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When opportunistic predators interact with swordfish harpoon fishing activities: shark depredation over catches in the Strait of Messina (central Mediterranean Sea)

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Abstract
We describe the interaction between harpoon fishing activity and sharks, which opportunistically depredated harpoon catches in the Strait of Messina. Shark bite marks were observed on harpooned swordfish during the period 2014–2020, with different damages to the catches. Most of the depredation events have focused on large swordfish, generally weighing more than 60 kg. Data on direct observations were implemented by interviews and questionnaires to fishermen aimed to recover the information on their local fishing and ecological knowledge. Fishermen provided additional data on shark-harpoon fishing interactions also supplying information on by-catch species (i.e., bluefin tuna). Therefore, these results suggest that sharks migrating through the Strait of Messina are occasionally attracted by injured prey, due to their ability to detect chemical cues, fish distress stimuli and body fluids (i.e. blood) in the water. In addition, our investigations showed an increase in shark attacks on harpooned fish over time, likely due to an increase in harpoon swordfish catches. This may be related to the effects of the driftnets' ban enforced by European Regulations in the last decades.

Keywords: *Elasmobranchs,* Xiphias gladius*, depredation, opportunistic behaviour, harpoon fishery, Mediterranean Sea*

Introduction

Top predator sharks occupy the highest trophic levels in the marine food web and play an important ecological and biological role in our oceans (Camhi et al. 2009), carrying out a top-down control on prey species from lower trophic levels (Carrier et al. 2012; Britten et al. 2014). Generally, opportunistic sharks feed on other sharks, turtles, tunas, swordfish and marine mammals (Ebert 1994; Vaske Júnior et al. 2009; Papastamatiou et al. 2010; Smith et al. 2018; Sprogis et al. 2018). Moreover, they have the ability to predict potential food pulse direction (Sims et al. 2006) and switch foraging techniques as response to a temporary increase in prey abundance (Weideli et al. 2015; Robbins & Renaud 2016), also using both active hunting and facultative scavenging (Long & Jones 1996; Roff et al. 2016). Their opportunistic predatory behaviour is enhanced by the capability to follow chemical cues, prey distress stimuli and body fluids (i.e. blood) in the water (Hobson 1963; Tester 1963). As known, animals in distress or in danger usually release chemicals and alarm clues into the water, attracting predators (Tester 1963).

This opportunistic behaviour often results in an interaction between sharks and fishing activities, when these predators are attracted by captured fish or baits (Gilman et al. 2007, 2008; MacNeil et al. 2009; Papastamatiou et al. 2010; Raby et al. 2014; Kumar

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et al. 2016; Mitchell et al. 2018, 2019; Ryan et al. 2019; Tixier et al. 2021). Indeed, sharks have been observed approaching the fishing catch at sea, using different behaviours: nudging, mouthing, visually selecting their prey or using olfactory sense (O'Shea et al. 2015; Mitchell et al. 2019). Shark depredation affects commercial and recreational fisheries worldwide and this interaction has been recorded for several fishing gears, mainly longlines and hook-and-lines (Gilman et al. 2007, 2008; MacNeil et al. 2009; Raby et al. 2014; Kumar et al. 2016; Mitchell et al. 2018, 2019; Ryan et al. 2019; Tixier et al. 2021). Recently, Tixier et al. (2021) analysed the global patterns of the depredation conflicts between several large marine predators and fisheries across the world, underlining the importance of shark interactions with longlines. On one hand, this interaction causes economical losses to fisheries (such as fishing gear and catches' damages, catches' reduction, financial losses, time, etc.) as well as increase the risks of injury for the opportunistic sharks, which may be hooked, caught or receive a fisherman' reaction (e.g., lethal responses from fishers) (Stevens et al. 2000; Lewison et al. 2004; Gilman et al. 2007; Bradai et al. 2018; Tixier et al. 2021). This is a major concern when vulnerable or threatened sharks are involved.

Although the interaction between sharks and longlines has been often reported, currently there is still a lack of information on the depredation by sharks on other Mediterranean fishing activities. Thus, the main aim of this paper is to analyse, for the first time, data on some interactions recorded between sharks and harpoon fishing activities targeting Mediterranean swordfish. This information, collected by direct observations, photos, interviews and questionnaires on the local fishing and ecological knowledge, details some shark attacks to fishing catches in the Strait of Messina (central Mediterranean Sea).

Study area

The Strait of Messina is a narrow sea channel which connects the Ionian and Tyrrhenian Sea and is considered one of the most important biodiversity hotspots in the Mediterranean Sea (Battaglia et al. 2017). This area has a strategic importance in movements of large pelagic species such as swordfish, bluefin tuna, cetaceans, sharks and rays (Fergusson et al. 2000; Romeo et al. 2003, 2015; Canese et al. 2011; Battaglia et al. 2018, 2020). The peculiar hydrodynamic regime, characterized by tidal and upwelling currents (Vercelli 1925; Mosetti 1991), makes possible the presence of important food resources in the area, which usually attract several large predators (Romeo et al. 2012; Battaglia et al. 2013, 2017, 2020). Furthermore, both bluefin tuna and swordfish converge in this area when the reproductive period approaches, to reach nearby spawning grounds in the southern Tyrrhenian Sea and use the Strait's environment and food resources to restore their energies (Romeo et al. 2011, 2015; Battaglia et al. 2013, 2018; Perzia et al. 2016). In the Strait of Messina, a very ancient harpoon fishing activity targeting swordfish is usually carried out (Romeo et al. 2015; Battaglia et al. 2018), as a result of the abundance of swordfish from late spring to summer. The harpoon fishing activity is carried out using a peculiar vessel ("feluca"), equipped with a very high mast, where about 3–4 fishermen spend their day observing the sea surface, in order to individuate the presence of swordfish. Harpoon vessels have also a long plank where a fisherman throws the harpoon against the sighted animal (see details in Battaglia et al. 2018). To date, overall 10 vessels belong to the Sicilian swordfish harpoon fleet. This fishing activity also offers to researchers the possibility of observing and monitoring the behaviour of large pelagic animals at surface (Romeo et al. 2003, 2009, 2011).

Material and methods

Data collection has been carried out in the fishing ground of swordfish harpoon fishery, the Strait of Messina and surrounding areas (Figure 1), between April and September of each year, on a daily basis by scientific observers, from 2014 to 2019, also including April - June 2020.

Data collection from interviews and questionnaires

Information was collected at landing places, by interviewing fishermen which usually operate on harpoon vessels. When a shark attack on a harpooned swordfish had been recorded, the following data were collected: location, swordfish weight, photo of the damage on fishing catch, description of the attack. Additionally, fishermen were also asked if any shark or other large marine animals had been sighted in the days leading up to the attack.

The bite marks were examined in order to distinguish if the attack was performed by a shark or another marine predator. The comparison was made by the consultation of the dental morphology of bites described by Long and Jones (1996), Secchi and Vaske (1998), Shimada (2002), Lowry *et al.*, (2009) and Marshall and Goldbogen (2015).

Furthermore, in order to collect historical data on these events, a questionnaire was provided to 20

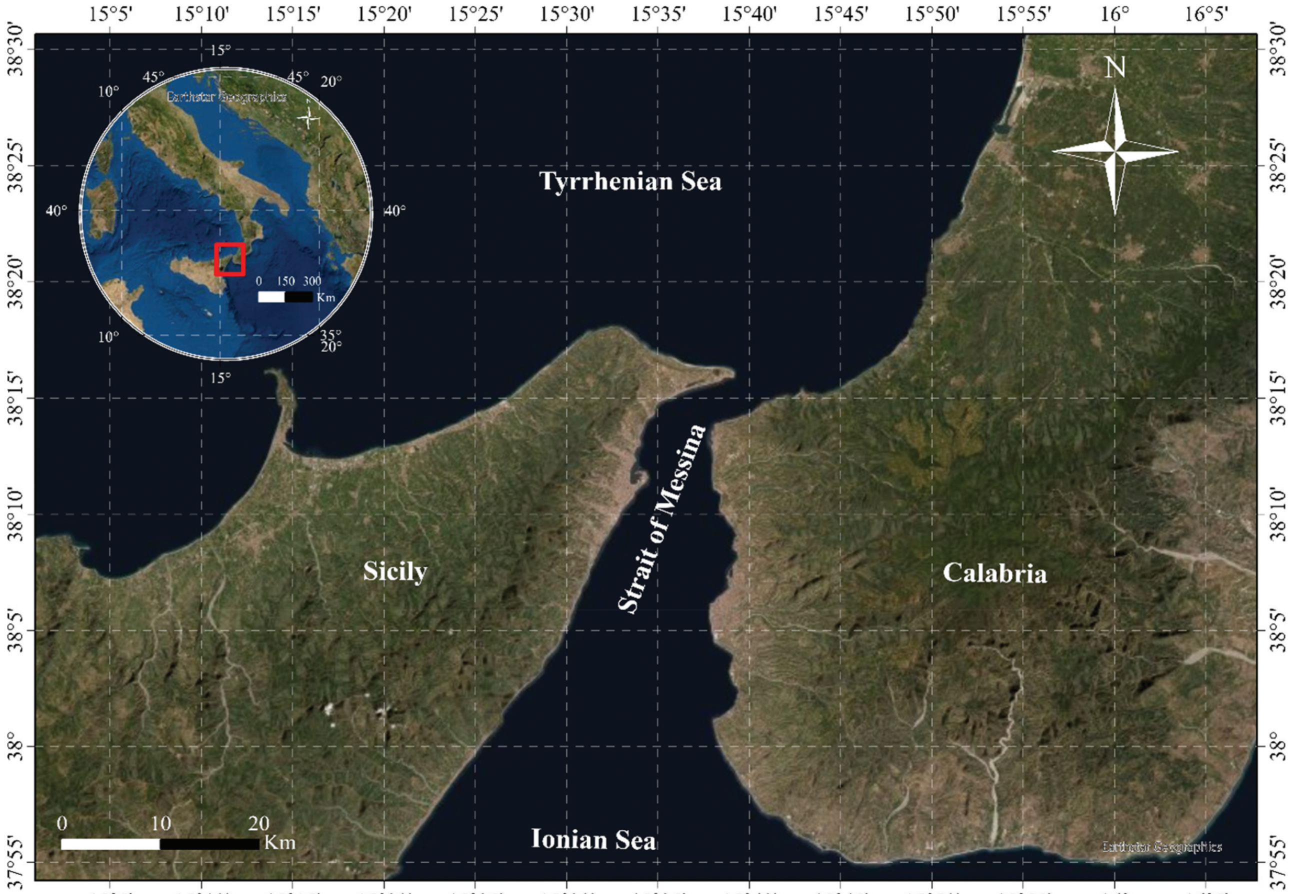

Figure 1. Geographic location of the study area (central Mediterranean Sea).

professional fishermen working on-board of the 10 Sicilian harpoon vessels. Based on their fishing experience, fishermen were grouped into three different categories: group 1 (over 40 years of fishing experience), group 2 (between 20 and 40 years), group 3 (<20 years). The questionnaire was aimed to ask information on fishermen's local fishing and ecological knowledge in order to understand if they have ever seen a shark attack on a harpooned fish, if they thought that shark attacks had increased or decreased in the last few years, if they were able to identify the species and describe the type of damage on the catch. The full list of questions is reported in Appendix 1 (supplementary material).

Catch per unit effort (CPUE)

In order to understand if the number of attacks reported in the monitored period (2014–2020) is linked to an increment of fishing effort (number of days at sea, i.e. fishing days) or to an increase of swordfish catches over the years, the catches per unit effort, CPUEs (number of swordfish * fishing days^{-1}), from logbook data of one harpoon vessel were calculated. These data were daily collected, according to Romeo et al. (2015), Perzia et al. (2016) and Battaglia et al. (2018).

Results

Overall, seven cases of shark attacks to harpooned swordfish have been directly documented between 2014 and 2020, as reported in Table I and shown in Figure 2.

The analysis of the bite marks on catches was attributed to sharks on the basis of their appearance: Figure 2(a–e) shows bite marks with clear-cut edges, Figure 2 (f) reports the image of a wide and circular bite (Figure 2(f)), while Figure 2(b) shows scars.

Shark attacks documented in Figure 2 were mainly focused on swordfish larger than 60–80 kg, but the predator has never directly observed by the fishermen

Table I. Summary of recent shark attacks to harpooned swordfish in the Strait of Messina (period: 2014–2020). The description of the attack and the type of damage are reported.

Record	Year	Swordfish weight * (kg)	Shark sighting	Description
1	July 2014	70	No shark was observed at the surface. Shortfin mako shark was observed a previous week the attack	The swordfish, after being harpooned, dove at about 20 m. After 10 min, it suddenly reduced its resistance and was easily pulled up on board by the fishermen. A double large bite mark on the swordfish abdomen was observed (Figure 2 (a))
2	August 2015	80 kg	No shark was observed at the surface. Shortfin mako shark was observed a few day before the attack	The swordfish, after being harpooned, dove at about 40 m. After 30 min, it suddenly reduced its resistance and was easily pulled up on board by the fishermen. A clear cut around the abdomen part of the body was observed.
3	July 2017	65 kg	No shark was observed at the surface. No record of shark observed days before the attack	The swordfish, after being harpooned, dove at about 20/30 m. After 15/20 min, it suddenly reduced its resistance and was easily pulled up on board by the fishermen. Marks are similar to a fast and caution bite probably due to the movement of the swordfish and the vicinity to the sword (Figure 2(c)).
4	August 2019	75 kg	No shark was observed at the surface. No record of shark observed days before the attack	The swordfish, after being harpooned, remained at depth for about 10 min (no details on the approximate depth) it suddenly reduced its resistance and was easily pulled up on board by the fishermen. A clear cut-bite on the swordfish abdomen was observed (Figure 2(d)).
5	August 2019	60 kg	No shark was observed at the surface. Blue shark was observed a few days before the attack	The swordfish, after being harpooned, dove at about 20 m. After 15 min, it suddenly reduced its resistance and was easily pulled up on board by the fishermen. A teeth marks but not complete bite was observed (Figure 2(b)).
6	May 2020	75 kg	No shark was observed at the surface. Blue shark was observed a few days before the attack	No details on the time and deep dive of the swordfish were provided. Bite shows a clear cut edge on the swordfish dorsal area (Figure 2(e))
7	June 2020	35 kg	Shark was observed at the surface. However, fishermen did not recognise the species. They believe was not a blue shark, which was observed 3 days earlier. In addition, a species of shark resembling the thresher shark was reported in the same period.	The swordfish, after being harpooned, dove at about 10/15 m. After 10 min, it suddenly reduced its resistance and was easily pulled up on board by the fishermen. The entire caudal part (just before the anal fin) of the swordfish was removed by a bite (Figure 2(f)).

*Swordfish weight refers to the fish without the missing part removed by the bite.

during the attacks. Indeed, after being harpooned, the swordfish usually moves from surface to deeper waters (about 40–60 m), taking a variable time (between 10 and 30 min, depending on fish size) in an attempt to escape, before getting tired or dying. In general, a large bite mark was observed on the swordfish body (Figure 2), although multiple bite marks were evident in one case (Figure 2(a)).

The questionnaires were filled in by fishermen with different levels of experience, ranging from 13 to 70 years of fishing activities (Figure 3(a)). Overall, 70% of fishermen witnessed an attack on a harpooned fish, while 30% of them never observed this event (Figure 3(b)). Most of the attacks occurred in the Strait of Messina, but some fishermen also reported cases for the Tyrrhenian and Ionian Sea, in equal amount (Figure 3(c)). The less experienced fishers (group 3) claimed that the attacks remained unchanged over time, while the fishermen from groups 1 and 2 reported that the number of shark attacks on catches has increased over the last 5 years (Figure 3(d)). Historical information gathered from questionnaires revealed that the highest number of attacks on harpooned catches (Figure 3(e)) involved fish weighing between 60 and 80 kg (50% of cases) and between 80 and 100 kg (30%). Less than 15% of cases involved fish of 40–60 kg and 100–120 kg, while there is no information on fish weighing more than 120 kg and less than

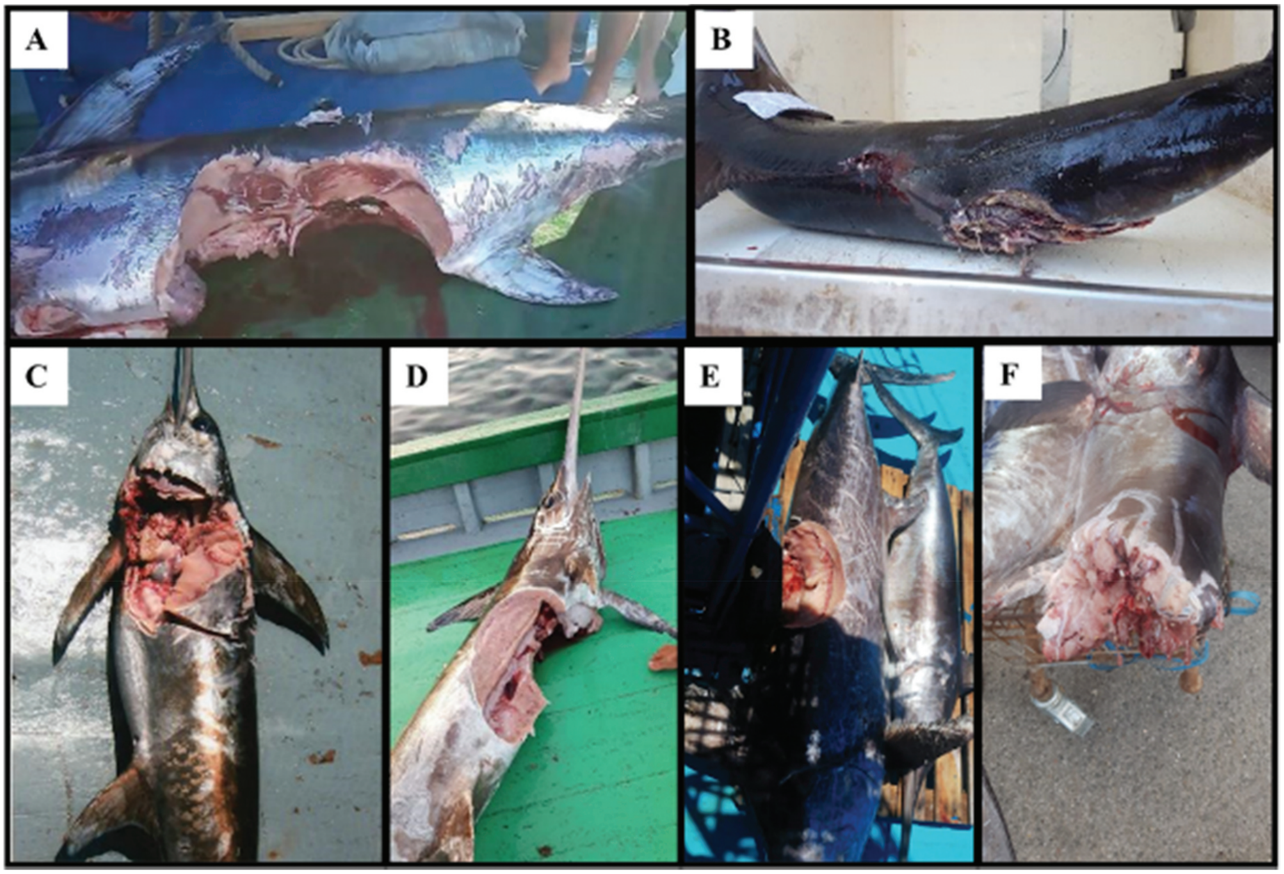

Figure 2. Photos of shark bite marks over harpooned swordfish. A = individual caught in July 2014, weighting approximately 70 kg. B = individual caught in August 2019, weighting about 60 kg. C = individual caught in July 2017, weighting 65 kg. D = individual caught in August 2019, weighting 75 kg. E = individual caught in May 2020, weighting 75 kg. F = individual caught in June 2020, weighting 35 kg. Weight data refer to the fish without the missing part.

40 kg. Furthermore, as shown in Figure 3(f), the shark attacks occurred in 82% of the cases over harpooned swordfish (14 individuals) and in only 18% of cases over harpooned bluefin tuna (three individuals); there was no information on other bycatch species (except tuna).

Analysing the information obtained from both direct observations and questionnaires were evident that the attacks focused on the central part of the swordfish's body (ventral area in 52% of cases, dorsal area in 35% of cases and caudal areas in 13% of cases) (Figure 4(a)).

According to the personal point of view of fishermen, the possible cause of the increase in shark attacks on harpooned fish could be related to an effect (positive) of the reduction of illegal fishing activities (e.g. driftnets fishing) (50%) or to climate change (30%) (Figure 4(b)). Moreover, in the last 3 years (2018–2020) was evident a raise in swordfish CPUE values of harpoon fishing, even though the fishing days remained almost constant (range: 53–64 days at sea) (Figure 5). Fishermen reported also that in the last 5 years there was an increase in large pelagic fauna sightings (i.e. shark, turtles, mammals, etc.) as well as juvenile sharks (especially blue sharks) (Table II). Finally, in some cases, fishermen have also reported that they had observed the presence of different shark species such as blue shark (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*), and great white shark (*Carcharodon carcharias*) a few days before the attacks (Table II) but they never saw those sharks attacking the harpooned fish as mentioned at the beginning of this section.

Discussion

The present study describes some cases of interactions between Sicilian harpoon fishing and sharks in

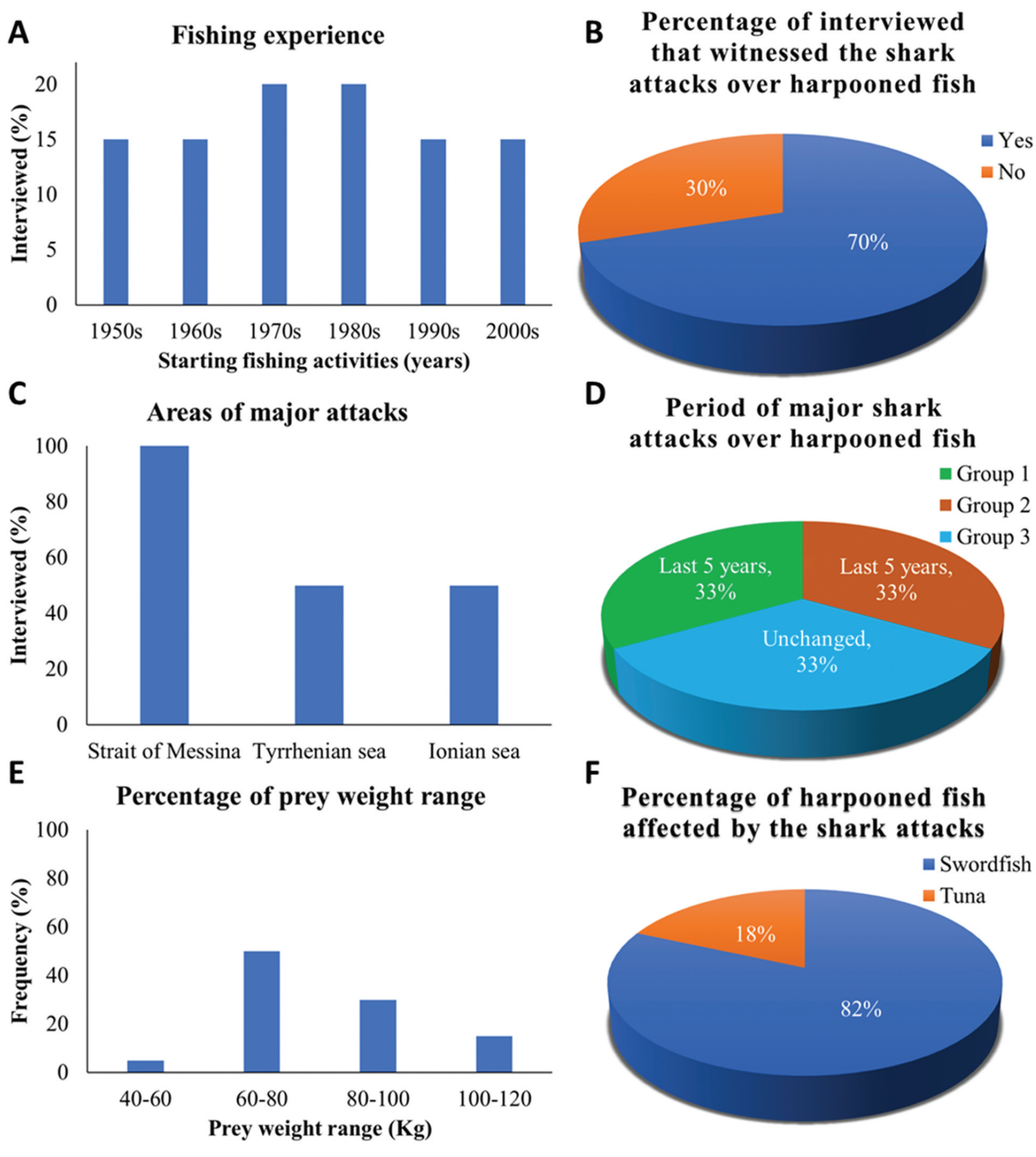

Figure 3. Results of the questionnaire provided to harpoon fishermen (n = 20). Period of starting the harpoon fishing activity (a); Percentage of fishermen witnessed in person to an attack over harpooned fish (b); Area where the attacks were observed (c); Period of major shark attack over harpooned fish (d); percentage of main prey weight (e) and prey species attacked (f).

the Strait of Messina, which opportunistically preyed on harpooned fish.

The analysis of the bite marks' features on catches (Figure 2) allowed to understand that the animals responsible for the attacks were sharks. Indeed, only few Mediterranean predators are able to cause such large damages on catches. Among cetaceans, potential large predators such as *Orcinus orca* and *Pseudorca crassidens* have rarely been observed in the Mediterranean (Di Natale & Mangano 1983; Reeves & Notarbartolo Di Sciara 2006; Mo 2010) and they leave shabby borders on the prey, often

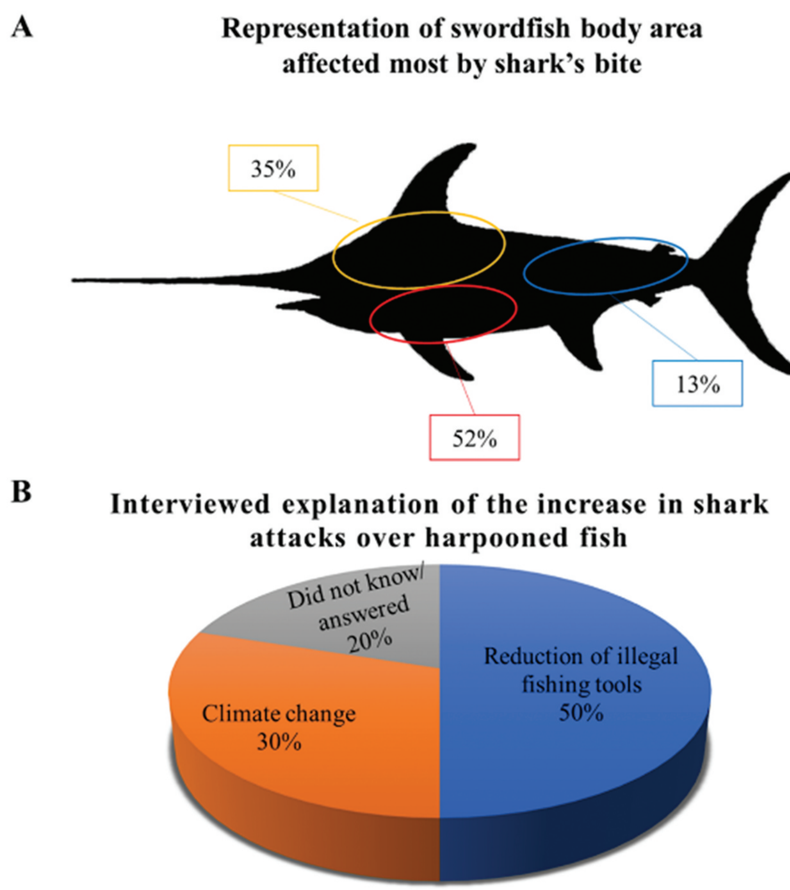

Figure 4. Graphical representation of the main body area where the bites were inflicted by sharks to the swordfish (a) and main reason provided by the interviewed regarding the cause of the increase of sharks attacks over harpooned fish (b).

eating the entire body of the fish without the head (Secchi & Vaske 1998; Dalla Rosa & Secchi 2007). Furthermore, cetaceans usually rise to the surface to breathe, but no marine mammals have been observed by fishermen before, during and after the attacks. Sicilian harpoon fishermen usually spend about 10–12 hours at sea, each day, searching and hunting swordfish (Romeo et al. 2015; Perzia et al. 2016; Battaglia et al. 2018) and the presence of cetaceans would certainly have been noticed. For these reasons, the hypothesis of an opportunistic attack by a cetacean is rather unlikely. On the contrary, sharks usually leave clear-cut edges (Long & Jones 1996; Secchi & Vaske 1998; Dalla Rosa & Secchi 2007; Sperone et al. 2012), similarly to the bite marks shown in Figure 2. According to several authors, this is due to the particular morphology of shark dentition and the rapid head shaking movements, which allow the predator to saw through the prey (Frazzetta 1988; Carrier et al. 2012).

The harpoon fishing ground in the Strait of Messina and surrounding seas is located in an important area for migratory movements for several pelagic species. Most migratory sharks have been observed in this area: *Alopias vulpinus, Alopias superliciosus, Carcharhinus brachyurus, Carcharhinus brevipinna, Carcharhinus limbatus, Carcharhinus plumbeus, Carcharias Taurus, C. carcharias, Heptranchias perlo, I. oxyrinchus, Lamna nasus, P. glauca, Odontaspis ferox, Sphyrna zigaena* (Celona et al. 2001, 2005; Vacchi & Serena 2010; Sperone et al. 2012; Leonetti et al. 2020). In addition, according to the available literature (Celona et al. 2005; Potoschi et al. 2010), a stable population of bluntnose sixgill shark (*Hexanchus griseus*) inhabits the Strait of Messina. In the described events, it is possible that, during fishing operations, the blood and fish distress alarm cues generated by the injured animal (i.e. harpooned catch) have attracted a migrant shark, which took advantage of it to feed on an easy prey. Generally, when a fisherman harpoons a fish (i.e. swordfish, tuna,

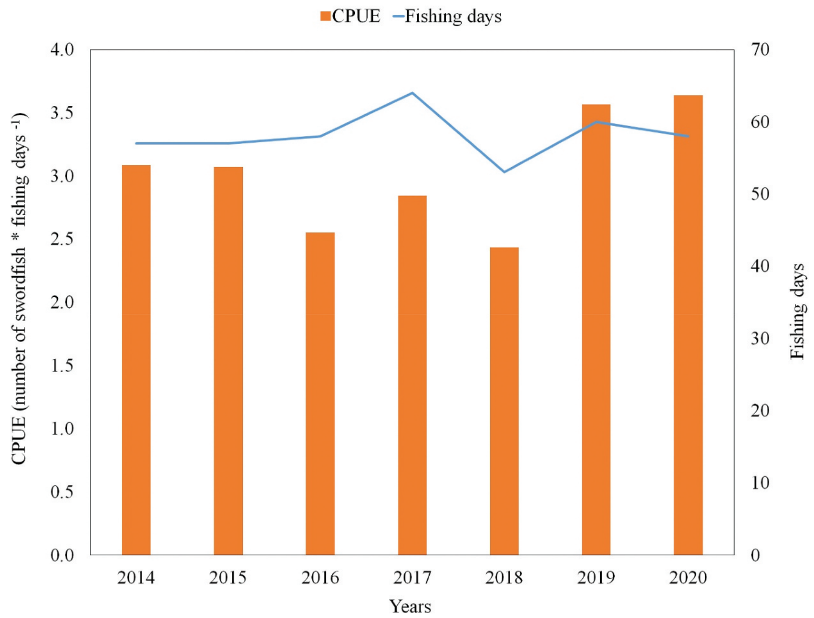

Figure 5. Catches per unit effort (CPUE) expressed as number of swordfish caught per day by a Sicilian harpoon vessel. The days at sea are also reported and data were calculated for the fishing period 2014–2020).

Table II. Pelagic fauna reported by harpoon fishermen including sharks observed before the attacks and pelagic megafauna increased in the last few years.

Species observed before the attacks	Pelagic megafauna increased since 2014
Prionace glauca	Adult pelagic sharks
Isurus oxyrinchus	Juvenile sharks
Carcharodon carcharias	Giant devil ray
	Marine Turtles
	Marine Mammals
	Mediterranean spearfish
	Other billfish
	Swordfish

billfish) at the surface, the injured animal reacts by diving into deeper waters and fights to escape the capture. Usually, the animal dies for exsanguination or becomes tired and it is hauled aboard by fishermen. This operation generally takes less than 30 minutes or more, depending on the fish size and the type of injury (i.e. whether the harpoon hits a vital spot or not). The bite marks on the prey lead to the hypothesis that the predator probably used the "bite and spit" technique, delivering the first bite and waiting for the prey to die for exsanguination, as described by Tricas and McCosker (1984). However, in our cases, the predator was unable to consume the entire prey, since its first attack caused the death of the harpooned fish or reduced its resistance and, as a result, the fishermen were able to bring on board the catch before a second attack. Our investigations showed that the attacks were mainly delivered on the abdomen and, occasionally, dorsally or in the caudal zone. This shark behaviour may be justified by a precautionary approach aimed to avoid potential injuries by the swordfish rostrum. Indeed, cases of sharks injured by swordfish have already been documented and demonstrate the swordfish's aggressive self-defensive or territorial behaviour (Ellis 2013; Penadés-Suay et al. 2017, 2019; Romeo et al. 2020). Other authors (Long & Jones 1996; Sperone et al. 2012) observed that the great white shark bites over odontocetes where mainly located to the caudal peduncle, the urogenital region, the abdominal area and the dorsal area. Comparable damages have been observed in images of shark depredation events on swordfish and tunas (Secchi & Vaske 1998; Dalla Rosa & Secchi 2007). In shark-longline fishery interactions, large damages on catches have been also observed and sometimes fishermen have recovered only head remains of the hooked fish (Dalla Rosa & Secchi 2007). This is mainly due because the longline is usually set for longer time and sharks as well as other predators have more time to depredate the catches or inflict more damages. In the case of harpoon fishing, as described above, the harpooned fish remain at sea for a limited period and the opportunistic predator have little time to complete its attack.

Our data are based on documented records of attacks on catches and the phenomenon could be probably underestimated. Indeed, fishermen referred that some small swordfish individuals got lost after being harpooned; it is still unclear whether they escaped the capture due to the detachment of the harpoon or because the entire fish was eaten/depredated by the predator (these events were not recorded as attacks in this study).

Since the attacks took place at depth and the fishermen were unable to directly observe the predator and its size, it is difficult to attribute each attack to a specific predator. In few cases, fishermen reported the presence of some large sharks (probably *P. glauca, I oxyrhinchus, C. carcharias*) few days before the attacks in the Strait of Messina. In this area, sharks' interaction with pelagic fauna was also observed without interfering with fisheries (Malara et al. 2020).

The questionnaires and interviews allowed to gather important information on local fishing and ecological knowledge from harpoon fishermen. They can be considered as "sentinels of the sea" since usually spend between 10 and 12 hours per day, on the top of the sighting platform of the harpoon vessels, scanning the sea surface at 20–30 m above the sea level (for details see Romeo et al. 2009; Battaglia et al. 2018). Those vessels represent an important sighting platform for large marine fauna swimming near the sea surface (Romeo et al. 2003, 2009). However, the discrepancy in answers among fishermen is possibly due to the lesser fishing experience of the younger generation of fishermen involved in this study (group 3), since their comparison refers to a shorter time period.

According to fishermen answers, the presence of juvenile blue sharks has been reported during August in the 5 years prior to the interviews. These data agree with the recent observations of Leonetti et al. (2020), which reported the increase in shark populations and juveniles of *P. glauca* and *I. oxyrhincus* around the Calabrian Ionian coasts. According to fishermen's thought, these data could be explained by the positive effect of the driftnets' ban in the Mediterranean Sea (EC Regulations 849/97, 1239/98 and 809/2007; ICCAT Rec. 03–04; GFCM Rec. 2005/3), which reduced the number of by-caught sharks and produced a recent increase in elasmobranchs in the study area. However, the increase of juvenile blue sharks in the study area maybe also related to a climate change effect in the last years, which could cause in shark populations a behavioural shift as response to variations of environmental conditions (Crear et al. 2020).

Furthermore, our data on the harpoon CPUE values confirm an overall positive trend in swordfish catches in the study area, as previously observed by Romeo et al. (2015) and Battaglia et al. (2018). It is possible that a higher frequency of the shark interactions with harpoon fishing may be explained by an increase in harpooned swordfish individuals and, then, by the higher availability of potential easy prey for large opportunistic predators such as sharks.

On the basis of these results, however, we plan to increase the monitoring of these phenomena and interactions in the future, in order to understand whether the attacks are due to occasional encounters with migrating sharks or to residential species as well as to further understand this opportunistic behaviour.

Disclosure statement

No potential conflict of interest was reported by the authors.

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