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Retained Hooks in the Threatened Blue Shark (*Prionace glauca*) in the Northern Catalan Coast: Fisheries Management and Shark Conservation

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Abstract

The seas worldwide have undergone significant transformations, impacting the communities. Among the most affected groups are sharks, whose populations have experienced a substantial global decline. In the Mediterranean Sea, most shark species are also declining in numbers. Fishing activities, particularly by-catch, stand out as its primary contributing factor. Here we study the prevalence and impact of retained hooks and trailing lines in a sample of 87 free-ranging blue sharks from the canyon of Northern Catalan Coast. We observed an average of 0.30 ± 0.38 sharks/hour. Seventeen sharks (retained hook prevalence = 0.20) presented one or more retained hooks (from commercial and recreational fishing) or skin lesions resulting from such interactions, ranking among the highest reported values within the literature. Statistically significant differences were observed between month and age classes. A higher retained hook prevalence was observed in July (0.31) compared to June (0.09) and August-September (0.20). It was also higher in small juveniles (0.31) than in large juveniles (0.10). An 11.8% of the affected sharks had two retained hooks (1.24 hooks/shark). 53.3% of affected sharks exhibited nylon threads attached to the hooks (averaging 0.98 m in length), and 7.7% of them showed two. A total of 90.9% of the affected sharks were found with hooks specifically designed for capturing swordfish. Our results suggest that Western Mediterranean blue shark populations may be seriously exposed to by-catch events and their consequences, which is particularly concerning given their “Critically Endangered” status. Urgent measures are needed to mitigate potential mortality and sub-lethal effects.

Keywords: Blue shark; Prionace glauca; Hooks; Skin lesion; Conservation; By-catch; Longline fishery

Abbreviations: CCC: Cap de Creus Submarine Canyon; dF: Degrees of freedom; ER: Encounter rate; IUCN: International Union for the Conservation of Nature; MaxN: Residence time or Time (minutes) between the arrival and the departure; N: sharks observed; NE: Northeast; PVC: Polyvinyl chloride; RHP: Retained hook prevalence; SD: Standard deviation; SST: Sea surface temperature; TL: Total length; YOY: Young of the Year

Introduction

The seas worldwide have experienced important transformations, which have directly affected the communities that rely on them. Predators are among the most affected groups by these drastic changes, and especially sharks, whose populations have experienced a substantial global decline [1,2]. Particularly, the Mediterranean Sea stands out among the most severely affected sea by anthropogenic activities [3]. Nonetheless, it harbours a rich diversity of sharks (up to 49 reported species), the majority of which are experiencing significant population declines and confronting diverse conservation challenges [4-7]. Contributing factors for such populations declines include the collapse of their primary prey, pollution, human-driven habitat transformation, and other related causes [8]. While sharks are not target species in the fishing industry, both demersal and pelagic fisheries using large fishing lines are responsible for numerous by-catch events. These accidental captures are identified as the main cause behind shark population declines in the Mediterranean Sea over the last decades, impacting a significant portion of species in an unsustainable manner [4,5,9-11]. In addition, by-catch does not only impact adult specimens, but also affects juvenile stages [12].

The blue shark *(Prionace glauca)* is a cosmopolitan and medium-sized shark, classified as Near Threatened (NT) by the IUCN red list [13]. Taking into account its high fishing rate compared to other shark species, it is likely one of the most common shark species worldwide [14,15] observation that remains consistent in the Mediterranean Sea [9,16,17]. Likely due to this fishing pressure, blue shark populations have experienced a significant decline in the Mediterranean Sea [15], leading to its classification as a "Critically Endangered" species by the IUCN [3,8]. The blue shark is a pelagic species with great mobility. Recently, several studies have highlighted [18,19]:

a) its capacity to make annual movements of hundreds to thousands of kilometers

b) the existence of seasonal migrations between different areas of interest throughout the annual cycle

c) that these zones can be different for the different age classes or sexes

d) that significant concentrations can occur in relatively small spaces

e) that some of these areas have a special interest during their reproductive season

f) that in the western Mediterranean Sea, a significant breeding area may be located in the Gulf of Lion.

These and other distinctive characteristics of their population dynamics and ecology make them notably susceptible to by-catch throughout their various biological stages, as well as through diverse fishing methods and equipment. While shark catches are often underreported, recent studies have highlighted the significant impact of by-catch events on the blue shark in the Mediterranean Sea [16], considering it as a scenario of increasing and unsustainable pressure [11].

More recently, a study carried out in the Balearic Islands using Baited Remote Underwater Video has revealed a high prevalence (50%; n=10) of retained hooks and trailing fishing lines in blue sharks [17]. Regardless the small sample size, their results are not biased by captures. Therefore, the high prevalence found in this study raises a legitimate concern, suggesting that a substantial proportion of the population may be affected by this scenario. According to these authors, the release of specimens resulting from by-catch, often retaining embedded hooks, could be far from being an innocuous practice. Instead, it could have significant repercussions on their thriving, potentially leading to unnoticed mortality events. Residual embedded hooks can cause various types of external and internal lesions, including but not limited to secondary infections, poisoning or fatal damage to internal organs [20-22].

Few studies have explored the impact and temporal variations of retained fishing hooks on shark populations worldwide. The present study provides new insights into this topic, focusing on a subpopulation of blue sharks from the Gulf of Lion (Northern Catalan coast) during the end of spring and summer months, area and season that has been recently identified as a unique mating, parturition and nursery scenario in the Mediterranean Sea [19]. The objectives of the present study were

a) to assess the occurrence, sex and age of blue sharks from the Gulf of Lion during summer months

b) to assess the prevalence of residual hooks and trailing lines

c) to describe types of skin lesions derived from residual hooks and trailing lines in the observed specimens.

Results from our study can contribute to inform blue shark conservation strategies at a local and international scale, and have the potential to be applied to diverse shark species inhabiting temperate climates.

Methods

Study area

Cap de Creus is located in the north-east of the Catalan coast (NE of the Iberian Peninsula), extending over 10 km to the Mediterranean Sea (Figure 1). Approximately 5 km from the tip of Cap de Creus there is the Cap de Creus Submarine Canyon (CCC), which cuts the continental shelf about 38 km from the coast, exposing deep sea areas in close contact with the coast. The head of the CCC is located in front of the Spain-France frontier, and descends in a southeast direction for about 70 km, reaching a maximum width and depth of 6 km and 2,000 m respectively [23]. The present study is focused on a square section of 25 × 19 km from the upper part of the CCC (Figure 1) which includes depths between 0 and 750 m and an overall uneven and rough sea bottom. The south wall of the canyon is dominated by terraces and large cliffs, while the north side exhibits continuous and steep walls with significant overhangs. Due to its climatological and oceanographic conditions, the CCC is an area of high productivity and great biological wealth, which has been identified as the main "biodiversity hotspot" in the Spanish Mediterranean Sea [24]. Our study area has also recently been highlighted as a hotspot of great interest and use by *P. glauca* in the Mediterranean Sea, especially between the end of spring and summer, and to a lesser extent, during the autumn [19]. The high presence of *P. glauca* during this period suggests that the CCC is within the main potential mating,

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reproduction and nursery area of the species in the western half of the Mediterranean Sea. In addition, it is included in a zone where the existence of a permanent marine circulation system has been shown [25].

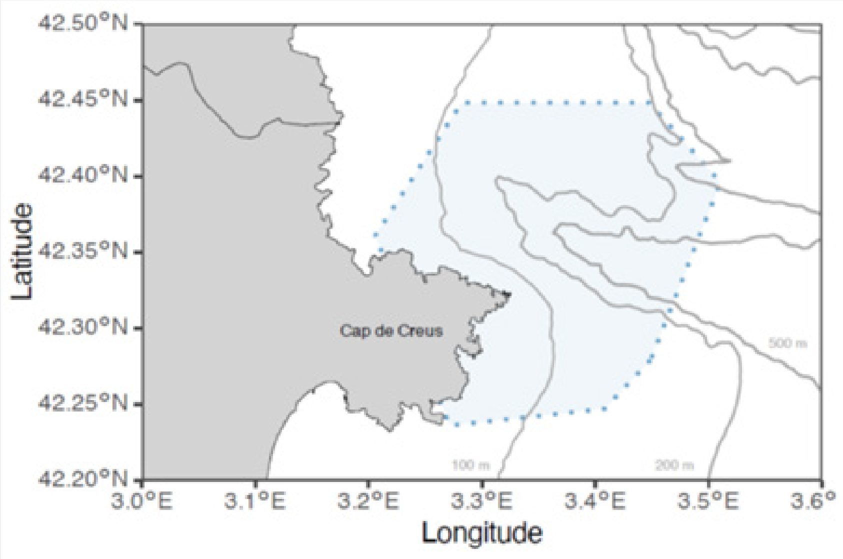

Figure 1: Study area (Cap de Creus Submarine Canyon), showing the surveyed area delimited by a discontinued blue line.

Fieldwork

We used a grind of sardine *(Sardina pilchardus)* and/or European anchovy *(Engraulis encrasicolus)* mixed with sea water as chum. This technique, which attracts carnivores and scavengers, allows the observation of rare and elusive species, being globally used to attract sharks. Blue sharks from our study came attracted by the chum, dispensed in small amounts and continuously from a 7.5 m long zodiac-type boat. We also used: two white and perforated PVC pipes (62.0cm length × 12.0cm diameter) with sardines inside and hanging at 5m deep fore and aft; and a head or fragment of tuna or other pelagic fish from the fishing activity attached to a buoy and rope. The latter was designed with the aim that sharks circled both pipes and stayed close to the boat, so that they could be closely observed, photographed and filmed.

We used a non-invasive technique to obtain information from all sharks. Before diving, we took underwater footage and photographs from the boat, to quickly gather information in case the sharks moved away. After the acclimatization period, researchers submerged in water and took more detailed graphic and video material. Images were captured using a Canon G7X still camera with Nauticam NA-G7XMKII waterproof case and two Gopro Hero 10 cameras. We collected the following information

a) number of blue sharks

b) sharks' sex

c) sharks' total length

d) presence of wounds, scars, stains, spots, abrasions or other elements that allow their individual recognition

e) presence and characteristics of retained hooks and their nylons

f) injuries related to the presence of these hooks.

Photography and video analysis

We analysed the photographs and individually recorded the type of hook, its relative size and position, and injuries derived from them. Types of hooks were identified with the help of a professional longline fisherman from the Port of Vilanova i la Geltrú (Catalonia). According to the type, length and material of the hook, and the way they were rigged, we established three categories of hooks

a) Atlantic bonito *(Sarda sarda)*, little tunny *(Euthynnus alletteratus)* or similar (total length of the hook (L)= 40.0 - 50.0 mm; ø shank= 1.5 - 2.0 mm)

b) swordfish *(Xiphias gladius)* and, occasionally, also the albacore *(Thunnus alalunga)* (L= 70.0 - 85.0 mm; ø= 2.5 - 3.0 mm)

c) Atlantic bluefin tuna *(Th. thynnus)* (L= 65.0 - 80.0 mm; ø= 5.0 - 7.0 mm). The total length of hooks was calculated according to Poisson and colleagues [6].

Sharks length and age class assessment

Since sharks were not caught or handled, their total length (TL) was estimated by comparing their length with the length of

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researchers, scuba pointer sticks, and other known elements from the boat. We estimated an inherent error in measurement of ± 10 cm, which allowed us to classify sharks into age classes according to their longitudinal range. As a reference, we used the values obtained for this species in its overall distribution area [26], and particularly in the Mediterranean Sea [27] (Table 1). Sharks were classified as adults when their TL reached the value of mature and sexually active specimens.

Table 1: Correspondence between the total length (TL) and the estimated age of blue sharks used for this study, according to the studies carried out in the whole distribution area [26] and, especially, the Mediterranean Sea [27].

Age class	Age class description	Total length (TL) (cm)		Description
		Females	Males	
0+	Newborn	35 - 50		Born during the calendar year of the observation.
1+	Small Juveniles	51 - 84		Born during the precedent calendar year of the observation.
2+	Small Juveniles	85 - 124		Born two seasons before of the calendar year of the observation.
3+	Large juveniles	125 - 169		Born three seasons before the calendar year of the observation.
4+	Pre-adults	170 - 199	170 - 189	Born four seasons before the calendar year of the observation.
5+ or older	Adults	≥ 200	≥ 190	Born five or more seasons before the calendar year of the observation.

Statistical analysis

Newborn and young of the year (YOY; less than one-year-old) were excluded from the analysis to align with the published literature, since they are rarely observed in other areas of the Mediterranean Sea [12,18,26,27]. We estimated the maximum residence time (MaxN) for each specimen by calculating the time (minutes) between the arrival and the departure. In order to standardize the sampling effort, we calculated the number of different sharks observed (N) per chumming hour (Encounter rate, ER=N.h^{-1}). Results were presented as "retained hook prevalence" (RHP), establishing the probability that a shark of a particular age, sex or time period had a retained hook and/or derived lesion at the time of observation. The comparison of the absolute frequencies observed in the different analyses was carried out using the Chi-Square test.

Results

Observed sharks and maximum residence time

We carried out a total of 49 pelagic shark surveys (255.6 hours) between April and October 2023. The number of sessions varied per month: April (n= 3), May (n= 4), June (n= 15), July (n= 18), August (n=7), September (n=1) and October (n=1). The number of surveys was lower in the months of April, September and October due to adverse weather and sea conditions. Surveys were conducted during daylight, from 7 a.m. to 5 p.m. (GMT), and lasted an average of 5.25 hours (SD=0.75; range 3.0 - 6.2).

Between June 3rd and September 28th, we observed a total of 87 blue sharks (excluding newborns and YOY): 43 in June, 39 in July, 4 in August, and 1 in September. Shark's size, sex, retained hooks and fishing lines, scars and superficial marks allowed us to identify most of the sharks. Only one of the sharks was observed twice. Of the sharks for which we could estimate the age (n=86), 14.0% were adults (≥ 5+), while the remainder were juveniles.

Considering all specimens, sharks were observed for a total of 84 h 58 min. The average maximum residence time (MaxNave) for the studied sharks was 58.6 min (SD = 45.6 min; range 1 min – 2 h 58 min). The ER was 0.30 ± 0.38 blue sharks/hour.

The sea surface temperature (SST) in this area fluctuated between 15.2°C and 27.1°C during the study period, with temperatures ranging from 19.9°C to 24.9°C on days when sharks were observed. The average visibility, as estimated using the Secchi disk, was 16.01 m (ranging 8 - 29 m).

Occurrence of residual hooks and trailing lines

A total of 17 sharks (RHP=0.20) showed either retained hooks (n=15) or scars derived from rejected hooks (n=2) (Table 2). Considering all 17 affected sharks, statistically significant differences were observed between the proportion of sharks affected in the different months (Figure 2), showing the lowest occurrence in June (RHP=0.09) and a threefold increase in July (RHP=0.31). Both August and September showed a RHP of 0.20, but the small sample sizes from these months did not support formal statistical significance. Statistically significant differences were neither found between the different age classes (χ^2 = 4.73; 2 dF; p=0.093) (Figure 3). However, small juveniles (RHP=0.31) showed a statistically significant higher occurrence than large juveniles (RHP=0.10) (χ^2 = 4.14; q dF; p=0.042). We did not find statistically significant differences in the occurrence of retained hooks and trailing lines between males (n=12, RHP=0.24) and females (n=16, RHP=0.12) (χ^2 = 0.33; 1 dF; p=0.563).

We found 26.7% of the affected sharks with two residual hooks or scar (n=15). On average we found 1.27 hooks/shark, SD=0.46; range 1-2 hooks/shark). Hooks were equally found in the left (n=11) and right (n=10) sides of the face (χ^2 = 0.048; 1 dF; p=0.827). Some hooks caused double wounds, entering the body, exiting, and then re-entering. As a result, the number of

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external holes observed in the affected blue sharks ranged from 1 to 3, averaging 1.57 holes/shark (SD=0.76) for which this count could be determined (n=14) (Table 2). The exact location of hooks varied: most hooks were found in the oral commissure (85.7%), but other were also found in the cheek (35.7%) and in other parts of the mouth (7.1%) (n=14).

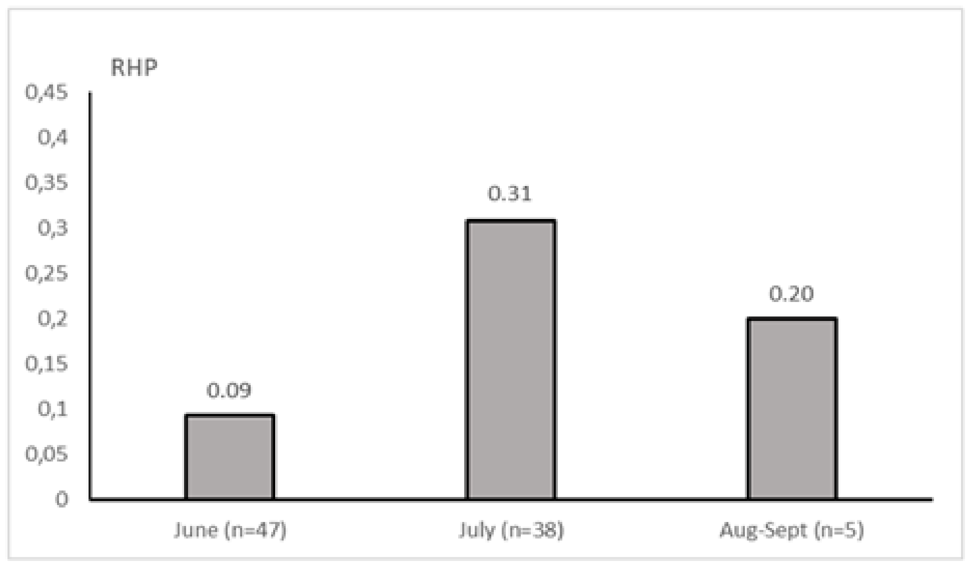

Figure 2: Retained hook prevalence (RHP) for blue sharks during June, July and August-September, respectively. Statistically significant differences are found between June and July ($\chi2$ = 6.00; 2 dF; p=0.014).

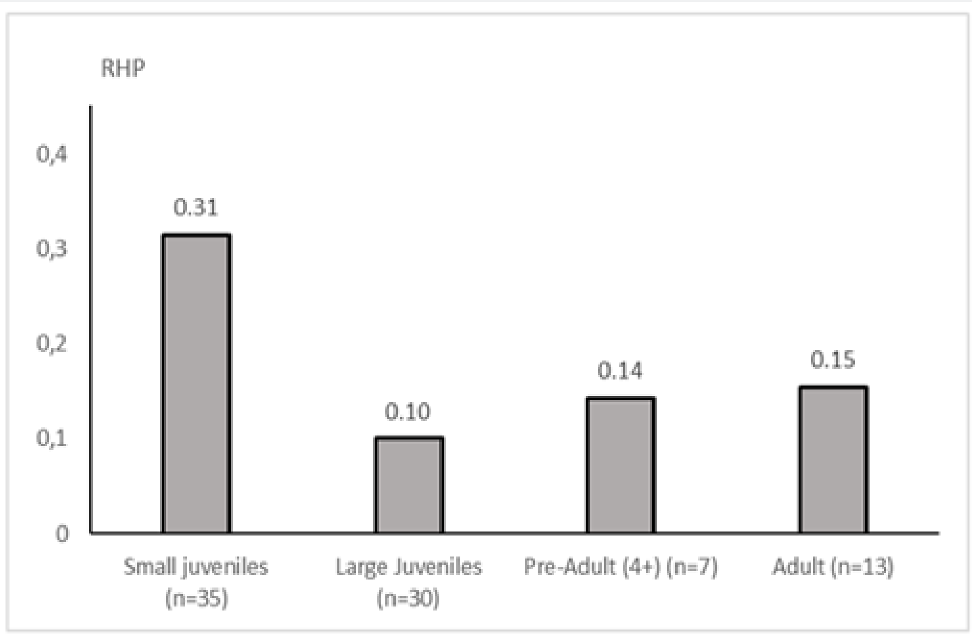

Figure 3: Retained hook prevalence (RHP) for the different age categories in blue sharks during the study period (June-September 2023). Statistically significant differences are found between small juveniles and large juveniles ($\chi2$ = 4.14; q dF; p = 0.042).

Based on their appearance, we could identify 10 (90.9%) hooks used for swordfish (or similar) fishing, whereas the remaining hook (9.1%) originated from Atlantic bonito or albacore fishing activities. No hook was identified as Atlantic Bluefin tuna target. The fishing origin was determined for 8 hooks: commercial activities (n=6) and recreational activities (n=2). Eight (53.33%)

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sharks of those with residual hooks (n = 15) showed nylon trailing lines attached to the hooks. Additionally, one shark showed two trailing lines. The average length of the observed trailing lines (n=8) was 0.98 m (SD=0.73; range 0.05 - 2.00). Three sharks showed a trailing line of more than 1.8 m long, two of which showed only the residual perforation of the hook but this was not externally visible.

Table 2: Observed blue sharks with retained hooks, trailing lines or scars derived from them. TL= total body length (estimated by comparison with known elements). Nr/Bl= total number of hooks/total number of lesions; L/R: presence of hooks on the left/right sides of the face. Ny/L= number of nylon threads/estimated nylon length (m) if present. M: male, F: female; (na) not available.

ID	Date	Sex	TL (m)	Age category	Hook/Scar	Nr/Bl	L/R	Place	Ny/L (m)
1	6/6/2023	M	2	Adult (≥ 5+)	Hook	1/-	1/0	na	1/?
2	10/6/2023	M	1	2+	Hook	1/-	0/1	na	0/na
3	24/06/2023	M	1.1	2+	Hook	1/-	1/0	na	1/?
4	25/06/2023	F	1.2	2+	Hook	2/3	1/1	Cheek/Commis-sure	1/> 1.00
5	6/7/2023	M	1.8	Pre-adult (4+)	Scar	1/1	1/0	Commissure	0/na
6	9/7/2023	M	1.4	3+	Hook	2/2	0/2	Cheek/Commis-sure	0/na
7	12/7/2023	M	1.3	3+	Hook	1/1	1/0	Commissure	0/na
8	14/07/2023	M	1.1	2+	Hook	1/1	1/0	Commissure	1/0.15
9	16/07/2023	M	1.2	2+	Hook	1/2	1/0	Cheek/Commis-sure	0/na
10	17/07/2023	F	0.9	1+	Hook	1/1	0/1	Mouth	1/2.00
11	19/07/2023	M	1.1	2+	Hook	1/2	0/1	Cheek/Commis-sure	0/na
12	19/07/2023	?	1	2+	Hook	1/1	1/0	Commissure	0/na
13	19/07/2023	?	1.1	2+	Hook	1/1	1/0	Commissure	1/1.50
14	31/07/2023	M	1.2	2+	Hook	1/1	0/1	Commissure	0/na
15	31/07/2023	M	1.1	2+	Hook	2/3	1/1	Mouth/Commis-sure	2/>2.00 and 0.60
16	31/07/2023	M	2	Adult (≥ 5+)	Scar	1/1	0/1	Cheek	0/na
17	28/09/2023	F	1.3	3+	Hook	2/2	1/1	Commissure	2/0.50 and 0.05

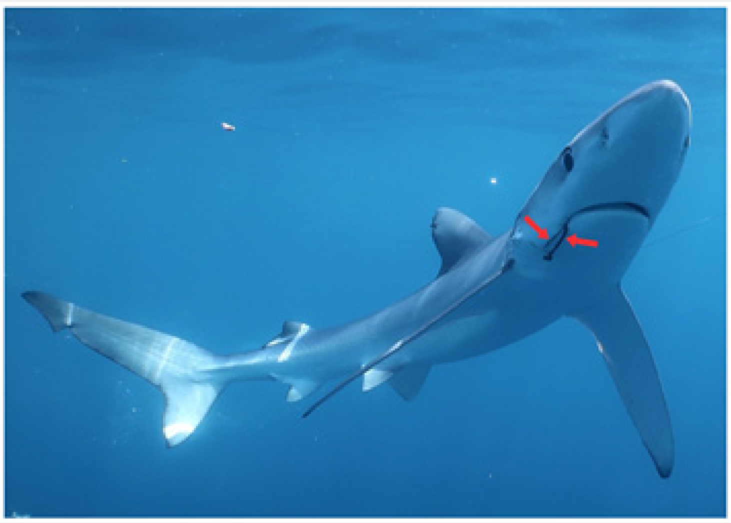

Figure 4: A blue shark showing two trailing lines (red arrows) without visible external lesions associated to them.

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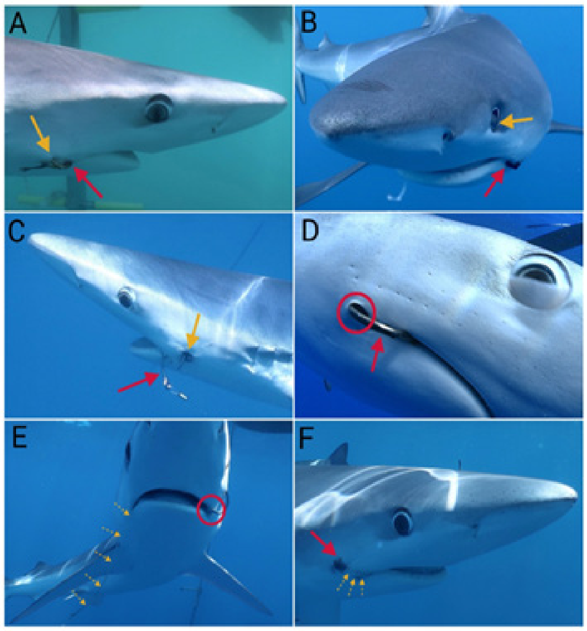

Figure 5: Skin lesions found in blue sharks affected by residual fishing hooks and trailing lines from the Gulf of Lion (Northern Catalonia coast) during the Summer 2023. (Figure 5A) A fishing hook coming from the right oral commissure (red arrow) and piercing the adjacent skin from outside to inside (yellow arrow). The same animal showed another fishing hook protruding from the left commissure and hanging freely, without piercing the skin (not visible in the photograph). (Figure 5B) Circular left oral commissure perforation (red arrow) with a protruded fishing line piece of 5 cm long. Additionally, the shark presented a permanent left nictitating membrane paralysis (yellow arrow). (Figure 5C) A fishing hook protruding from the skin of the left cheek (red arrow). The edges of the skin associated with the hook perforation appear retracted and hyperpigmented (yellow arrow). (Figure 5D) A pierced fishing hook in the right oral commissure (red arrow). The skin around the pierced area appears retracted, which widens the diameter of the skin perforation (red circle). The direction of the pierced hook cannot be determined, since there is no visible fishing line associated. (Figure 5E) A fishing hook protruding from the skin of the left upper jaw, turning towards the left oral commissure, where the point and barb of the hook can be seen (red circle). A fishing line piece of one-meter-long appears from the right oral commissure (yellow discontinued arrows), which probably belongs to the same protruding hook. (Figure 5F) A circular area of hyperpigmentation in the left cheek (red circle). The oral commissure of the same side shows a linear pressure notch (yellow discontinued arrows). The appearance and location of both lesions are suggestive of an old fishing hook perforation.

Figure 6: A pierced fishing hook in the right oral commissure (red arrow) of a blue shark. Although no lesions are visible, the hook looks pierced in the skin and derived lesions are expected from it.

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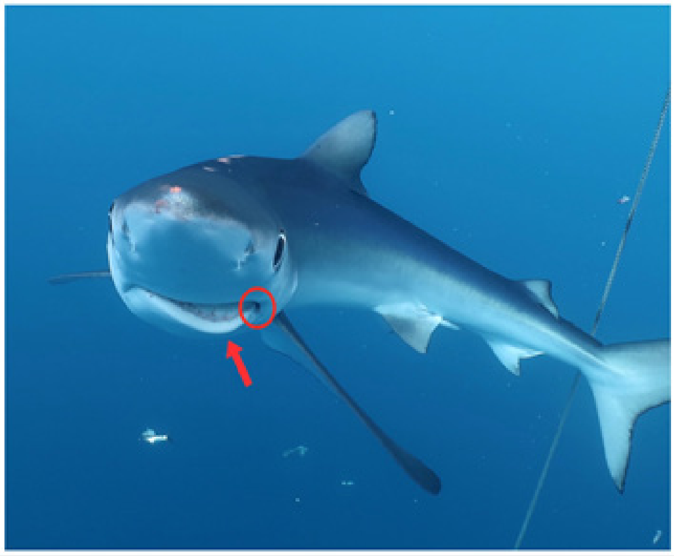

Figure 7: Left lower jaw dislocation (red arrow) and permanent exposure of the lower tooth rows in a blue shark. The circular perforation from the left oral commissure (red circle) is compatible with an old fishing hook lesion.

Skin lesions derived from residual hooks and trailing lines

The study of the photographs and videos allowed us to examine the external impact of hooks and trailing lines in 13 sharks. While six sharks showed trailing lines without visible external lesions (Supplementary material, Figure 4), seven sharks (8% of total observed sharks) exhibited variable dimensions of skin lesions associated to residual hooks or trailing lines (Figure 5 and Supplementary material, Figure 6). Two sharks exhibited additional injuries, namely jaw dislocation (Figure 7) and nictitating membrane paralysis (Figure 5B), which could not be directly attributed to the consequences of residual hooks or trailing lines. However, these injuries strongly suggested a potential association with such interactions.

Discussion

The Gulf of Lion and the north of the Catalan coast as a blue shark recruitment area

In our study, we found more than a ten-fold increase in shark sightings per time unit during the end of spring and summer ($N.h^{-1}$=0.297) than Abril and colleagues [17] found in the Balearic Islands (N.h-1=0.02). Additionally, we found a very low number of repeatedly observed sharks. Both findings suggest that our study area is within an important spot for blue shark concentration, abundance and/or temporary residence during these months. A recent study from Poisson and colleagues [19], used satellite-tagged blue sharks to examine their movements and home ranges in the Western Mediterranean Sea. By satellite-based environmental data, the authors identified the Gulf of Lion and the north of the Catalan coast as the main mating, reproduction and nursery area of the Western Mediterranean Sea for the species, which aligns with our results and highlights the Gulf of Lion as an important Mediterranean spot for blue shark conservation.

Surging prevalence of retained hooks in juvenile sharks and during July

Our findings reinforce the substantial prevalence of blue sharks affected by retained hooks, consistent with the observations made by Abril and colleagues in the Balearic Islands [17]. While their study reported a 50% prevalence of retained hooks among sharks, albeit with a smaller sample size than ours, the present study reveals a notably 20% occurrence. Nonetheless, both studies show significantly higher rates compared to global trends, where only 1.8 - 2.8% of blue sharks are reported to be affected [28,29]. In addition, we observed 12% of affected sharks with more than one retained hook, which suggests an even greater increase in fisheries interactions.

Overall, we found different prevalence values between age and month categories. One out of three small young sharks were affected by hooks (RHP=0.31), while the other age groups showed statistically significant lower prevalence (but yet important: 0.10 - 0.15). Notably, small juveniles are those specimens that have had less time to be in contact with fishing activities and therefore, we should expect a lower prevalence than adult specimens. On the other side, blue sharks are considered opportunistic feeders [30]. The time required for small young sharks to learn efficient hunting techniques, combined with their limited feeding apparatus and mechanisms in comparison to adults for targeting free prey [31], may bring them into closer proximity to fishing

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hooks. Since a large number of investigations highlight the high mortality prevalence in juvenile sharks during longline fishing operations [32-34], further exploration of the feeding behaviour of blue sharks and its relationship with by-catch events and related health consequences is needed, especially at a local scale. On the other side, the lower prevalence found in adult sharks could be related to undetected mortality associated to hooks, or linked to the ability of sharks to naturally expel old retained hooks and undergo rapid healing [21]. While blue shark movements and migrations may influence the observed differences in prevalence between age categories, Poisson and colleagues [19] stated that our study area and time align with a concentration of adult blue sharks, therefore mitigating this potential bias.

Specimens observed in July were significantly more affected by retained hooks (RHP=0.31) than in June, which was the month with the lower prevalence of them all. Although the reasons for this surge are unknown, an increase in the fishing pressure may lead to a higher prevalence of blue shark fishing interactions. Blue sharks are not a target species in our study area and the number of local longline vessels is currently very low (official data from the Department of Climate Action, Food and Rural Agenda), even significantly lower than the number reported by a work in the Catalonian waters [7]. Therefore, the limited number of local longline vessels makes it unlikely that they are the only ones responsible for the elevated prevalence of retained hooks during that month. However, fishing boats come from other Mediterranean countries to fish in our area during specific periods [6], which may potentially increase the overall by-catch impact. Additionally, from late June to August, there is a rise in recreational fishing activities across the Mediterranean Sea, which has been related to bycatch events in other areas of its global distribution area and affecting many other shark species [1]. Sudden immigration of juvenile sharks from other areas of the Mediterranean Sea with a higher fishing pressure than ours is possible but unlikely since the Gulf of Lion has been identified as a blue shark recruitment area [19]. Further research, spanning multiple years, is essential to elucidate the underlying reasons for the surge of retained hooks in specific months and age categories.

More than retained hooks

Shark mortality associated to by-catch events may manifest during the capture process or in the subsequent release, with estimated rates of 6 - 13% and 10 - 35% for the former and latter cases, respectively [6,33,35,36]. Sharks affected by retained hooks can experience a spectrum of internal pathological processes post-release, as documented in previous studies [28,37]. These include gastric wall and oesophageal perforations, hepatic lacerations, foreign body reaction (fibronecrotic masses), intestinal obstruction and perforation, esophagitis, gastritis, hepatitis, and proliferative peritonitis [28,34,37].

Despite the inability to investigate the potential presence of internal hooks or fishing lines within our observed sharks and their associated impacts, our current study highlights that surviving specimens from by-catch events exhibit injuries or foreign materials that may compromise their quality of life, survival likelihood, prey capture efficiency, or even reproductive success. Notably, a significant number of sharks exhibited one or two trailing fishing lines, impinging on their motility and potentially entangling with various body parts such as fins, an issue previously highlighted by Abril and colleagues [17]. Additionally, a substantial proportion of sharks exhibited either retained hooks or external scars, providing insights into the direct detrimental effects on these specimens. Specific studies to explore the consequences of these lesions are lacking in our case, yet reports regarding by-catch induced secondary health impacts in sharks worldwide are increasing [28,37-41]. In our study, we identified two sharks displaying jaw dislocation and nictitating membrane paralysis respectively, likely attributable to secondary consequences of hook trauma since they both exhibited direct skin lesions caused by hooks. The nictitating membrane is an anatomic structure only present in the largest order of sharks, the *Carcharhiniformes* (which blue sharks belong to) [42], which covers their eyes during feeding activities to protect against mechanical damage. Therefore, it is essential for prey capture success [42]. Similar to our observed shark with a dislocated jaw, Ritter [37] found a high prevalence of jaw injuries related to hook ripping, including jaw dislocation and rotation. Jaw injuries can affect both suction and gouging, the main mechanisms involved in sharks' feeding process [43,44]. Injuries to any anatomic structure involved in prey capture can affect the shark's feeding success, and therefore impair their thriving. Comprehensive experimental data, including by-catch post-release survival, monitoring of health indicators, and thorough post-mortem examinations are essential to fully understand the magnitude of the impact.

Fishing activities and blue shark conservation strategies

Although historically shark population declines were mainly attributed to the impact of commercial fisheries, it is now evident in specific regions that recreational fishing activities could rival or surpass shark by-catch events compared to those of commercial fisheries [45]. Furthermore, a significant portion of the worldwide chondrichthyan catch is categorized as by-catch and is not reflected in official fishery statistics, being almost totally unregulated [46]. Therefore, the causes and consequences of shark by-catches may be significantly underestimated.

In the Mediterranean Sea, the blue shark represents the most caught pelagic shark [7,47]. Our results indicate a high prevalence of blue sharks' by-catch incidences in the waters of Cap de Creus Submarine Canyon (CCC). These observations are primarily attributable to both commercial and recreational fishing activities, mostly targeting swordfish. Notably, swordfish

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fisheries have been identified as a primary contributor to the by-catch of sharks [16,48]. Some authors are even more alarmed by the potential effects of overfishing which may have been produced by recent increases in effort and by changes in the conditions of swordfish fishing [49].

Recent research shows that the blue sharks inhabiting the western Mediterranean Sea make extensive movements and migrations throughout the year, including trajectories extending northward of Africa, along the Iberian, French and Italian coastlines, and the main islands [18,19]. In this case scenario, sharks may be subjected to multiple opportunities to be caught during fishing activities in different places and throughout the entire year [36], explaining almost in part the sudden increase in the prevalence of blue sharks affected by retained hooks that we found in July.

Since *P. glauca* is classified as "Critically Endangered" by the IUCN in the Mediterranean Sea [3,8], conservation measures should be taken simultaneously throughout the entire Mediterranean Region. Mitigation strategies for fishing should be also adopted by both recreational and commercial fishing [50,51]. For instance, the development of new fishing methodologies and gear, including changes in hook design, fishing depths and fishing systems that avoid the presence of sharks, have been proposed as potential mitigating strategies [50,52]. Additionally, banning fishing activities during the breeding season or excluding some areas from fishing activities could help to ameliorate the impact of by-catch events in this particular and important area of blue shark recruitment. The implementation of these strategies is urgent, but should be contingent upon a thorough evaluation of their potential benefit to sharks' welfare and health, as well as the concurrent assessment of economic and ecological consequences that may arise [53].

Conclusion

The results obtained in our study highlight both the impact of fishing activities on blue shark health and the need to preserve the Gulf of Lion and the north of the Catalan coast to align with global blue shark conservation strategies. Particularly in the Mediterranean Sea, the IUCN classifies the blue shark as Critically Endangered [3,8] and the Gulf of Lion is identified as their main mating, reproduction and nursery area of the NW Mediterranean Sea. Therefore, all potential causes of discomfort, impairment of health, fitness and reproductive success, as well as death, hold particular importance in our study area. Involvement of policymakers and the implementation of more stringent measures in the environmental sector and fishing industry –including by catch mitigation strategies and fisherman helping and training- will be required for the conservation of blue shark populations in this area.

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