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research paper

Characterizing loggerhead sea turtle, *Caretta caretta*, bycatch in the US shark bottom longline fishery

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ABSTRACT.—Sea turtle bycatch in longline fishing gear is an ongoing threat to the recovery of sea turtle populations. While considerable research has focused on pelagic longline fisheries, very little attention has been paid to captures of sea turtles in bottom longlines. Estimates of sea turtle takes in the shark bottom longline fishery have raised concern that this fishery may be impacting loggerhead sea turtle, *Caretta caretta* (Linnaeus, 1758), populations. However, there are no current management actions designed to reduce the bycatch of sea turtles in fisheries that target sharks using bottom longline gear because no studies have identified which factors, if any, influence the capture of a loggerhead sea turtle. We used generalized linear models to determine which factors influence the probability of loggerhead sea turtle captures in the shark bottom longline fishery, and which factors are related to at-vessel mortality. While a variety of fishing techniques were considered as factors, no particular fishing method was found to predict a capture of a sea turtle. The most significant factor in predicting the capture of a loggerhead sea turtle in shark bottom longline gear was the area fished. Soak time was found to predict at-vessel hooking mortality with the median time for a mortality to occur was 14–15 hrs. While no definitive fishing factor was identified in the capture or mortality of a loggerhead sea turtle, research is needed using controlled methods for further examining the factors affecting captures of sea turtles in this and other bottom longline fisheries.

Sea turtle bycatch in longline fishing gear is an ongoing threat to the recovery of sea turtle populations (James et al. 2005, Lewison and Crowder 2007). All six species of sea turtles found in US waters are listed as critically endangered, endangered, or vulnerable on the International Union for the Conservation of Nature (IUCN) Red List (http://www.iucnredlist.org/) and listed under the United States Endangered Species Act (ESA) as endangered or threatened with extinction. Interactions between sea turtles and longlines can occur with sea turtles either feeding directly on bait or becoming entangled with either the gangion or mainline (Witzell 1999). Sea turtle bycatch in longlines have been known to cause serious injuries and mortality, triggering mandatory mitigation measures including time and/or area closures and gear modifications (Watson et al. 2005, Parga 2012).

A growing number of studies have investigated factors affecting the capture of sea turtles in commercial fishing gear. Research has focused on trawls (Brewer et al. 1998), gill nets (Murray 2009, Gilman et al. 2010), and pelagic longlines (e.g., Watson et al. 2005, Gilman et al. 2007, Kot et al. 2010). However, while considerable research has focused on these fisheries, very little attention has been paid toward captures of sea turtles in bottom longlines.

The commercial shark bottom longline fishery is active in the US Atlantic Ocean from around North Carolina to Florida and throughout the eastern Gulf of Mexico. The fishery is active year-round, but is subject to seasonal closures based on quota limits and activity in other fisheries (e.g., some fishers switch to more profitable species during certain times of the year). Historically, vessels in this fishery target primarily large coastal shark species [e.g., sandbar shark, *Carcharhinus plumbeus* (Nardo, 1827), and blacktip shark, *Carcharhinus limbatus* (Müller and Henle, 1839)] with bottom longline gear (Hale and Carlson 2007, Morgan et al. 2009). Bottom longlines normally consist of about 8–24 km of longline mainline with weights placed at the start, middle, and end, and about 500–1500 hooks attached at intervals. The gangion length averages 2.2 m in bottom longline gear, but because of the fishing depths, sea turtles are prevented from surfacing, resulting in different, and potentially higher mortality rates than in pelagic longline fisheries. There are no current restrictions on hook usage for bottom longlines targeting sharks, and fishers will commonly use larger circle and J hooks (primarily size 18/0–20/0 for circle hooks, and 12/0–14/0 for J style hooks). Bait can vary from shark and skate to different kinds of teleosts such as little tunny, *Euthynnus alletteratus* (Rafinesque, 1810), and snake eels, *Ophichthus* spp. The longline is generally set at sunset and allowed to soak overnight before hauling back in the morning. Currently, about 198 US fishers are permitted to target sharks (excluding dogfish) in the Atlantic Ocean and Gulf of Mexico, and an additional 252 fishers are permitted to land sharks incidentally.

Estimates of sea turtle takes in the shark bottom longline fishery have raised concern that this fishery may be impacting loggerhead sea turtle, *Caretta caretta* (Linnaeus, 1758), populations. For example, in the Gulf of Mexico and northwest Atlantic Ocean, the shark bottom longline fishery incidentally captured an estimated 420 and 163 loggerhead sea turtles in 2005 and 2006, respectively (National Marine Fisheries Service 2007a, 2011). However, there are no current management actions designed to reduce the bycatch of sea turtles in fisheries that target sharks with bottom longline gear because no studies have identified which factors, if any, influence the capture of a loggerhead sea turtle. Herein, we characterize loggerhead sea turtle bycatch and evaluate environmental variables and fishing techniques associated with their capture. An understanding of factors related to the capture of this species can aid in the management of this fishery and contribute to the recovery of loggerhead sea turtle populations.

Methods

Observer Coverage.—National Marine Fisheries Service, Panama City Laboratory, currently administers the shark bottom longline observer program. Scientific observers are trained in fishery and biological data collection and sampling, and species identification. Observers are required to record catch and effort information from each longline haul during each sampled trip (a "trip" is defined as the time period between a fishing vessel's departure from port and its return to port). Vessels are selected for observer coverage based on a stratified random sampling design with quarter (1, 2, 3, 4) and region (northern Atlantic, southern Atlantic, and Gulf of Mexico) as the stratification variables (Enzenauer et al. 2015, and references therein). The sample for each stratum (quarter*region) is selected using the prior year's logbook data to estimate the total sea days by all vessels in that stratum. Based on the available funding, the approximate number of sea days to be sampled is estimated for the entire year. These sea days are then allocated to strata proportional to last year's effort. Trips are randomly selected from the list of vessels recorded from the prior year, and the vessel owners/captains are notified that trips taken this year will include an observer until a minimum number of sea days are observed.

Amendments to the Consolidated Atlantic Highly Migratory Species Fishery Management Plan implemented a shark research fishery in 2008, which allows National Marine Fisheries Service to select a limited number of commercial shark vessels on an annual basis to collect life history data and catch data for future stock assessments (National Marine Fisheries Service 2007b). Specifically, only commercial shark fishers participating in the research fishery are allowed to land sandbar sharks and must carry an observer on 100% of all trips (compared to a target coverage level of 5%–10% outside the research fishery).

Data Treatment and Analysis.—Observations of this fishery by on-board scientific observers have been conducted since 1994 by two separate monitoring programs (Morgan et al. 2009, Enzenauer et al. 2015). Prior to 2005, observer coverage was coordinated by the Florida Museum of Natural History (Morgan et al. 2009), but that program did not collect detailed information on sea turtle interactions. In addition, because of a lack of observations made on vessels in the shark research fishery with those outside the research fishery before 2008, we restricted our analysis to data collected from 2008 to 2015. Data were further refined to remove all "undefined" or "unclassified" data (e.g., multiple or unknown hook types).

We used a fixed effect generalized linear model to determine which factors influence the probability of catching a loggerhead sea turtle. While leatherback sea turtles, *Dermochelys coriacea* (Vandelli, 1761), have been observed, their low occurrence ($n = 2$) precluded any analysis. A number of factors were selected that potentially influence the catch of a sea turtle based on their assumed importance in other studies and our own hypotheses (Table 1). A combination of continuous and categorical explanatory variables included: area, latitude, season, depth, hook type, bait used, soak time, and sea surface temperature. We did not consider hook size as a factor. Shark fishers are targeting the biggest sharks and, as such, the sizes of hooks used were all large with little variability (primarily 18/0–20/0 for C hooks, and 12/0–14/0 for J style hooks). Because of the high proportion of zeros relative to the number of sea turtle interactions, a zero-inflated negative binomial distribution was assumed to account

Table 1. Candidate factors hypothesized to affect the catch of loggerhead sea turtles, *Caretta caretta,* in the shark bottom longline fishery.

Variable	Type	Description	Biological interpretation (hypothesis)
Space			
Area	Categorical	Gulf of Mexico, US south Atlantic	Some areas are more likely to have encounters owing to unmeasured characteristics
Latitude	Categorical	24°N–36°N	
Time			
Season	Categorical	Winter = October–March, Summer = April–September	Seasonal migration patterns may make sea turtles more susceptible to capture
Environment			
Sea surface temperature	Continuous		Ocean characteristics affect the dispersal and movements of sea turtles
Depth	Continuous	Mean depth of the set	
Fishery			
Hook type	Categorical	J hook, circle hook	Certain fishing characteristics can make sea turtle encounters more likely
Bait type	Categorical	Teleost (general), elasmobranch	
Scientific fishery	Categorical	Yes (a set conducted under the shark research fishery), no (a set not conducted under the shark research fishery)	
Soak	Continuous	Time (hrs) from when the last hook entered the water until the first hook was hauled back	

for the potential that there were more zeros than expected (e.g., McCracken 2004). Models were fit with a log link function and the natural logarithm of the number of hooks per set as an offset.

Factors most likely to influence the probability of capturing a sea turtle were evaluated in a forward stepwise fashion (e.g., Ortiz and Arocha 2004, Cortés et al. 2007, Brodziak and Walsh 2013). Initially, a null model was run with no factors entered into the model. Models were then fit in a stepwise forward manner adding one independent factor. Each factor was ranked from the relative greatest-to-least reduction in deviance per degree of freedom when compared to the null model:

$$\%Dev_t = 100 \times (Dev_{null} - Dev_f)/Dev_{null}$$

where $\%Dev_t$ = the percentage of reduction in deviance explained by the addition of each factor, Dev_{null} = the deviance per degree of freedom from the null model, and Dev_f =the deviance per degree of freedom due to the addition of a factor.

The factor with the greatest reduction in deviance was then incorporated into the model providing the effect was significant (P < 0.05) based on a chi-square test, and the deviance per degree of freedom was reduced by at least 1% from the less complex

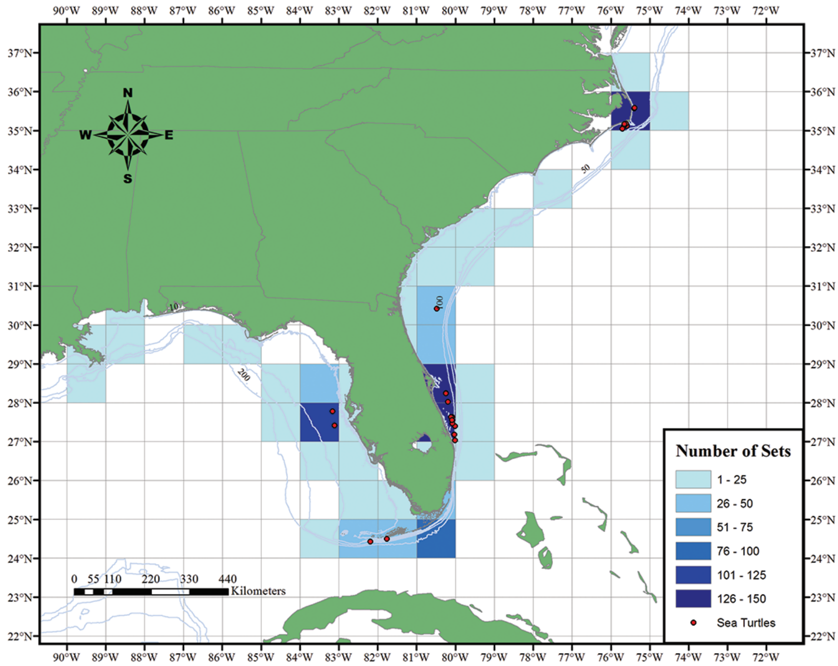

Figure 1. Distribution of observed fishing effort and locations of loggerhead sea turtle (*Caretta caretta*) interactions, 2008–2015.

model. The process was continued until no factors met the criteria for incorporation into the final model. All analysis was conducted using the SAS statistical computer software (v9.4) with the PROC GENMOD procedure.

We applied a generalized linear model of sea turtle mortality (Alive-0/Dead-1) to isolate potential predictors of at-vessel mortality. Sea turtles recorded by observers as "fresh dead" or "comatose/unresponsive" were categorized as "dead," while conditions "alive," "alive unknown (injury status unknown)", or "alive injured" were categorized as "alive." Variables hypothesized to affect at-vessel mortality included water depth, sea surface temperature, hook type, bait type, hooking location [internal (e.g., in the mouth) or external (e.g., on a flipper)], and soak time [time (hrs) from when the last hook entered the water until the first hook was hauled back]. Variables were evaluated in a forward stepwise approach as previously described.

Results

After refinement, the final data set contained a total of 791 hauls. Of those hauls, loggerhead sea turtles were observed captured in 22 hauls. Sea turtles were observed caught in all years except 2013.

Since 2008, most sea turtles were captured off the east coast of Florida, with other captures distributed off North Carolina and throughout the eastern Gulf of Mexico (Fig. 1). Loggerhead sea turtle bycatch occurred in all seasons. Observers reported loggerhead sea turtles caught in depths ranging between 18 and 78.5 m (mean = 34.9 m), and in waters with sea surface temperatures ranging between 13.3 and 30

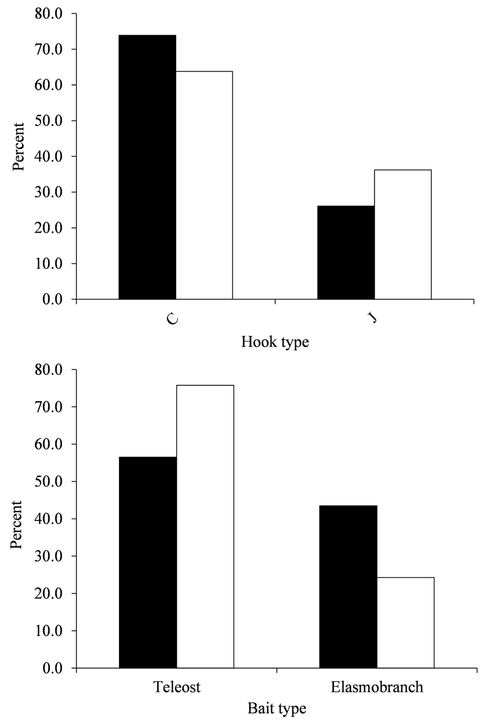

Figure 2. Percent frequency of sea turtle (*Caretta caretta*) captures by depth and sea surface temperature (solid bars). The total percent frequency of hauls by depth and sea surface temperature (open bars) by the fishery is provided as a comparison. C = circle hook, J = J hook.

°C (mean = 23.5 °C) (Fig. 2). Considering fishing operational methods, the majority of sea turtles were captured on gangions using circle hooks (77.2%), although circle hooks are currently the predominant hook type in the fishery. The predominant bait types that caught sea turtles were teleosts, but elasmobranchs also were noted in 45.4% of captures (Fig. 3).

Of the loggerhead sea turtles caught, the average size for those measured (curved carapace length from notch to tip) by observers (*n* = 4) was 77.4 cm (range = 67–87 cm). The remaining turtles captured were only estimated in carapace length (mean = approximately 96 cm). This potential size bias may be due to difficulties in boating and measuring large turtles, thus resulting in more estimated sizes for larger turtles. Among the sea turtles caught, most (59.1%) were hooked internally, while the rest were entangled in the gangion or hooked in the flipper. Observers recorded the at-vessel condition of sea turtles as 72.7% were alive [e.g., alive injured or alive unknown (injury status unknown)] and 27.3% were dead (e.g., fresh dead/comatose/unresponsive).

The most significant factor for predicting the capture of a loggerhead sea turtle was area (Table 2). Water depth and latitude were also significant factors, but when added to the model with area, these factors were no longer significant. The only significant factor affecting at-vessel mortality was soak time (Table 3). No other factor was found to influence at-vessel mortality. The predicted median soak time for an at-vessel mortality to occur was 14.6 hrs (Fig. 4).

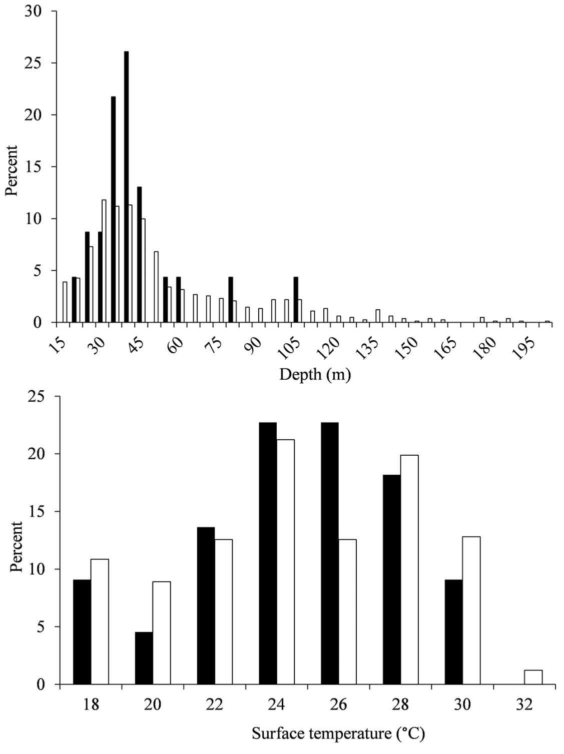

Figure 3. Percent frequency of sea turtle (*Caretta caretta*) captures by hook type and bait type (solid bars). The total percent frequency of hauls by hook size, hook type and bait type (open bars) by the fishery is provided as a comparison.

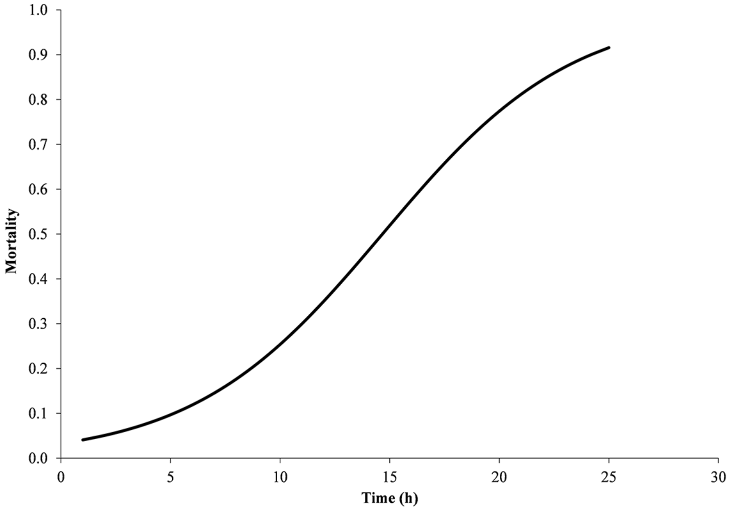

Figure 4. Predictive model for the effect of soak time on the proportion of at-vessel mortality for loggerhead sea turtles (*Caretta caretta*).

Table 2. Deviance table for the model to predict a loggerhead sea turtle, *Caretta caretta,* capture in the shark bottom longline fishery. Factors were retained in the model if they accounted for at least 1% of the total reduction in deviance and were significant according to a χ^2 test ($P < 0.05$). An asterisk indicates that the iteration limit was exceeded and the model output was questionable. n = the number of observations. ΔDev = the percentage of reduction in deviance explained by the addition of each factor (see text for details).

Factor	*n*	df	Deviance	Deviance/df	ΔDev	Chi square	*P*
Null	791	789	215.2	0.27			
Area	791	788	206.2	0.26	4.0	7.27	0.007
Latitude	791	788	210.3	0.27	2.1	5.24	0.022
Depth	791	788	210.4	0.27	2.1	3.56	0.049
Bait type	791	788	212.1	0.27	1.3	3.30	0.069
Scientific fishery	791	788	213.1	0.27	0.8	1.48	0.224
Hook type	791	788	214.0	0.27	0.4	1.08	0.298
Soak	791	788	214.5	0.27	0.2	0.80	0.372
Sea surface temperature	791	788	214.9	0.27	*	0.23	0.632
Season	791	788	215.0	0.27	*	0.16	0.693
Area + Depth	791	787	204.4	0.26	4.7	1.48	0.224
Area + Latitude	791	787	205.7	0.26	4.1	0.41	0.521

Discussion

The present study represents the first attempt to characterize sea turtle bycatch in the US shark bottom longline fishery. Much of the previous research identifying factors to reduce sea turtle interactions in hook-and-line fisheries has been conducted for pelagic longlines targeting tunas and swordfish (e.g., Watson et al. 2005, Pradhan and Leung 2006, Gilman et al. 2007). Bottom longlines are a globally ubiquitous fishing gear for targeting a variety of species, including sharks (e.g., Afonso et al. 2011, Cartamil et al. 2011, Jones et al. 2011). In addition, bottom longlines in the southeast US target reef fish and have been documented to incidentally capture loggerhead sea turtles (Scott-Denton et al. 2011). While information would not be directly comparable, patterns emerging from our study may help to shed light on factors affecting sea turtle bycatch in other bottom longline fisheries.

While a variety of fishing techniques (Table 1) were considered as factors, no particular fishing method was found to predict a capture of a sea turtle. The only significant factors in predicting the capture of a loggerhead sea turtle in shark bottom longline gear were the area fished, latitude, and the water depth. Most sea turtle interactions occurred in water depths between 20 and 40 m, but fishing effort does occur out to 200 m depth. The actual depth or duration of the interaction is not known, however, as turtles may be hooked at any point during the setting or haulback of gear. Loggerhead neretic foraging sites are typically in waters <100 m deep (Hawkes et al. 2006, 2011, Luschi et al. 2006, Broderick et al. 2007, Hart et al. 2012, Foley et al. 2014). Dive depths and duration depend on factors such as season, water depth, benthic foraging habitat, and size class. In a Florida study, loggerhead dive foraging behavior changed with most females diving to shallow depths (<15 m) in their primary residence area during summer months, and they dived to 20–40 m in secondary residence areas used primarily in winter months (Foley et al. 2014). Loggerhead dive depths and durations increased during the winter, with extended over wintering dives recorded in the range of 6–7 hrs (Hawkes et al. 2006), and a record longest

Table 3. Deviance table for the model to predict loggerhead sea turtle, *Caretta caretta,* at-vessel mortality in the shark bottom longline fishery. Factors were retained in the model if they accounted for at least 1% of the total reduction in deviance and were significant according to a χ^2 test ($P < 0.05$). An asterisk indicates that the iteration limit was exceeded and the model output was questionable. n = the number of observations. ΔDev = the percentage of reduction in deviance explained by the addition of each factor (see text for details).

Factor	*n*	df	Deviance	Deviance/df	ΔDev	Chi square	*P*
Null	22	20	25.8	1.29			
Soak	22	19	18.5	0.97	24.4	7.27	0.007
Research fishery	22	19	23.1	1.21	5.9	2.73	0.099
Season	22	19	23.5	1.24	3.9	2.25	0.133
Hook location	22	19	23.6	1.24	3.6	2.18	0.140
Hook type	22	19	25.3	1.33	*	0.50	0.479
Depth	22	19	25.3	1.33	*	0.48	0.488
Temperature	22	19	25.7	1.35	*	0.11	0.736
Bait type	22	19	25.7	1.35	*	0.07	0.793

breath-holding dive recorded for a marine vertebrate of 10.2 hrs (Broderick et al. 2007).

Gangion length in relation to the distance to the surface and soak time are critical factors in considering at-vessel mortality risk. In shallow-set pelagic longline fisheries, the gangion are long enough for an incidentally captured turtle to surface for air, resulting in low at-vessel mortality rates. However, in bottom longline fisheries, the gear is set such that gangions are not long enough to reach the surface, and at-vessel mortality can result from drowning depending on soak times. Shark fishers generally soak their gear overnight and results from the present study indicate the median soak time at which at-vessel mortality occurred was 14–15 hrs. Thus, a potential management action to reduce at-vessel sea turtle mortality would be to restrict soak times.

The majority of states from North Carolina through Texas ban longline fishing in their waters. State bans on commercial bottom longline fishing were not designed to reduce sea turtle mortality specifically, but based on results from our study, this may indirectly reduce bycatch by precluding fishing in shallower depths. In response to increased sea turtle bycatch in bottom longlines targeting shallow water reef fish in the Gulf of Mexico, an emergency rule prohibited longline fishing shoreward of the 91.4 m contour (United States Federal Register 2009). The effectiveness of this measure has yet to be determined.

The current lack of ability to predict potential areas or times of high loggerhead sea turtle bycatch limits the effectiveness of time-area closures. Even if high encounter areas are identified, time area closures may also have adverse effects. Fishing effort may shift to adjacent and potentially more sensitive areas, where no management regulations exist (Gilman 2002, Kotas et al. 2004). For example, in a case study of the effect of time-area closures to mitigate leatherback sea turtle bycatch, Senko et al. (2014) noted that relatively few leatherback turtles in the North Atlantic utilized an area closed to US pelagic longliners. Most satellite tagged animals traveled much farther distances to other non-protected areas of high pelagic longline fishery activity (James et al. 2005). In addition, during the closure of the Hawaii longline swordfish (*Xiphias gladius* Linnaeus, 1758) fishery, leatherback sea turtle bycatch was simply redistributed to other fisheries. Importation of fish products from other longline fleets, that replaced the Hawaiian swordfish fishery, exhibited considerably higher ratios of leatherback sea turtle bycatch to the capture of swordfish (Gilman et al. 2006).

Circle hooks have been generally regarded to reduce mortality of sea turtles due to their propensity for hooking in the mouth rather than in the digestive tract. However, in bottom longline fisheries where the inability to surface for air is a potential cause for at-vessel mortality, the hook type or hooking location would not be expected to influence at-vessel mortality rates. In our study, circle hooks were not a significant factor and thus would not be predicted to decrease at-vessel mortality rates of loggerhead sea turtles caught on shark bottom longlines. This result was not surprising considering that the main factor determining at-vessel mortally of sea turtles may be submergence time, which is probably not related to hook type. This finding is also consistent with some reviews of pelagic longline fisheries that suggest that circle hooks are not universally effective at reducing sea turtle mortality (Gilman et al. 2006, Read 2007). Therefore, while circle hooks may have the potential to reduce the overall mortality of sea turtles in pelagic longline fisheries, statistically robust experiments should be conducted prior to any requirement of their use (Read 2007).

We found no relationship with hooking mortality and any environmental factor or fishing practice besides soak time (Table 3). We had expected sea turtle bycatch mortality to be a function of fishing depths and soak times of bottom longline gear, but actual forced submergence time of a turtle may be the primary cause of mortality. Forced submergence times were not measured and the interaction can occur at any time or depth, including during setting or haulback of the gear. Fishing depth may not have been a significant factor because all fishing depths result in forced submergence, turtles are not thought to be able to surface and breathe in this fishery. Most of the sea turtles captured were reported alive at-vessel. Individuals that were released were reported to be in good condition, and it is reasonable to assume that those animals hooked in the digestive tract were more likely to suffer post-release mortality than externally hooked turtles (Gilman et al. 2007), particularly if there is line remaining on the hook. A study examining post-release survivorship in bottom longline caught sea turtles both released in good and poor condition is necessary to fully evaluate the impact of this fishery.

Bottom longlines targeting shark do not appear to affect sea turtle populations as much as other bottom longline fisheries. Estimates of total take (i.e., captured by the gear) in the Gulf of Mexico bottom longline fishery targeting snappers and groupers for 2006–2008 were 714.7 loggerhead sea turtles (95% confidence limits: 296.9–1720.5) (National Marine Fisheries Service 2009). While these fisheries overlap in their fishing activities in areas where loggerhead sea turtles occur, the difference in level of take among these longline fisheries may be related to bait type. Shark fishers do not normally use squid for bait unlike bottom longlines targeting reef fish, where its use is commonplace. Experiments conducted in the pelagic longline fishery found that mackerel bait significantly reduced loggerhead sea turtle bycatch over hooks that were baited with squid (Watson et al. 2005).

This broad-scale summary of sea turtle bycatch data from the shark bottom longline fisheries observer program has improved our understanding of loggerhead sea turtle–fishery interactions. However, while a number of factors were examined, no definitive factor was identified in predicting the capture or mortality of a loggerhead sea turtle. Research is clearly needed using controlled methods for reducing sea turtle bycatch, as well as a further examination of the factors affecting sea turtle capture in other bottom longline fisheries.

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