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Capture time, size and hooking mortality of bottom longline-caught sharks

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ABSTRACT

The primary gear type used to harvest coastal sharks in the U.S. Atlantic shark fishery is bottom longline. Recent stock assessments have found several species of coastal sharks in U.S. Atlantic Ocean waters have declined from 60% to 80% of virgin levels. To aid in stock rebuilding, alternative gear restriction measures such as reduced soak time, restrictions on the length of gear, and fishing depth restrictions have been considered but not implemented. In order to evaluate the effectiveness of some of these management measures, controlled experiments were performed using hook timers and time depth recorders, assessing the factors affecting mortality during longline capture for the four most abundant species that incurred at-vessel mortality: sandbar (*Carcharhinus plumbeus*), blacktip (*Carcharhinus limbatus*), bull (*Carcharhinus leucas*), and blacknose (*Carcharhinus acronotus*). Our results indicate that as hook time and shark size increased mortality rates for the sandbar and blacktip sharks increased. Predicted models indicated mortality rates increased steadily for the three species but appeared to increase the most after 10, 6, and 1 h on the hook for sandbar, blacktip and blacknose shark, respectively. Sandbar sharks larger than approximately 170 cm FL are more susceptible to hooking mortality. Blacknose shark mortality rates increased as hook time increased but bull shark mortality rates were not affected by any factor. The probability of a hook being bitten increased the most between 5 and 12 h after the fishing gear had been set and the mean amount of time hooks were in the water prior to being bitten was 4, 5 and 9 h for sandbar and blacknose sharks, blacktip, and bull sharks, respectively. A significant difference was found between these means for sandbar and bull sharks and between blacknose and bull sharks. Shark species were commonly caught at different temperature and depth ranges. These results could be used by fisheries management to implement restrictions of fishing depth and soak time to aid in the recovery of coastal sharks species.

1. Introduction

The primary gear type used to harvest coastal sharks in the U.S. Atlantic shark fishery is bottom longline (Morgan et al., 2009; Hale and Carlson, 2007). Longline characteristics vary regionally with gear normally consisting of about 8–24 km of longline and 500–1500 hooks (Morgan et al., 2009; Hale and Carlson, 2007). Gear is generally set at sunset, allowed to soak overnight before hauling back in the morning (Morgan et al., 2009; Hale and Carlson, 2007). Currently there are no restrictions on the bottom longline fishing gear used in this fishery (i.e., length of set, number of hooks, soak time) (NMFS, 2007).

Recent stock assessments have found sandbar sharks, *Carcharhinus plumbeus*, to be depleted 64–71% from unexploited population levels (NMFS, 2006), dusky sharks, *Carcharhinus obscurus*, have declined by at least 80% with respect to virgin population levels (Cortés et al., 2006) and, hammerhead sharks (i.e., *Sphyrna lewini*, *Sphyrna mokarran*, and *Sphyrna zygaena*) declined by about 70% in abundance from 1981 (Jiao et al., 2009). Recent amendments to the Consolidated Atlantic Highly Migratory Species Fishery Management Plan (NMFS, 2007) based on updated stock assessments have drastically reduced the major directed shark fishery in the U.S. Atlantic. The revised measures affect quotas, drastically reduce retention limits, and modify the authorized species in commercial shark fisheries. Specifically, commercial shark fishermen not participating in a special research fishery are no longer allowed to land sandbar sharks and are limited to 33 other large coastal species in a trip. Thus, any fishers that catch sandbar sharks are required to release them.

Demographic modeling of sandbar sharks (Cortés, 1999; Brewster-Geisz and Miller, 2000) and several species of large coastal sharks (Cortés, 2002) have shown that juvenile survivorship is the main factor affecting population growth rates, and thus protection of the juvenile stages may be an effective management tool for stock rebuilding. This fact was recognized in

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the 1998 Shark Evaluation Workshop (NMFS, 1998), the ensuing 1999 Federal management plan (FMP) for Atlantic Tunas, Swordfishes, and Sharks (NMFS, 1999), and the recent stock assessment of large coastal sharks (NMFS, 2007). The 1999 FMP proposed a minimum size limit of 137 cm fork length for large coastal sharks in all shark fisheries. However, this management measure has only been implemented for the recreational sector and does not appear to be effective yet for longline fisheries because sharks like scalloped hammerhead and dusky shark are regularly dead when brought on board and the general lack of information on how soak time and gear depth affect mortality rates of sharks caught on bottom longline gear.

Alternative measures such as reduced soak time, restrictions on the length of gear, and fishing depth restrictions could reduce mortality of sharks and allow fishers to release unwanted species to the water alive, while still effectively catching targeted species. In order for such management measures to be considered, data concerning the correlation between soak time and fishing mortality for individual species, capture time by depth and temperature are needed.

2. Materials and methods

The Florida Program for Shark Research located at the University of Florida, conducted a series of fishing experiments off the coast of Florida (both in the Gulf of Mexico and Atlantic Ocean) using leased vessels from the commercial large coastal shark bottom longline fleet. Contracted vessels set 8.0–9.7 km of bottom longline gear with a total of 250 gangions with 18/0 circle hooks with a 10° offset (Lindgren-Pitman brand). Soak times ranged from 6 to 10 h for over-night sets and 4–6 h for day sets. Fishers provided the bait (same types as used during the open season) and selected the fishing locations. The fishing process was similar to the open fishing season (Hale and Carlson, 2007) but differed slightly by using fewer hooks, less total length of mainline and a shorter soak time. The modifications were made in an effort to maximize the number of sets made per trip, and to reduce fishing mortality.

Hook timers (HT 600, Lindgren-Pitman Inc.) were attached to each hook following Sigler (2000). Hook timers were set out at time 0 (initial deployment of the longline gear) and became activated when a shark bit the hook, thereby pulling the magnet and activating the digital clock. Time of capture was calculated as the elapsed time on the digital clock. Length of time the hooks were in the water before being bitten was estimated by subtracting hook time from total soak time. This length of time was used to indicate whether the hooks were bitten during the setting of the gear (first 10 min of the set), while the gear was being retrieved (last 10 min of the set), or while the gear was fishing on the bottom (Somerton and Kikkawa, 1995). Based on the fact that the gear is weighted and sinks quickly and on discussions with vessel captains, it was assumed that gear setting and retrieval each took approximately 10 min.

Time depth recorders (DST milli, Star-Oddi) were set to record temperature and depth at 1-min intervals (Boggs, 1992) and were attached to the beginning, middle and end of the mainline (Somerton and Kikkawa, 1995) to obtain temperature and depth information along the length of the mainline. Time depth recorders were programmed through a communication box and laptop personal computer (Boggs, 1992) before attaching them to the gear. The data collected by the recorders were downloaded after the haulback was complete. During the haulback, we recorded whether or not the hook timer was activated, the time indicated on activated hook timers, identified the captured species, noted whether the shark was alive or dead when brought aboard, measured fork and total lengths, and recorded sex of the shark. Sharks alive on haulback were tagged with a dart tag and released.

We assessed the factors affecting mortality during longline capture for the four most abundant species that incurred at-vessel mortality: sandbar (*C. plumbeus*), blacktip (*Carcharhinus limbatus*), bull (*Carcharhinus leucas*), and blacknose shark (*Carcharhinus acronotus*). The nurse shark (*Ginglymostoma cirratum*) and Atlantic sharpnose shark (*Rhizoprionodon terraenovae*) were excluded from any hook timer analysis because only one mortality was associated with nurse sharks and Atlantic sharpnose had an overall low percentage of tripped hook timers. Logistic regression was used to predict the relationship with mortality (yes/no) and hook time, depth, bottom water temperature and size (FL). Variables were considered significant $P < 0.05$. The final model was chosen based Akaike's Information Criterion (AIC; Akaike, 1974).

Logistic regression was used to predict the amount of time hooks were in the water prior to being bitten. The dependent variable was tripped hook timers by species (yes/no) and time (hook time in water prior to biting) as the independent variable. Student's *t*-tests were performed to determine if the mean amount of time hooks were in the water prior to being bitten was significantly different between the four species. Variables were considered significant $P < 0.05$ (Zar, 1984). All statistical analysis was performed in SAS Statistical Software (SAS, version 9.1, SAS Inst., Inc., Cary, NC).

3. Results

A total of 55 individual longline sets were made between June 2005 and November 2007. The majority (45) of these sets were conducted in the Atlantic Ocean off the east coast of Florida. The sandbar shark was the most commonly caught shark species (23.4%

Table 1
The number and percentage of tripped hook timers for each individual species caught on bottom longline sets from 2005 to 2007 and what percentage of the shark and/or bycatch catch and total catch each species represented.

Species	Number timers tripped	Percent tripped	Percent shark/bycatch catch	Percent total catch
Sharks				
Sandbar, *Carcharhinus plumbeus*	455	98.3	25.0	23.4
Nurse, *Ginglymostoma cirratum*	405	96.0	22.8	21.3
Atlantic sharpnose, *Rhizoprionodon terraenovae*	94	33.6	15.1	14.1
Blacktip, *Carcharhinus limbatus*	183	96.8	10.2	9.5
Tiger, *Galeocerdo cuvier*	78	70.3	6.0	5.6
Blacknose, *Carcharhinus acronotus*	91	83.5	5.9	5.5
Bull, *Carcharhinus leucas*	69	95.8	3.9	3.6
Lemon, *Negaprion brevirostris*	65	92.9	3.8	3.5
Great hammerhead, *Sphyrna mokarran*	67	100.0	3.6	3.4
Scalloped hammerhead, *Sphyrna lewini*	21	100.0	1.1	1.1
Bonnethead, *Sphyrna tiburo*	7	43.8	0.9	0.8
Silky, *Carcharhinus falciformis*	8	66.7	0.6	0.6
Caribbean reef, *Carcharhinus perezi*	10	100.0	0.5	0.5
Dusky, *Carcharhinus obscurus*	4	100.0	0.2	0.2
Spinner, *Carcharhinus brevipinna*	2	100.0	0.1	0.1
Night, *Carcharhinus signatus*	0	0.0	0.1	0.1
Hammerhead, *Sphyrna* sp.	1	100.0	0.1	0.1
Smooth dogfish, *Mustelus canis*	1	100.0	0.1	0.1
Total	1561	84.3	100.0	93.5

total catch (TC) and made up 25% of the shark catch (SC)), followed by the nurse (21.3% TC and 22.8% SC), Atlantic sharpnose (14.1% TC and 15.1% SC), blacktip (9.5% TC and 10.2% (SC) and tiger (5.6% TC and 6% SC) sharks (Table 1).

The majority of hook timers were activated when the hook was fishing on the bottom (82.2%), 17.8% were activated with the fishing gear was being retrieved and no timers were activated while the hooks were being set. Hook timers were not always tripped when bitten (15.9%) and 36.5% of all tripped hook timers were retrieved with no animals attached to the hook. Several species of sharks including the Atlantic sharpnose, bonnethead (*Sphyrna tiburo*), silky (*Carcharhinus falciformis*), tiger and blacknose, sometimes had difficulties tripping the hook timer after biting the hook (Table 1), which could have been due to their smaller size (<100 cm FL) than other species caught. The remaining species were able to trip the hook timers at least ninety percent of the time (Table 1).

The CPUE at temperature and depth varied between species. The sandbar and Atlantic sharpnose sharks were caught in the widest temperature ranges and the blacknose shark was caught in the narrowest (Table 2). The sandbar shark was the only species caught in water temperatures ranging from <16 °C, although only a few were caught in this temperature range (Table 2). Sandbar and blacknose sharks were most commonly caught in water temperatures from 21 to 24 °C, while blacktip and Atlantic sharpnose sharks were most commonly caught in temperatures ranging from 25 to 28 °C (Table 2). The tiger shark was caught in colder waters, from 17 to 20 °C (Table 2). All of the most commonly caught species except for the sandbar shark were represented in the catch from all depth ranges (Table 2). The sandbar shark was never caught at depths of 0–20 m but was caught at depths of over 60 m (Table 2). The blacktip shark was also most commonly caught in water deeper than 60 m (Table 2). Tiger, blacknose and Atlantic sharpnose sharks were more frequently caught in water ranging from 41 to 60 m deep (Table 2).

Of the most commonly caught species with at-vessel mortality, the Atlantic sharpnose (91%) and blacktip (85%) sharks had the highest overall mortality rates and the bull shark (15%) had the lowest. Blacknose sharks also had a high overall mortality rate of 77% but the sandbar shark had a minimal overall mortality rate of 21%. Predicted logistic models indicated mortality rates increased steadily for sandbar, blacktip and blacknose sharks but rates increased the most after 10, 6, and 1 h for sandbar, blacktip and blacknose sharks, respectively (Fig. 1a–c). The final logistic model included hook time and size for sandbar shark (AIC = 352) but only hook time for blacknose (AIC = 32) and blacktip sharks (AIC = 92) (Table 3). Sandbar sharks larger than approximately 170 cm FL were most susceptible to hooking mortality (Fig. 1a). No factors affected the mortality of bull sharks.

The probability of a hook being bitten increased the most between 5 and 12 h after the fishing gear had been set (for all species) (Fig. 2a–d). For all species, the inflection points occurred at 8 h for species (Fig. 2a–d). The mean amount of time hooks were in the water prior to being bitten was 4 h for sandbar and blacknose sharks, 5 h for blacktip sharks and 9 h for bull sharks. There was a significant difference between these means for sandbar and bull sharks ($F = 1.82$, $P = 0.0009$) and between blacknose and bull sharks ($F = 1.89$, $P = 0.0167$).

4. Discussion

This is the first study of the U.S. shark bottom longline fishery that determined the amount of time individual sharks spent caught on a hook and what impact that amount of time had on mortality. Previous studies (Morgan and Burgess, 2007) using data collected by on-observers from this fishery have only been able to correlate fishing gear soak time (total amount of time fishing gear was in the water) with mortality. Our results indicate a positive relationship

Table 2
The number of animals caught by hook hour and the catch per unit effort (CPUE) (number of sharks per 10,000 hook hours) by temperature and depth for five species of shark commonly caught during bottom longline sets made from 2005 to 2007.

Depth	Number caught	Hook hours	Catch per unit effort (CPUE)	Temperature	Number caught	Hook hours	Catch per unit effort (CPUE)
Sandbar, *Carcharhinus plumbeus*							
0–20	0	28,216	0	0–16	5	3,920	12.8
21–40	104	25,646	40.6	17–20	32	7,370	43.4
41–60	116	29,675	39.1	21–24	255	50,873	50.1
>60	133	29,554	45.0	25–28	61	49,638	12.3
				>29	0	1,293	0
Atlantic sharpnose, *Rhizoprionodon terraenovae*							
0–20	49	28,216	17.4	0–16	0	3,920	0
21–40	13	25,646	5.1	17–20	1	7,370	1.4
41–60	43	29,675	14.5	21–24	38	50,873	7.5
>60	13	29,554	4.4	25–28	78	49,638	15.7
				>29	1	1,293	7.7
Blacktip, *Carcharhinus limbatus*							
0–20	41	28,216	14.5	0–16	0	3,920	0
21–40	18	25,646	7.0	17–20	1	7,370	1.4
41–60	15	29,675	5.1	21–24	29	50,873	5.7
>60	91	29,554	30.8	25–28	135	49,638	27.2
				>29	0	1,293	0
Tiger, *Galeocerdo cuvier*							
0–20	3	28,216	1.1	0–16	0	3,920	0
21–40	8	25,646	3.1	17–20	13	7,370	17.6
41–60	33	29,675	11.1	21–24	38	50,873	7.5
>60	28	29,554	9.5	25–28	21	49,638	4.2
				>29	0	1,293	0
Blacknose, *Carcharhinus acronotus*							
0–20	15	28,216	5.3	0–16	0	3,920	0
21–40	10	25,646	3.9	17–20	0	7,370	0
41–60	34	29,675	11.5	21–24	35	50,873	6.9
>60	6	29,554	2.0	25–28	30	49,638	6.0
				>29	0	1,293	0

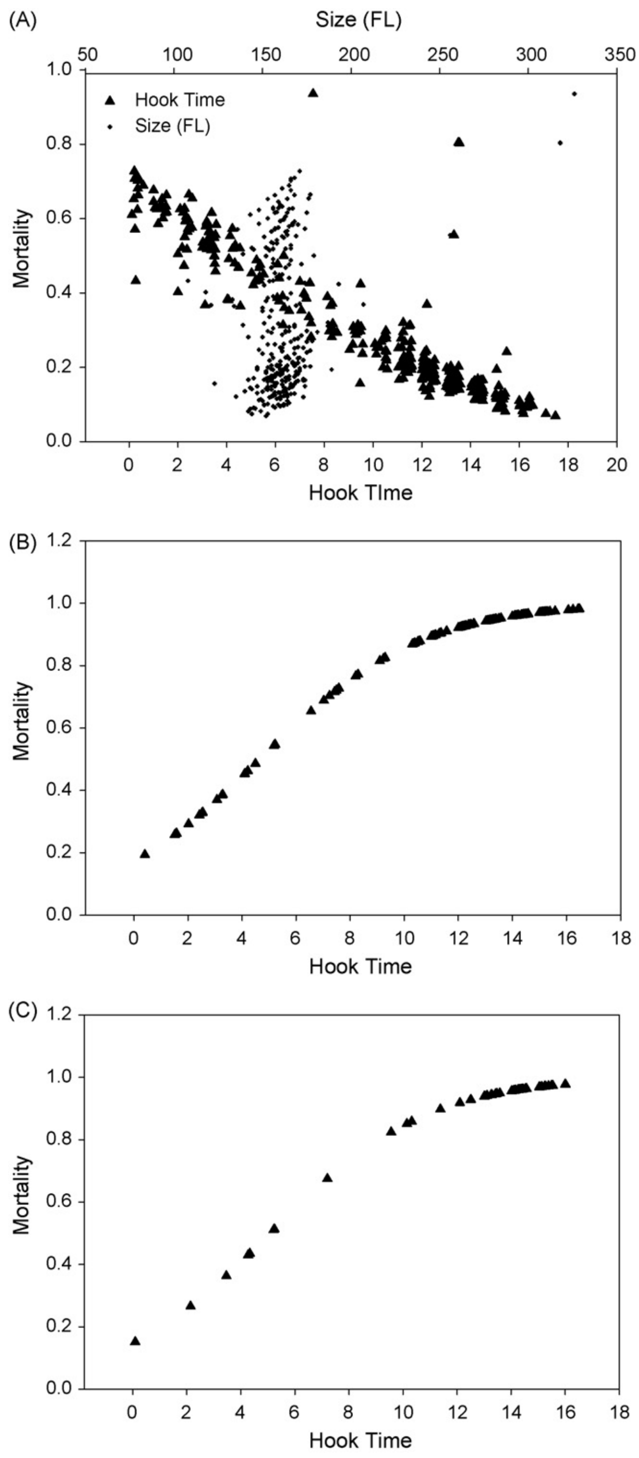

Fig. 1. (a–c) Logistic regression predictive models for the factors affecting mortality (hook time and size) for the (a) sandbar, (b) blacktip and (c) blacknose sharks.

between hook time, size and mortality for the sandbar sharks and a positive relationship between hook time and mortality for the blacktip and blacknose sharks. We did not find any relationship between mortality and hook time, size, temperature or depth for bull sharks.

Research has previously shown that soak time (Diaz and Serafy, 2005; Morgan and Burgess, 2007) can affect mortality rates of sharks. Soak time, and more specifically actual time on a hook, is an important factor in mortality rates for many species of carcharhinid sharks because many species rely on ram ventilation to force oxygenated water over their gills (Carlson et al., 2004). These species must be able to either increase their swimming speed or mouth gape in order to compensate for the decrease in available oxygen, due to capture on a longline. Morgan and Burgess (2007) suggested that it would be difficult for sharks to increase their swimming speed while hooked on a longline in order to compensate for loss of oxygen.

Table 3
Summary results for logistic regressions for *Carcharhinus plumbeus, C. limbatus* and *C. acronotus* sharks, including, final variables, degrees of freedom (DF), parameter estimates, standard error (SE), Wald Chi-square and *P*-value.

Variable	DF	Parameter estimate	SE	Wald Chi-square	*P*-value
Sandbar					
Intercept	1	−9.5	1.9	24.8	<0.0001
Hook time	1	0.2	0.06	17.7	<0.0001
Size	1	0.03	0.01	8.3	0.004
Blacktip					
Intercept	1	−1.6	0.6	6.2	0.0125
Hook time	1	0.3	0.06	28.8	<0.0001
Blacknose					
Intercept	1	−1.8	1.1	2.6	0.1090
Hook time	1	0.3	0.1	10.5	0.0012

Size has previously been shown to be an important component of mortality in various fisheries including the bottom longline fishery but results have varied. Studies have shown the mortality of longline-caught Atlantic cod (*Gadus morhua*) and halibut (*Hippoglossus hippoglossus*) was highest at small sizes (Neilson et al., 1989; Sangster et al., 1996; Milliken et al., 1999). Diaz and Serafy (2005) showed the proportion of blue sharks (*Prionace glauca*) caught on longline gear and released alive increased with size. In our study, sandbar shark mortality increased with size, which contradicts results of Morgan and Burgess (2007). Differences in results are likely due to Morgan and Burgess (2007) relying on total soak time for their analysis, rather than the actual time on hook. However, why sandbar shark mortality increased with increasing size is still unknown. Larger sandbar sharks may struggle more when caught on longline gear, which could increase blood lactate levels and consequently increase mortality. Bigger sandbar sharks, having a larger gape, could also be more susceptible to being hooked in the alimentary canal rather than the mouth which has been shown to increase mortality (Yokota et al., 2006). Future studies could investigate these hypotheses with comparisons among other species.

The 1999 Federal management plan (FMP) for Atlantic Tunas, Swordfishes, and Sharks (NMFS, 1999), proposed a minimum size limit of 137 cm fork length for large coastal sharks, including sandbar shark in all shark fisheries. However, this management measure was not implemented because of the lack of information on how soak time affect mortality rates of sharks. The increasing mortality rate with size found for sandbar sharks supports this management recommendation. The logistic model predicted at 170 cm FL mortality increased.

The probability of a hook being bitten for sandbar, blacktip, blacknose and bull sharks, increased the most from 5 to 12 h after a set had been made, although the mean hooking time was between 4 and 5 h (except for the bull shark). This could be due to a decrease in the odor concentration of the bait over time (Sigler, 2000) or due to differences in the baits used in this study. Somerton and Kikkawa (1995), using hook timers and time depth recorder data, also showed catch rates for the pelagic armorhead increased over time to a maximum, at which point catch rates began to decrease, suggesting that limitations on soak time would not adversely affect the fishery.

The large percentage of hook timers that were tripped but were retrieved without a fish attached were probably a result of either:

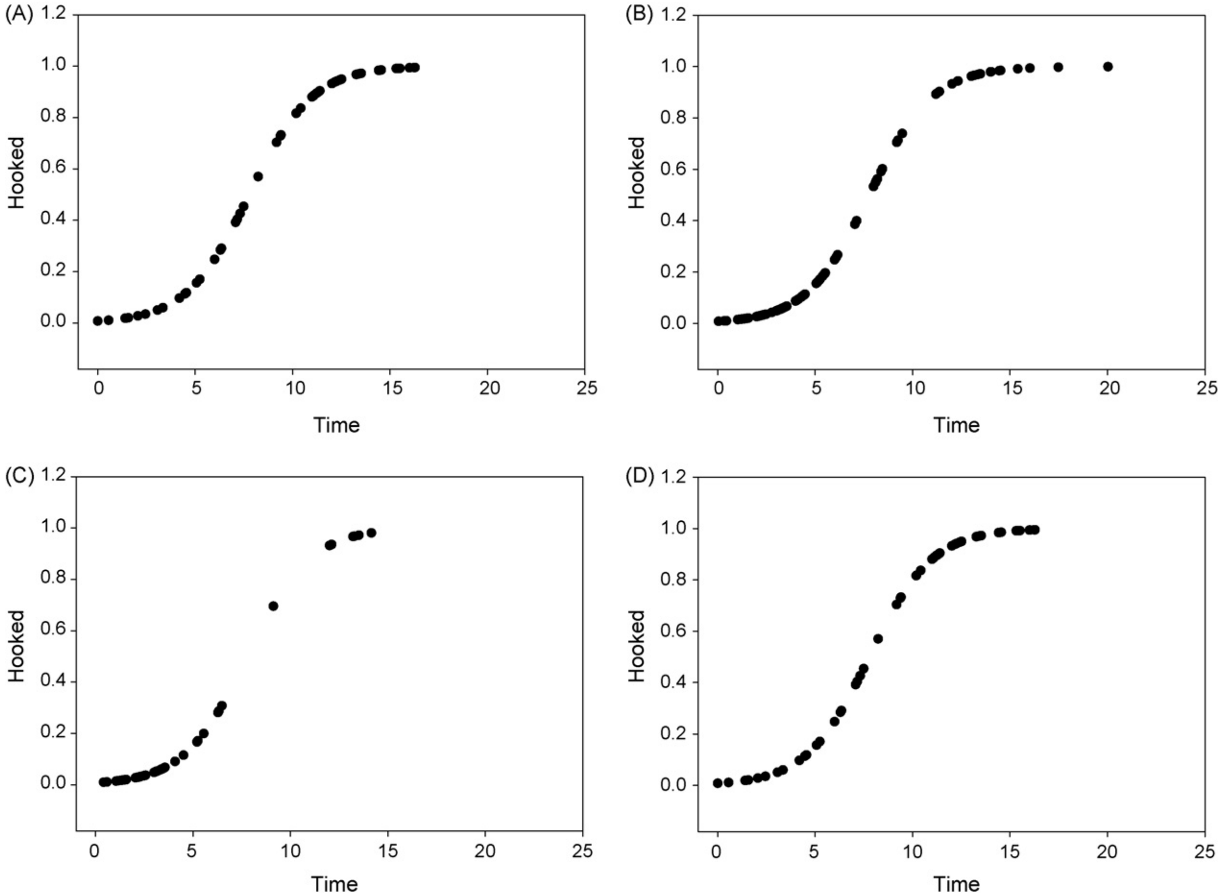

Fig. 2. (a–d) Logistic regression models predicting a hooking event based on time in the water for (a) sandbar, (b) blacktip, (c) blacknose and (d) bull sharks.

(1) sharks and/or fish removing the bait without being captured, (2) large sharks escaping the hook after capture or (3) the hook being caught on the sea floor bottom and activated. This information is of importance to fishermen because it indicates that a large percentage of their catch may be lost during the fishing process. It may be of interest to fishermen and managers to further investigate the reasons for this.

Hook timers were most often activated while the gear was on the bottom because the mainline used in bottom longline fishing is weighted and sinks very quickly, allowing little time for fish to be attracted to and bite the baited hooks. There were hook timers that were tripped while the gear was being retrieved. However, it was impossible to determine whether the fish were actually biting the hook for the first time as it was being retrieved or whether they were already hooked but did not trip the hook timer until the gear was hauled on board. The vessels used mechanical winches to retrieve the gear and it is very possible and likely that for less active species such as the nurse shark, this forceful pulling action caused the hook timers to be activated.

Our results show that mortality rates for several species of sharks increased with increased time on the hook, that size was a contributing factor and that the probability of a hook being bitten increased from 5 to 12 h after hooks entered the water. We also found that individual species were commonly caught at different temperature and depth ranges. These results can be used by fisheries managers to implement restrictions of fishing depth, soak time and size without significantly affecting the targeted catch. Research into the physiological effects of bottom longline capture, hooking location and behavioral observations after capture on bottom longline gear could provide additional information on the effects of fishing on mortality rates for bottom longline caught sharks.

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