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Hooking mortality of scalloped hammerhead *Sphyrna lewini* and great hammerhead *Sphyrna mokarran* sharks caught on bottom longlines§

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The scalloped hammerhead *Sphyrna lewini* and the great hammerhead *S. mokarran* are typically caught as bycatch in a variety of fisheries and are listed as globally Endangered by the International Union for the Conservation of Nature. Due to very high at-vessel mortality for these species, research is needed on fishing methods to reduce mortality for longline-captured sharks. A series of fishing experiments were conducted employing hook timers and temperature–depth recorders on contracted commercial vessels fishing with bottom-longline gear to assess factors related to mortality. A total of 273 sets were deployed with 54 485 hook timers. Scalloped and great hammerheads had at-vessel mortality rates of 62.9% and 56.0%, respectively. Median hooking times for scalloped and great hammerheads were 3.5 h and 3.4 h, respectively, and 50% mortality was predicted at 3.5 h and 3.8 h. When these data are considered for potential management strategies to reduce the mortality of hammerhead sharks, a limitation on gear soak time would probably improve hammerhead shark survivorship. However, it may prove to be difficult for a fishery to remain economically viable if the soak time is limited to less than the median hooking time for the target species. Additional management options, such as time/area closures, may need to be explored to reduce bycatch mortality of scalloped and great hammerheads.

Keywords: bycatch, hook timer, logistic regression, soak time, time on the hook

Introduction

The scalloped hammerhead *Sphyrna lewini* and the great hammerhead *S. mokarran* are large, coastal and semi-pelagic sharks with a global, tropical distribution (Compagno 1984). Both species are caught as bycatch in a variety of coastal and pelagic fisheries and, although not targeted, their large fins make them economically desirable (Abercrombie et al. 2005). Recent stock assessments for the North-West Atlantic Ocean and Gulf of Mexico populations of scalloped and great hammerheads indicate that their populations have declined significantly from historic, unfished levels. Hayes et al. (2009) concluded that the North-West Atlantic and Gulf of Mexico scalloped hammerhead population has been depleted by approximately 83% since 1981. Jiao et al. (2011) found that the great hammerhead shark population, of the same region, likely became overfished in the mid-1980s and experienced overfishing periodically from 1983 to 1997. Globally, the International Union for the Conservation of Nature (IUCN) Red List assessments for scalloped and great hammerheads classify both of these species as Endangered (Baum et al. 2007; Denham et al. 2007). In 2013, and in terms of the US Endangered Species Act, the East Atlantic and Pacific distinct populations of the scalloped hammerhead were listed as Endangered and those of the Central and South-West Atlantic and Indo-West Pacific as Threatened (USA 2014).

In order to reduce levels of fishing mortality and aid in the recovery of the populations, management measures could include reduced quotas or a prohibition on landings of scalloped and great hammerheads. However, such management measures might not be sufficiently effective for longline fisheries because hammerhead sharks suffer high hooking mortality. Data collected by onboard observers in the USA shark bottom-longline fishery for the period 1994–2005 indicate that 70–95% of scalloped hammerheads and 86–90% of great hammerheads are dead prior to being landed on the fishing vessel, depending on the gear soak time (Morgan and Burgess 2007). Hammerhead sharks are caught as secondary species and hence a prohibition on landings would not necessarily reduce their mortality, because they would continue to be caught by fishers targeting other sharks and most would be brought to the vessel dead. Thus, research on alternate fishing practices is necessary to be able to provide advice to managers on possible methods to reduce the mortality of hammerhead sharks.

Although there are some species-specific data concerning the correlation between soak time and fishing mortality (Morgan and Carlson 2010; Gallagher et al. 2014), there are no data available on how soak time and gear depth affect mortality rates of hammerhead sharks caught on bottom-longline gear. Management measures such as

§ This article is based on a paper presented at the ‘Sharks International 2014’ conference, held 2–6 June 2014, Durban, South Africa, and is part of a special issue ‘Advances in Shark Research’ edited by DA Ebert, C Huveneers and SFJ Dudley reduced soak time and restrictions on gear characteristics and fishing depth could reduce mortality of hammerhead sharks and allow for the live release of unwanted species. Here, we report on the effect of a variety of fishing and environmental factors that influence the mortality rate of scalloped and great hammerheads.

Material and methods

A series of fishing experiments employing bottom longlines were conducted on contracted commercial fishing vessels and participants in the US Highly Migratory Species Shark Research Fishery. Monofilament or steel cable mainline was weighted to the seafloor and baited gangions were attached at regular intervals using the technique common to the USA coastal shark fishery (Morgan et al. 2009). A gangion consisted of a hook crimped to monofilament line of between 1.2 and 4.6 m in length that was crimped to a longline snap with a built-in swivel. Hook timers (LP HT-600) were attached between the gangions and the mainline. Hook timers are triggered once the necessary amount of force is applied to the hook. A magnet is pulled away from the reed switch and the unit is activated. The amount of time elapsed since the magnet was removed is displayed on an LCD screen on the hook timer in one-minute increments.

Temperature–depth recorders (TDRs; Lotek LAT1100) were also attached at the beginning, middle and end of the mainline. The TDR records temperature and depth (pressure) every 2 min and is capable of logging data for up to 30 continuous days.

Onboard biologists recorded fishing-gear characteristics (e.g. mainline type, gangion length, etc.), set/haul data (e.g. date, time and GPS coordinates of gear deployment and retrieval, number of hooks, type of bait, etc.), and catch data. The catch data included the time the animal was brought alongside the vessel, the time displayed on the activated hook timer, hook type, hook location, species identity, disposition, size, sex, and fate of the specimen. Once the data were recorded for a given animal, the magnet was reapplied to the reed switch to zero the timer, effectively making it ready for the next deployment. Temperature–depth recorder data were downloaded, using a serial communication device and laptop computer, after each monitored trip.

Catch per unit effort (CPUE) was defined as the number of sharks caught per 1 000 hook hours. The CPUE was calculated for each set and then averaged by depth stratum and temperature. Soak time was estimated from the difference between median set time and median haul time.

Logistic regression was applied using a binomial generalised linear model (GLM) to predict hooking time for hammerhead species. Each hooking event derived the amount of time before hooking (0) and the amount of time on the hook (1). Two binomial GLMs of shark mortality (Alive-0/Dead-1) were fitted for each species. The first model included only time on the hook and the second attempted to isolate one of the other predictors of shark mortality. The variables depth, bottom temperature, size (fork length), sex, hook type, bait type, gangion length, and weight on the mainline (kg km^{-1}) were included individually

Table 1: Candidate factors hypothesized to affect mortality rates of scalloped and great hammerheads caught on bottom-longline gear

Variable	Type	Description
Soak time	Continuous	Time (h) from when the hook entered the water until the hook was hauled back
Size	Continuous	Fork length of captured shark (cm)
Temperature	Continuous	Mean bottom temperature of the set (°C)
Sex	Categorical	Male or female
Depth	Continuous	Mean depth of the set (m)
Hook type	Categorical	Circle hook (size 16/0) Circle hook (size 18/0) Circle hook (size 20/0) J hook (size 12/0)
Bait type	Categorical	Eel fresh Eel frozen Teleost fresh Teleost frozen Elasmobranch fresh Elasmobranch frozen
Gangion length	Continuous	Length of gangion used (cm)
Weight on mainline	Continuous	Anchored weight on longline (kg km^{-1})

with time on the hook in the bivariate model (Table 1). The final form of the second model was chosen based on statistical significance ($p < 0.10$) and Akaike's information criterion (AIC; Akaike 1973). Goodness-of-fit was assessed for each model using the Hosmer and Lemeshow test (Hosmer and Lemeshow 2000). All analysis was conducted using the R statistical package (R Development Core Team 2008). Logistic curves were plotted using the 'popbio' package (Stubben and Milligan 2007) and the 'resource selection' package (Lele et al. 2013) was used to assess goodness-of-fit.

Results

In total, 273 longline sets were made between June 2010 and December 2013 in coastal waters off the south-east of the USA for a total of 479 648.9 hook hours (Figure 1). In general, soak times varied from 1.5 to 22.6 h (mean = 9.4 h; SD 5.8), the mainline length averaged 7.2 km (0.9–22.2 km; SD 4.0) and number of hook timers used per set ranged from 10 to 601 (mean = 199 per set; SD 188).

Among captured sharks, the sandbar shark *Carcharhinus plumbeus* was the most commonly caught species (26.8%; Table 2). Scalloped and great hammerhead sharks made up 5.0% and 2.2% of total catch respectively. Hook timer activation was high for most species (>80%), but three species exhibited low activation rates. The Atlantic sharpnose *Rhizoprionodon terraenovae*, the blacknose *Carcharhinus acronotus* and silky *Carcharhinus falciformis* sharks activated less than 50% of hook timers (Table 2).

At-vessel mortality rates varied by species. The Atlantic sharpnose shark and spinner shark *Carcharhinus brevipinna* exhibited the highest at-vessel mortality. Scalloped and great hammerheads had an at-vessel mortality of 62.9% and

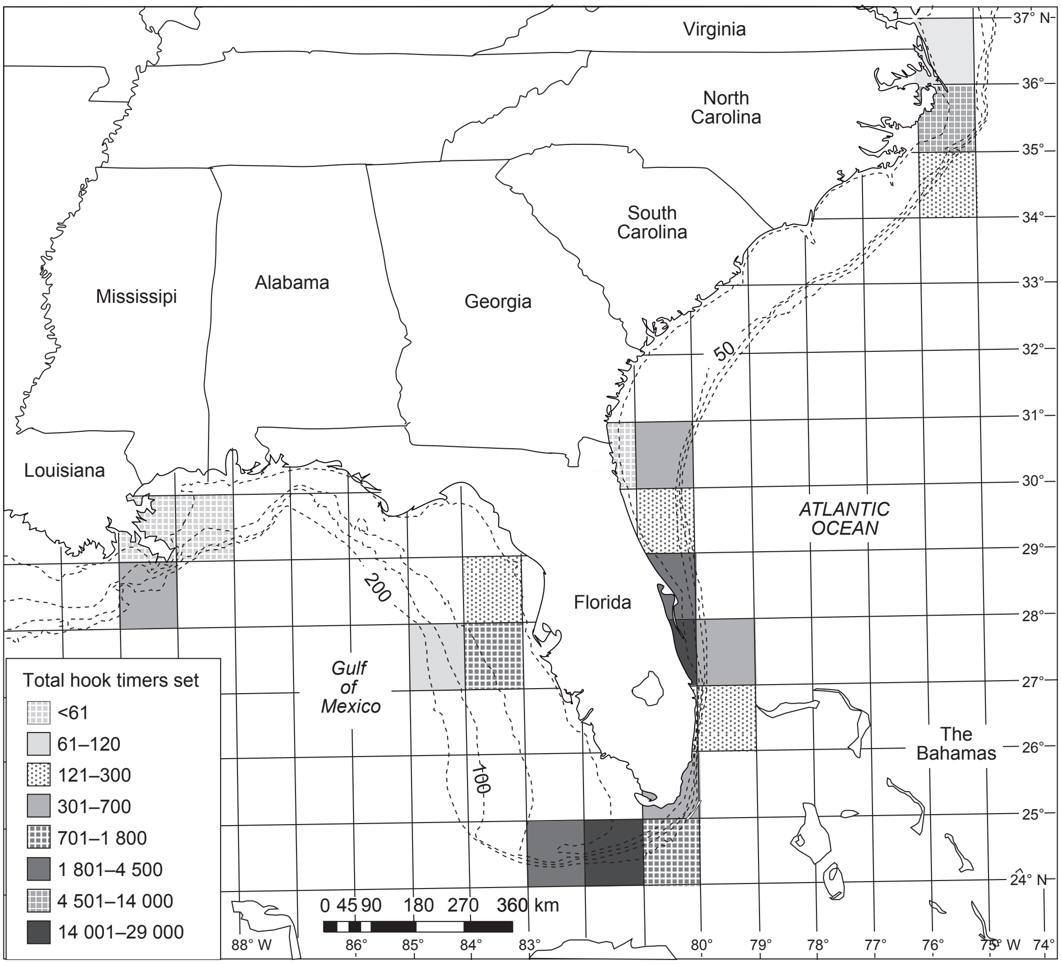

Figure 1: Locations of the longline sets off the coast of the south-eastern United States, displayed as the number of hook timers used per 1° square

Table 2: The number and percentage of activated hook timers, percentage of total catch, and percentage at-vessel mortality for each individual species caught on bottom-longline sets between June 2010 and December 2013. Data for species that were <0.3% of total catch have been omitted

Scientific name	Common name	Number of timers activated	Activated (%)	Total catch (%)	Percentage at-vessel mortality
Carcharhinus plumbeus	Sandbar shark	835	89.5	26.8	16.9
Rhizoprionodon terraenovae	Atlantic sharpnose shark	348	38.6	25.9	89.4
Ginglymostoma cirratum	Nurse shark	284	91.3	8.9	0.3
Carcharhinus limbatus	Blacktip shark	265	88.0	8.6	70.8
Galeocerdo cuvier	Tiger shark	215	79.6	7.7	8.9
Sphyrna lewini	Scalloped hammerhead shark	164	93.7	5.0	62.9
Carcharhinus leucas	Bull shark	107	87.7	3.5	2.5
Carcharhinus acronotus	Blacknose shark	75	68.2	3.2	66.4
Carcharhinus obscurus	Dusky shark	98	94.2	3.0	70.2
Sphyrna mokarran	Great hammerhead shark	71	94.7	2.2	56.0
Carcharhinus falciformis	Silky shark	16	45.7	1.0	57.1
Carcharhinus brevipinna	Spinner shark	27	84.4	0.9	81.3
Negaprion brevirostris	Lemon shark	21	87.5	0.7	4.2
Carcharias taurus	Sand tiger shark	13	100.0	0.4	0.0

56.0% respectively. The sand tiger shark *Carcharias taurus*, while caught in low numbers (n = 13), had a zero at-vessel mortality rate.

Catch per unit effort for hammerhead species varied with depth and bottom temperature (Table 3a, b). Few scalloped hammerheads were caught in shallow water (0–20 m), but

Table 3: The number of animals caught and the catch per unit effort (CPUE; number of sharks per 1 000 hook hours) (a) by depth and (b) by temperature for two species of hammerhead caught on hook timers between June 2010 and December 2013. Bottom temperature readings that were not available are marked n/a

(a) Depth (m)	Hook hours	Scalloped hammerhead *Sphyrna lewini*		Great hammerhead *Sphyrna mokarran*	
		n	CPUE	*n*	CPUE
0–20	164 117.4	4	0.078	28	0.397
21–40	171 528.8	58	0.660	13	0.106
41–60	76 358.7	46	2.676	16	1.084
61–80	37 761.6	29	0.869	12	0.293
81–100	17 429.5	22	1.696	5	0.208
>100	12 452.9	16	1.064	1	0.114
(b) Temperature (°C)					
8–12	10 686.3	9	0.992	0	0
12–16	8 292.8	13	1.265	0	0
16–20	85 084.9	44	1.649	1	0.022
20–24	141 943.3	89	1.379	35	0.865
24–28	153 457.9	8	0.357	32	0.458
28–32	19 035.8	0	0	0	0
n/a	61 147.9	12	0.487	7	0.098

African Journal of Marine Science 2015.37:267-273.

the majority of great hammerheads were encountered in this depth stratum (Table 3a). No great hammerheads were caught in temperatures <16 °C whereas scalloped hammerheads displayed a wider temperature tolerance, with captures in the range 8–28 °C (Table 3b). Neither hammerhead species was caught above 28 °C.

Median hooking times were 3.5 h and 3.4 h for scalloped and great hammerheads respectively (Figure 2; Table 4a). Logistic regression predicted 50% mortality at 3.5 h and 3.8 h for scalloped and great hammerhead sharks respectively (Figure 3; Table 4b). The final logistic model for predicting a mortality event included covariates time on the hook and depth for scalloped hammerheads (AIC = 133.8), and time on the hook and gangion length for great hammerheads (AIC = 35.2) (Table 4c). Goodness-of-fit was high for five of the six models (Hosmer and Lemeshow test; $p > 0.20$); the fit was reasonable for the scalloped hammerhead hooking time model ($p = 0.015$).

Discussion

Scalloped and great hammerheads have among the highest mortality rates of sharks caught in bottom-longline gear. Morgan and Burgess (2007) reported similar rates for hammerhead sharks brought to the vessel-side. Afonso et al. (2011) reported 100% mortality for scalloped hammerheads in bottom-longline fishing experiments off Brazil. Whereas at-vessel mortality for each hammerhead species in this study was lower than those reported in previous studies (Morgan and Burgess 2007), this may have been a consequence of shorter average soak times. Fishery observers also reported lower mortality of scalloped hammerheads associated with shorter soak times (mean =

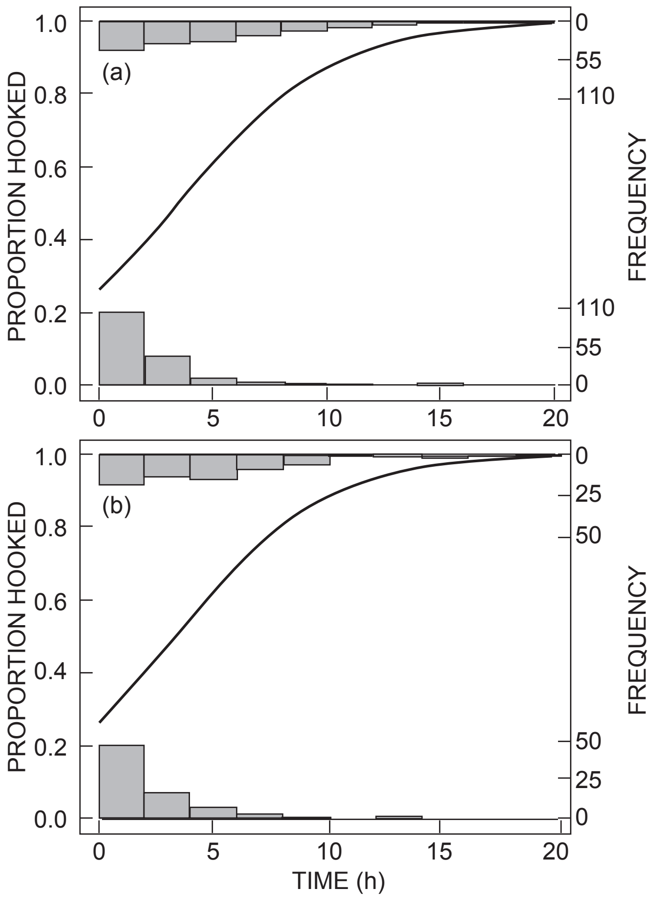

Figure 2: Logistic regression predictive models for the effect of time on the proportion hooked for (a) scalloped hammerheads and (b) great hammerheads. The lower grey bars represent the frequency of time before a shark was hooked and the upper bars the amount of time a shark was on the hook. Model details are provided in Table 4a

5.1 h) in the reef-fish bottom-longline fishery in the Gulf of Mexico (Scott-Denton et al. 2011). Soak time (Diaz and Serafy 2005; Morgan and Burgess 2007) and, more specifically, time on the hook (Morgan and Carlson 2010) have been demonstrated to affect mortality rates of sharks. Sphyrnid and many carcharhinid sharks are reliant upon ram ventilation (Carlson et al. 2004). However, we hypothesise that as hammerhead sharks have a smaller gape relative to their body size (JKC unpublished data) this may limit the volume of water entering the mouth and flowing over the gills. Thus, captured hammerhead sharks may need to expend more energy to force oxygen over their gills, leading to increased stress levels and eventual mortality. Moreover, a recent study of five coastal shark species identified the great hammerhead as the most vulnerable to fishing capture stress, with this species exhibiting the highest lactate levels (Gallagher et al. 2014).

Catch rates of sharks caught using hook timers in this study were comparable to those reported by Morgan and Carlson (2010). In both studies, scalloped and great hammerheads constituted <5% of the total catch. Similarly, failure to activate hook timers by Atlantic sharpnose shark, blacknose and silky shark was also found by Morgan and

Table 4: Results for logistic regressions of (a) hooking time, (b) hooking mortality (simple model) and (c) hooking mortality (final model) for two species of hammerhead shark

Variable	Parameter estimate	SE	Wald Chi-square	*p*
(a) Hooking time				
Scalloped hammerhead *Sphyrna lewini*				
Intercept	–1.010	0.186	–5.430	<0.0001
Hooking time	0.292	0.047	6.274	<0.0001
Great hammerhead *Sphyrna mokarran*				
Intercept	–0.956	0.289	–3.303	0.0010
Hooking time	0.294	0.076	3.858	0.0001
(b) Hooking mortality (simple model)				
Scalloped hammerhead *Sphyrna lewini*				
Intercept	–2.377	0.443	–5.365	<0.0001
Hooking time	0.682	0.113	6.039	<0.0001
Great hammerhead *Sphyrna mokarran*				
Intercept	–5.513	1.517	–3.635	<0.0001
Hooking time	1.460	0.384	3.800	0.0001
(c) Hooking mortality (final model)				
Scalloped hammerhead *Sphyrna lewini*				
Intercept	–3.595	0.830	–4.330	<0.0001
Hooking time	0.742	0.121	6.142	<0.0001
Depth	0.016	0.009	1.832	0.0670
Great hammerhead *Sphyrna mokarran*				
Intercept	–17.715	7.054	–2.511	0.0120
Hooking time	1.844	0.524	3.518	0.0004
Gangion length	5.404	2.830	1.910	0.0562

Carlson (2010), likely due to their smaller size (<102 cm fork length) and their inability to exert sufficient force on the hook.

Median hooking time for hammerhead sharks was less than that for other longline-caught sharks. For example, Morgan and Carlson (2010) found median hooking times of 7–9 h for sandbar, blacknose, blacktip *Carcharhinus limbatus* and bull *Carcharhinus leucas* sharks. The shorter hooking times for hammerheads may be related to their ability to detect prey more rapidly than other sharks. Hammerhead sharks possess a dorso-ventrally compressed and laterally expanded neurocranium (cephalofoil) that increases the spacing between the nares and improves the swath of sampled seawater (Kajiura et al. 2005). This enhanced sensory system allows hammerheads to locate buried, benthic prey and may predispose these species to detect the odorant plumes of bottom-longline baits more efficiently than other sharks.

Hooking mortality was influenced by both time on the hook and fishing depth for scalloped hammerheads. Logistic models predicted a mortality of 50% in <4 h, which is a shorter period than has been observed in other coastal species. For example, the comparative figure for blacktip and blacknose sharks is 4–6 h (Morgan and Carlson 2010). As discussed above, hammerhead sharks may need to expend more energy to ventilate, thus increasing mortality in hooked animals. With regard to depth, although oxygen becomes more soluble at greater depths and lower temperatures, levels of oxygen can vary considerably near the sea bed, where depleting processes such as aerobic respiration and abiotic oxidation may cause anoxia.

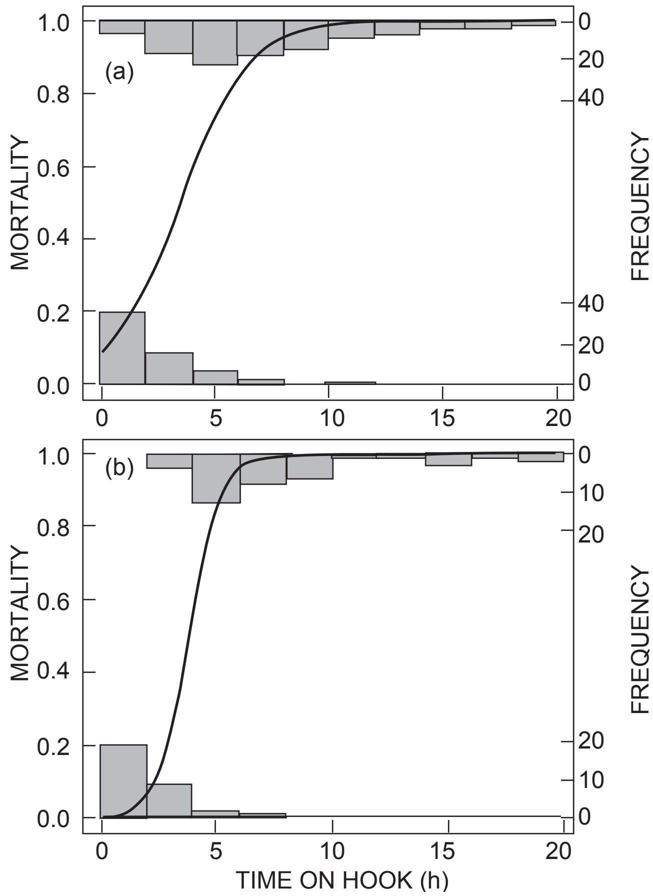

Figure 3: Logistic regression predictive models for the effect of time on the hook on mortality for (a) scalloped hammerheads and (b) great hammerheads. The lower grey bars show the number of live sharks brought to the vessel and the upper bars the number of dead sharks. Model details are provided in Table 4b

Dissolved oxygen concentrations were not measured in the current study; therefore it is unknown whether hammerhead sharks commonly utilise low-oxygen environments to locate and consume prey or whether oxygen concentrations fluctuate markedly within the soak period. Jorgensen et al. (2009) tracked a single hammerhead into the hypoxic zone in the Gulf of California for periods of up to 3 h, suggesting a certain degree of tolerance for such conditions. Seabed currents may also contribute to both the capture stress of the sharks and the rate of change in dissolved oxygen. Scalloped hammerheads have been shown to change their swimming behaviour according to current speed and direction (Klimley and Nelson 1984). When the shark is hooked and restrained at one location on the sea bed, its ability to react to strong currents or to abrupt changes in current direction may be restricted, potentially leading to increased capture stress.

Time on the hook also influenced the mortality rate of great hammerheads; however, gangion length also had a significant effect on mortality. Once a shark has been captured, it is restricted to a small, hemispherical volume of water with a radius equal to the gangion length plus the amount of give in the mainline. The give is dependent on the weight per kilometre of mainline and on other factors such as the size of the captured shark. A longer gangion should provide a larger volume of water to occupy. However, in this study, the model predicted that mortality occurs earlier when longer gangions are used. It is possible that a longer gangion would increase the potential for entanglement or would provide the hooked shark with a greater distance to run and fight the longline, thereby increasing the stress of capture. It is also possible, however, that the lower sample size for great hammerheads may have resulted in a false positive (Type I error) regarding the effect of the gangion length on shark mortality. Hence, further research is required to fully understand this relationship.

Despite some evidence that the use of circle hooks may lead to decreased mortality rates of sharks in commercial longline fisheries (e.g. Godin et al. 2012), hook type was a not-significant covariate in our final models. Circle hooks are designed to increase the likelihood of hooking a shark in the mouth or jaw, rather than in the gut, in order to reduce injury to the animal and hence decrease mortality (Cooke and Suski 2004). However, the performance of circle hooks varies, principally on account of different feeding behaviours and mouth morphologies (Cooke and Suski 2004). The cephalofoils of hammerhead sharks cause them to differ from most carcharhinid sharks in their approach to baited longlines (RD Grubbs, Florida State University Coastal and Marine Laboratory, USA, pers. comm.) and in the manner in which they feed, which may explain why hook type did not affect mortalities of hammerheads in this study.

Bottom longlines are a globally ubiquitous fishing gear for targeting a variety of species, and many bottom-longline fisheries take hammerhead sharks as bycatch (e.g. Jones et al. 2010; Afonso et al. 2011; Cartamil et al. 2011). Our data suggest that a limitation on soak time may benefit hammerhead sharks by allowing a greater proportion to be released alive. However, a balance needs to be found between bycatch reduction and fishery yield. For example, median hooking times for the two main target species in the USA shark fishery, the sandbar and blacktip shark, are approximately 5 h (SJBG and JKC unpublished data). Therefore, it may prove difficult for a fishery to remain economically viable if the soak time is limited to below the median hooking time for the target species. Hence it may not be feasible to limit soak time sufficiently to mitigate hooking mortality adequately. Consequently, further research on fishing methods is needed, and other management options, such as time/area closures, need to be explored for scalloped and great hammerheads.

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