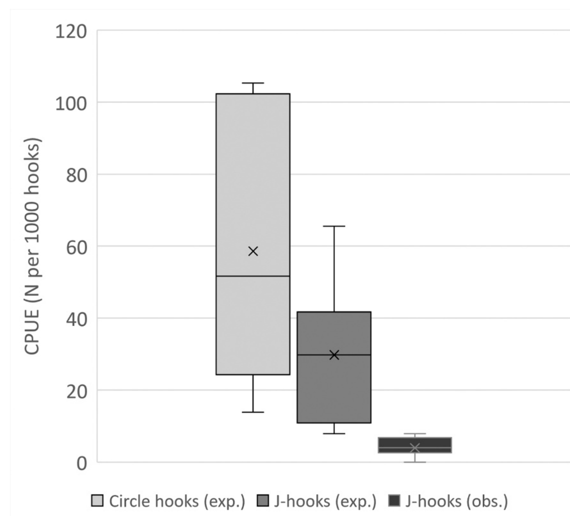

Fig. 2. Effect of hook type from different data sources on deep-water shark catch (exp. = fishing experiments; obs. = onboard observer data). Boxplots display the distribution of the data from the minimum to the maximum values (whiskers), the first quartile (lower line), median value (middle line), third quartile (upper line) and mean value (cross).

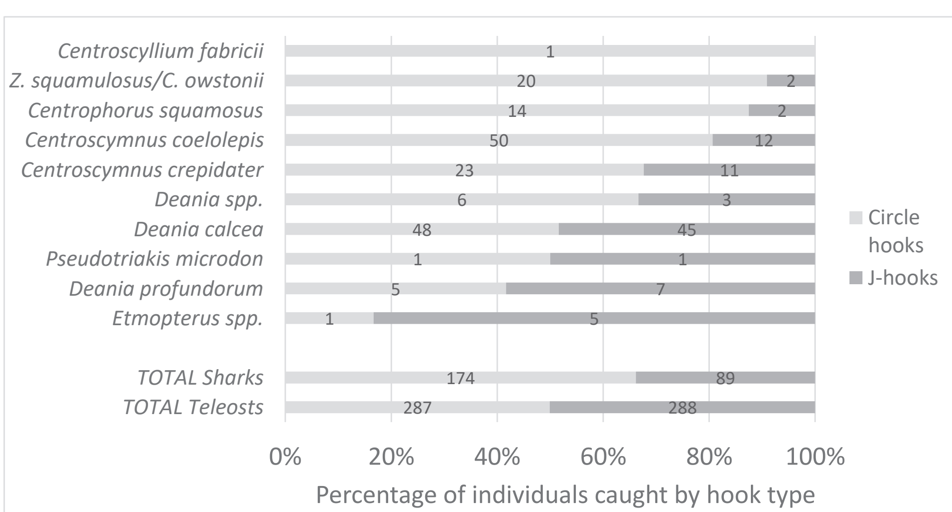

Fig. 1. Percentage of individuals of each species caught by hook type in the fishing experiments. Labels display the number of individuals caught by each hook type. Species are sorted by decreasing percentage caught on circle hooks.

with circle than with J-hooks ($t(5) = 2.745$, $p = 0.041$; Fig. 2). Interestingly, CPUEs from J-hooks with steel leaders used in the fishing experiments were significantly higher than from J-hooks with nylon leaders used in the commercial fishery at similar fished depths ($t(5.09) = -3.074$, $p = 0.027$; Fig. 2). The low number of bite-offs found with steel leaders in the fishing experiments suggest that steel leaders are effective in reducing the number of bite-offs, what may explain the higher catch rates of deep-water sharks found in the fishing experiments (steel leaders) when compared to observer data (nylon leaders). These results suggest that not only hook type but also the leader material may have a significant effect on the catchability of deep-water sharks, even if additional experiments are needed to test this hypothesis. Other factors such as the fishing area or season could also explain the difference in catch rates between the fishing experiments and observer data and should be further investigated. Deep hooking was rare in the fishing experiments for both hook type (8.0% on J-hooks, 6.7% on circle hooks), slightly higher but not significantly different to that recorded in the fisheries observer data (4.2% on average per set; $\chi^2(1, N = 27) = 3.220$, $p = 0.073$; Fig. 3). Overall, hooking position was not found to be significantly different between hook type in the fishing experiments ($\chi^2(1, N = 6) = 0.012$, $p = 0.913$). The vitality of individuals caught on circle hooks was slightly better than on J-hooks, with 60.6% vs. 56.8% recorded as 'vigorous' or 'stunned', and 39.4% vs. 43.2% as 'dead' or 'moribund', respectively (Fig. 4). Yet, these differences were not statistically significant ($\chi^2(1, N = 6) = 1.635$, $p = 0.201$). The proportion of 'vigorous' or 'stunned' individuals and of 'dead' or 'moribund' on J-hooks were not significantly different between the fishing experiments and onboard professional fishing vessels ($\chi^2(1, N = 27) = 0.001$, $p = 1$; Fig. 4).

The data from the experiments presented here allowed us to compare, for the first time, catchability, hooking position and overall condition of hooked deep-water sharks on circle and J-hooks, and therefore, evaluate the efficiency of circle hooks in reducing unwanted catch and increasing survival. Contrary to what was found for pelagic sharks (Carruthers et al., 2009; Pacheco et al., 2011; Reinhardt et al., 2018), the vitality of deep-water sharks did not significantly differ between circle and J-hooks, nor did the proportion of deep hooking, which was expected to be lower with circle hooks. The morphology and small size of deep-water shark mouths along with their scavenger/-opportunistic feeding behaviour and the quality of the suction-feeding, with some species such as the kitefin shark known to take bites out of larger prey (Dunn et al., 2010; Klimpfinger and Kriwet, 2020), may explain the low proportion of deep hooking on both hook types found in this study. Even though deep hooking was rare, at-vessel mortality was still substantial (around 40%) with both hook types. The at-vessel

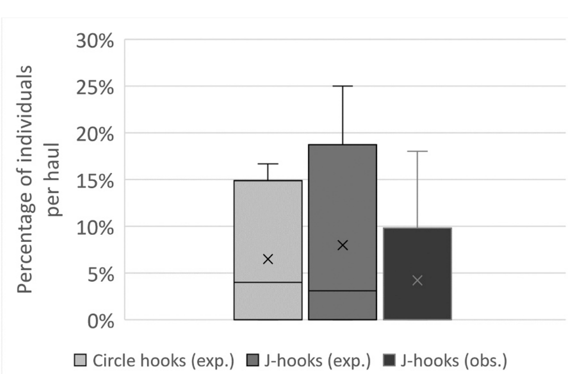

Fig. 3. Effect of hook type on the percentage of individuals per haul caught with deep (gut) hooking (exp. = fishing experiments; obs. = onboard observer data). Boxplots display the distribution of the data from the minimum to the maximum values (whiskers), the first quartile (lower line), median value (middle line), third quartile (upper line) and mean value (cross).

mortality was slightly higher yet comparable to the longline surveys using circle hooks in the Cantabrian Sea (NE Atlantic), for individuals captured dead and in poor condition (33.1% of catch; Rodríguez-Cabello and Sánchez, 2017), and those obtained for gulper sharks (*Centrophorus* sp.) caught with circle hooks in the Bahamas (30.8% of catch; Talwar et al., 2017).

From the experimental data presented in this study it stands out that besides not significantly reducing deep-hooking nor improving overall condition/vitality, circle hooks produced higher catches of deep-water sharks than J-hooks. Significantly higher catch rates on circle hooks are consistent with results for pelagic and coastal sharks (Afonso et al., 2011; Favaro and Côté, 2013; Reinhardt et al., 2018), and can result from either 1) a higher probability of a shark being hooked after biting the bait, or 2) a lower probability of escaping the hook after being caught (Afonso et al., 2011). For pelagic sharks, it has been hypothesized that the lower catch rates on J-hooks (with nylon leaders), compared to circle hooks, likely results from a higher number of bite-offs, since deep hooking is more common on J-hooks (Afonso et al., 2012). This cannot be the case here since our results show low proportion of deep-hooking and low number of bite-offs probably due to the use of steel leaders. In addition, of 174 sharks caught on circle hooks in our fishing experiments, 16 individuals (9.2%) escaped the hook while being hauled onboard, while only 5 escaped of 89 sharks caught on J-hooks (5.6%). No difference in species, size or weight of the individuals, or location of the hook, could be identified among the escaped individuals. This suggests that deep-water sharks may have a higher probability of escaping circle hooks. As such, the higher catchability of deep-water sharks with circle hooks likely results from a higher probability of the sharks being hooked after biting the bait. Circle hooks tend to slip over soft tissue and pivot as the eye of the hook exits the mouth, explaining why hooking predominantly occurs in the jaw (Kerstetter and Graves, 2006). The morphology of the mouths and feeding behaviour of deep-water sharks may promote greater effectivity of this hooking process.

We should acknowledge that our study comes with some caveats. Our sample size in terms of number of experimental fishing sets was kept relatively low, above all else to keep the mortality of deep-water sharks as low as possible, given the threatened status of many of these species (Nieto et al., 2015). Although the number of sets may seem small to support definitive conclusions, we are confident that the overall number of hooks deployed (over 6000 hooks) and the number of sharks caught (over 250 individual sharks) is sufficient to draw preliminary conclusions. The fact that we obtained similar results in the experiments as the onboard observer programme covering a much larger sample size further strengthens the confidence in our results. Overall, these results corroborate the similarity between the fishing gear used in this experiment and that used in the local bottom longline fishery (Menezes, 2003). Hence, the results from these experiments permit to draw relevant conclusions, applicable to the commercial fishery. The experiments were carried out at local scale in the Azores, but their application is broader and relevant to conservation and management of deep longlining globally. The results presented here can also benefit deep-water longline fisheries with similar characteristics and operating modes that exist in mainland Portugal (Coelho and Erzini, 2008; Figueiredo et al., 2005; Ramos et al., 2013) and other parts of the world (Durán Muñoz et al., 2011; Gordon et al., 2003; Rodríguez-Cabello and Sánchez, 2017).

In summary, our results indicate that circle hooks do not appear to be a suitable measure to mitigate deep-water shark bycatch in the deep-water longlines such as those used by Azorean and other European fleets. This reinforces the need to study and identify other effective bycatch mitigation measures (Fauconnet et al., 2022). Further measures to avoid deep-water shark bycatch, including shark repellents and evaluating how fishing tactics can contribute to bycatch avoidance should be studied. Das et al. (2022) recently proposed that the use of depth-based, area-based, and gear-based management strategies may help reduce deep-water elasmobranch bycatch. However, this approach would require a robust science-based management strategy and

Fig. 4. Effect of hook type on deep-water shark vitality for all species combined (exp. = fishing experiments; obs. = onboard observer data).

significant changes in the fishing methods, towards traditional handlines which catch less deep-water sharks than bottom longlines. The significantly lower catch rates found in the observer data with nylon leaders compared with the fishing experiments that used steel leaders further suggest that the use of nylon leaders in the commercial fisheries may be suitable to limit deep-water shark bycatch. However, sharks that avoid capture via bite-offs, especially those that are deep-hooked, may still experience high levels of mortality that remain unknown and unaccounted for (Afonso et al., 2012; Keller et al., 2020). Further testing on catchability and mortality from different leader material is needed. For the sharks that are not possible to avoid, practices should be optimized to increase potential survival. The substantial levels of at-vessel mortality found in this study raise serious concerns, and call for improved capture techniques, onboard handling and release practices to increase survival of released individuals (Fauconnet et al., 2020; Poisson et al., 2014, 2012). Post-release survival remains mostly unquantified, as is the impact of physiological stress and internal wounding (Barkley et al., 2016; Benoît et al., 2010). Preliminary results and results from other studies suggest post-release survival could be low (Rodríguez-Cabello and Sánchez, 2017; Talwar et al., 2017). As such, even if further research on ways to reduce at-vessel mortality and potentially increase post-release survival of deep-water sharks continues to be necessary, finding effective measures to avoid their bycatch is likely to bring more benefit for the conservation of deep-water sharks.

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CRediT authorship contribution statement

PA, TM, JF and LF: Conceptualization, Methodology, Validation. **PA and TM:** Funding acquisition, Resources, Supervision. **LF and DD:** Data curation. **LF:** Formal analysis, Visualization, Writing – original draft. **All:** Investigation, Writing – review & editing. **TM:** Project administration.

Declaration of Competing Interest

The authors 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

Data will be made available on request.

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