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RELATIONSHIP BETWEEN HOOK TYPE AND HOOKING LOCATION IN SEA TURTLES INCIDENTALLY CAPTURED IN THE UNITED STATES ATLANTIC PELAGIC LONGLINE FISHERY

Lesley W Stokes, Sheryan P Epperly, and Kevin J McCarthy

ABSTRACT

Because incidental capture in pelagic longline fishing gear potentially kills or injures thousands of sea turtles annually, solutions to reduce the frequency and mortality rate of these interactions are critical conservation priorities. Understanding factors that affect post-hooking mortality rates remains an important component to evaluating the population-level impact of these interactions. Post-release mortality may be dependent upon the nature of the interaction (hooking location and/or entanglement) and amount of gear remaining at release. Hooking location can impact the ability of the crew to remove gear, as deeply ingested hooks cannot be removed safely. We examined the effects of hook type (circle vs J-hooks), offset (degrees), and other factors on hooking location in leatherback, *Dermochelys coriacea* (Vandelli, 1761), and loggerhead, *Caretta caretta* (Linnaeus, 1758), sea turtles incidentally captured from 2000 to 2010 using fishery observer data. Significant differences in hooking location in loggerheads were observed between offset J-hooks and non-offset and 10° offset circle hooks; loggerheads were most often mouth/beak hooked with circle hooks, whereas most had swallowed offset J-hooks. Greater offsets appear to increase the frequency of deeply ingested hooks. Leatherback sea turtles were predominately externally hooked regardless of hook type, but mouth hookings occurred significantly more often on non-offset (0°) circle and J-hooks than on 10° offset circle hooks. When combined with outreach and education on careful release protocols, the use of circle hooks may increase post-interaction survival by modifying hooking location and facilitating maximum gear removal.

Pelagic longline fisheries target large pelagic fishes such as swordfish (*Xiphias gladius,* Linnaeus 1758), tuna (*Thunnus* spp.), and sharks (Squaliformes) in the western North Atlantic Ocean, and incidental capture of turtles is believed to be an important source of sea turtle injury and mortality. Migration patterns that include a pelagic phase transoceanic journey through the northwest Atlantic (Bolten 2003) put juvenile loggerhead [*Caretta caretta* (Linnaeus, 1758)] and leatherback [*Dermochelys coriacea* (Vandelli, 1761)] sea turtles at risk of interacting with these fisheries. Because incidental capture on pelagic longline fishing gear has the potential to kill or injure thousands of sea turtles every year (Camiñas 1997, Witzell 1999, Lewison et al. 2004, Wallace et al. 2010), solutions to reduce the severity of these interactions are critical to protecting sea turtles and fishery interests, and informing fisheries managers.

Our primary interest in the present study was to investigate factors, including hook type, bait type, geographic region, and turtle size (curved carapace length, CCL, in cm), that might influence the anatomical hooking location in loggerhead and leatherback sea turtles. We chose to focus on hooking location because of its direct impact on post-hooking survival (Ryder et al. 2006) and gear removal success (NMFS 2008) in incidentally captured sea turtles. These results may give insight into

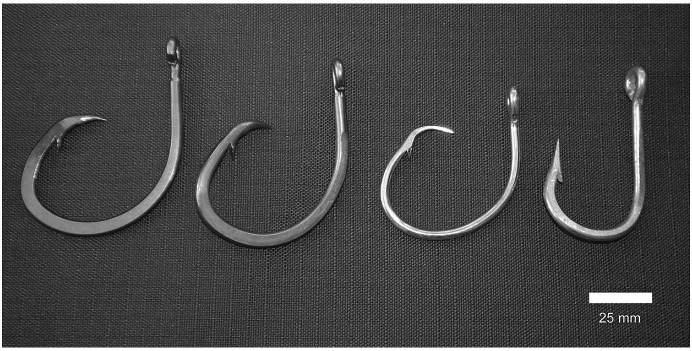

Figure 1. Circle and J-hooks as represented by a sampling of commonly used pelagic longline hooks in the United States fleet, depicted from left to right: 18/0 0° offset LP CIRBL; 18/0 10° offset LPCIRBL; 16/0 0° offset Mustad 39960D, and 9/0 20°–30° offset J-hook Mustad 76801 (no longer used by the US fleet).

the effectiveness of National Marine Fisheries Service (NMFS) regulations, which targeted a reduction in the incidence of swallowed hooks as well as reductions in total number of captures.

Pelagic longline gear consists of a mainline, approximately 10–40 mi (approximately 16–64 km) in length, on which 200–1000 baited hooks are suspended on leaders (gangions, see Watson and Kerstetter 2006 for a full description of gear used in the United States pelagic longline fleet). A variety of hook types is used worldwide, but two of the predominant categories of hook type historically found in pelagic longline fisheries are "circle hooks" and "J-hooks" (Fig. 1). In a review of longline terminal gear, Beverly and Park (2009) provide thorough details on hook anatomy, types, sizes, and offsets. Essentially, a J-hook has a barb roughly parallel to the shank of the hook, whereas a circle hook has a more circular shape with the barb perpendicular to the shank of the hook (Cooke and Suski 2004). Hook "offset" refers to the angle in degrees of the hook point relative to the shank of the hook (Fig. 2).

Circle hooks have gained popularity in some recreational fisheries, and the International Commission for the Conservation of Atlantic Tunas (ICCAT) has encouraged the use of circle hooks in Atlantic Ocean pelagic longline fisheries (Watson and Kerstetter 2006). Comparisons of circle hook and J-hook performance in sharks, billfishes, and other fish species have shown that many species of fish are more often hooked in the corner of the mouth rather than gut hooked when using circle hooks relative to J-hooks (Prince et al. 2002, Cooke and Suski 2004, Watson et al. 2005, Serafy et al. 2009, Epperly et al. 2012). Circle hooks generally rotate and set in the corner of an animal's mouth when pressure is applied to the line, preventing deep ingestion and gut hooking (Cooke and Suski 2004). Similar results have been found in incidentally captured hard-shelled sea turtles. Field studies investigating anatomical hooking location in sea turtles have demonstrated that deep ingestion occurred more often with J-hooks than with circle hooks, which were more likely to be lodged in the mouth (Watson et al. 2005, Piovano et al. 2009, Sales et al. 2010, Epperly et al. 2012).

These findings may have important implications for improving post-release survival odds. A review of anatomical hooking location in various fisheries concluded that hooking location was an important factor in determining mortality rates for several species; mortality rates were often higher with J-hooks that were deeply

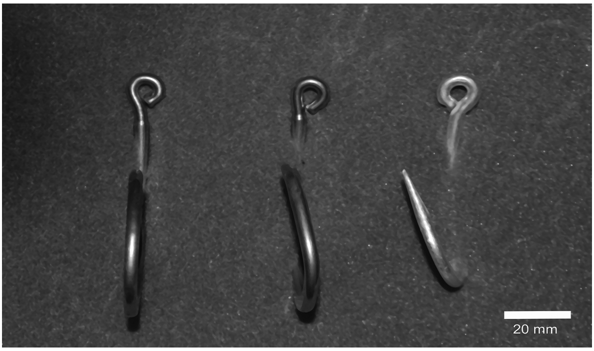

Figure 2. Hook offset (0°, 10°, and 20°–30°) as represented by a sampling of hooks models found in the data set, depicted from left to right: 18/0 0° offset LP CIRBL; 18/0 10° offset LPCIRBL; and 9/0 20°–30° offset J-hook Mustad 76801 (no longer used by the US fleet).

ingested (Bartholomew and Bohnsack 2005, Kerstetter and Graves 2006, Kerstetter et al. 2007, Prince et al. 2007, Reeves and Bruesewitz 2007, Serafy et al. 2009).

Gear modifications, such as switching from J-hooks to circle hooks, have the potential in some areas to reduce the incidence and severity of sea turtle interactions without seriously reducing target species catch (Watson et al. 2005). A significant reduction in loggerhead mortality was anticipated through the use of large non-offset or minimal offset circle hooks based on research conducted in the western North Atlantic Ocean (Watson et al. 2005) and the anticipation that more turtles would be hooked in the jaw on circle hooks relative to J-hooks (Bolten and Bjorndal 2004, Gilman et al. 2006, 2007, USDOC 2004). Regardless of hook type, loggerheads and other hard-shelled sea turtles often attempt to ingest bait, resulting in swallowed hooks (gut hooked) or hooks engaging the mouth or beak (rhampotheca, Watson et al. 2005).

Leatherback sea turtles are predominately externally hooked (foul hooked) or entangled regardless of gear type, and Watson et al. (2005) demonstrated that 18/0 circle hooks reduced the number of turtles externally hooked by pelagic longline gear. Circle hooks are expected to reduce external hooking because of the shielding effect of the hook design, as the point is turned perpendicularly back to the shank (Cooke and Suski 2004, Watson and Kerstetter 2006). In addition, minimizing hook offset is expected to reduce foul hooking; the point of an offset hook is more exposed and is more likely to embed externally in the turtle.

Gangion length in US shallow-set pelagic longline gear is usually long enough for hooked turtles to surface to breathe, and most turtles are released alive following interactions (Watson et al. 2005, Kerstetter and Graves 2006). Nevertheless, post-release mortality may occur depending on the severity of injury and the amount and location of the gear left on the turtle at release (Ryder et al. 2006). Necropsies conducted on loggerheads incidentally captured on longline gear have shown that swallowed hooks have the potential to cause serious internal damage, particularly when fishing line remains attached to the hook (Orós et al. 2005, Valente et al. 2007, Casale et al. 2008). These deeply ingested hooks can perforate the heart, critical blood vessels, or gastrointestinal tract (Orós et al. 2005, Casale et al. 2008), leading to traumatic injuries or infections that cause mortality hours, days, or months after release. Externally embedded hooks and those lodged in the heavily keratinized beak cannot

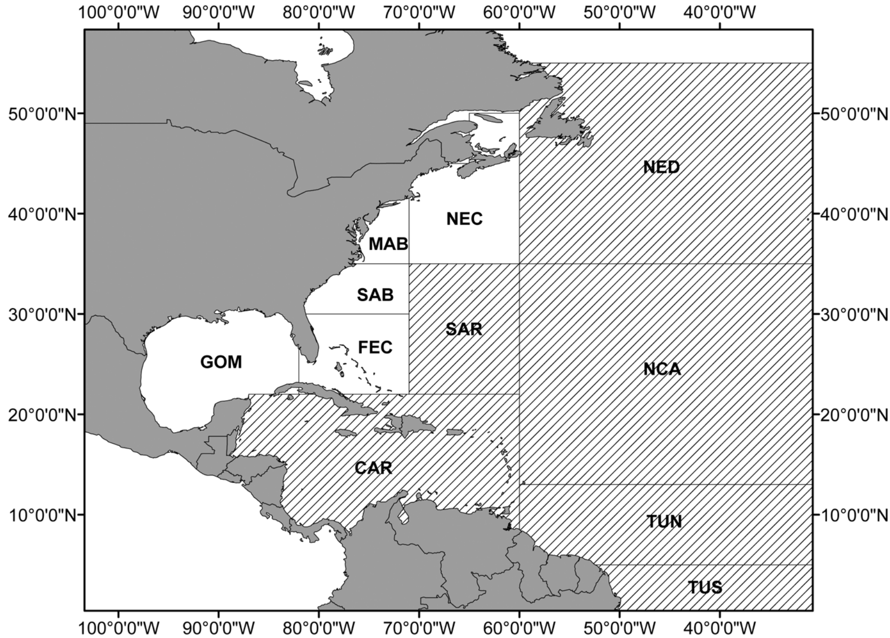

Figure 3. Oceanic zones (shaded) include Statistical Reporting Areas: Northeast Distant (NED), North Central Atlantic (NCA), Sargasso Sea (SAR), Tuna North (TUN), Tuna South (TUS), and Caribbean (CAR). Coastal zones (not shaded) include the Gulf of Mexico (GOM), Mid Atlantic Bight (MAB), Florida East Coast (FEC), Northeast Coastal (NEC), and South Atlantic Bight (SAB).

penetrate vital organs and blood vessels, and likely have less potential to cause acute, lethal injuries. Hooks embedded in the soft tissues of the mouth have the potential to cause sub-lethal injuries that interfere with foraging behavior or cause infection depending on whether certain sensitive structures (e.g., glottis, tongue, jaw joint) are involved (Ryder et al. 2006, Casale et al. 2008) and how much trauma was caused by the hook and line tension during the interaction.

Hooking location also can impact the ability of the crew to remove gear, as deeply ingested hooks cannot be removed safely, and removal is not recommended (NMFS 2008). When hooks are more accessible, they are easier to remove with minimal injury to the animal following careful release guidelines (NMFS 2008). In particular, removing line from the hook is essential, as even short lengths of ingested line can be lethal as a result of gut strangulation and intussusception (Orós et al. 2005, Valente et al. 2007, Casale et al. 2008). Maximizing gear removal is critical to improving a sea turtle's probability of survival (Ryder et al. 2006, Swimmer et al. 2006).

We sought to measure the impact of management regulations in reducing the incidence of swallowed hooks. Prior to 2004, the primary hook type used in the United States pelagic longline fleet was the 10°–30° offset J-hook (Watson et al. 2005). In July 2004, NMFS enacted regulations in the Atlantic pelagic longline fishery requiring the use of 16/0 or larger non-offset circle hooks, except in the Northeast Distant waters (NED, see Fig. 3), where 18/0 or larger hooks with an offset ≤10° were required (USDOC 2004). Those regulations targeted a reduction in the total number of sea turtle interactions and post-release mortality throughout the United States pelagic longline fishery (USDOC 2004). Requirements to possess and use sea turtle handling and release tools were also enacted at this time.

Since 1992, fishery observers have conducted scientific sampling of the United States large pelagic fisheries longline fleet (Beerkircher et al. 2004). When a sea turtle is incidentally captured, the observer documents the interaction in detail by recording gear characteristics such as bait type and size, hook type and size, hooking location and entanglement status, and amount of residual gear at release. For the present study, the parameters of primary interest were hook type, bait type, and turtle size based on previous research investigating how turtles interact with baited hooks (Watson et al. 2005, Stokes et al. 2011). In addition, we investigated water temperature and region [oceanic or coastal based on NMFS Pelagic Observer Program (POP) Statistical Reporting Areas (Fig. 3)] because of their potential effect on feeding behaviors. Oceanic stage loggerheads are generally smaller than coastal/benthic stage loggerheads (Bjorndal et al. 2000, Bjorndal 2003) and foraging behaviors may differ between the habitats (Bjorndal 1997, Reich et al. 2010); therefore, we tested for differences between the measured size distributions of loggerheads in oceanic and coastal regions. We did not investigate other factors that could have the potential to impact catch rates of both target and non-target species, such as season, the use of light sticks, gear depth, and gear soak duration (NMFS 2001).

The objectives of the study were to (1) compare hook type (circle or J) and bait type (squid or fish) as they relate to frequency of hooking location [e.g., mouth/beak, swallowed (gut), external (foul)], and (2) to investigate additional factors that influence hook location. We hypothesized that J-hooks would have a higher frequency of gut hooking/deep ingestion and that circle hooks would be more frequently lodged in the mouth or beak in loggerheads. We hypothesized that J-hooks might have a slightly higher frequency of foul-hooking compared to mouth hooking in leatherbacks. We examined the hooking locations of incidentally captured leatherback and loggerhead sea turtles in the United States Atlantic pelagic longline fleet from 2000 to 2010 as a function of hook type (circle or J), bait type (squid or fish), turtle size (CCL), water temperature (°F), and region (oceanic or coastal) using NMFS fishery observer data.

Materials and Methods

Pelagic Observer Program Data.—Data collected between 2000 and 2010 by NMFS Atlantic POP fishery observers were used to classify the nature of fishing gear–turtle interactions using specific hooking location and entanglement details from incidentally captured turtles. Prior to 2000, data collected by observers did not provide sufficient detail regarding hooking location to be included in this analysis. Data were collected during normal commercial pelagic longline fishery operations without any experimental modifications to standard fishing practices.

Detailed hooking location data were pooled into four categories: entangled, externally hooked, hooked in the mouth or beak (subsequently referred to as "mouth/beak" for loggerheads and "mouth" for leatherbacks, which have no beak), and swallowed. We statistically analyzed two categories of primary interest for loggerheads (mouth/beak and swallowed) and leatherbacks (external and mouth) based on how each species most often interacts with the hook. Other categories were assessed qualitatively, as insufficient sample size of externally hooked loggerheads and leatherbacks that had swallowed hooks prevented us from including data in the analyses. Because our primary focus was the role of hook type in hooking location, we did not statistically analyze data from sea turtles that were entangled in line only but not hooked, but we did assess these entangled turtles qualitatively. Records for which the hooking location, hook type, offset, or bait could not be determined, and records from experimental trips were excluded from our analyses, as were data from trips using circle hooks prior to regulatory changes in July 2004 due to small sample size and inconsistency of those sets with standard fishing practices.

For analysis, four hook categories were defined: non-offset and 10° offset circle hooks (subsequently referred to as C-0° and C-10°, respectively), and non-offset and 10°–30° offset J-hooks (subsequently referred to as J-0° as J-20°, respectively). The majority of the hooks in the J-20° category had offsets between 20° and 30°, with only one model (Lindgren Pitman LPSWOBL) having a smaller offset of approximately 10°. Comparisons of hooking location for J-hook models with a 10° offset and those with a 20°–30° offset indicated that these hooks were comparable in performance (percent of hooks swallowed). Hook size was not considered due to the relatively narrow range of sizes used [16/0 (primarily Mustad 39960D or Eagle Claw 2048) and 18/0 circle hooks (primarily Lindgren Pitman LPCIRBL); 7/0–10/0 J-hooks (Eagle Claw 9014, 9015, and 9016; Mustad 7698, 76800, and 76801; and Lindgren Pitman LPSWOBL)].

Circle hook offset and hook size were somewhat confounded, as the majority of the non-offset circle hooks (C-0°) in the data were 16/0 hooks and the majority of the offset circle hooks (C-10°) hooks were 18/0 hooks. That was due to United States fishery management regulations requiring that 16/0 hooks have no offset (USDOC 2004). Hook type and year of capture also were confounded due to the regulatory actions that eliminated the use of J-hooks in July 2004; therefore, year effects were not examined.

Statistical Methods.—Generalized Linear Model (GLM) analyses were used to model hooking location in both species as a function of: hook type (C-0° offset, C-10° offset, J-0° offset, J-20° offset), bait type (squid or fish), region (oceanic or coastal), CCL (using a subset of loggerhead data for which CCLs were available; modeled as a continuous variable), and water temperature (available for a subset of the data for each species; modeled as a continuous variable). Parameterization of each model was accomplished using the GENMOD procedure in SAS (Version 8.02 of the SAS System for Windows ©2000. SAS Institute, Inc., Cary, NC, USA). For each GLM analysis, a type-3 model was fit, a binomial error distribution was assumed, and the logit link was selected.

A forward stepwise regression procedure was used to determine the set of fixed factors and interaction terms that explained a significant portion of the observed variability in hooking location (McCullagh and Nelder 1989). Each potential factor was added to the null model sequentially, and the resulting reduction in deviance per degree of freedom was examined. The factor with the highest explanatory power (the largest reduction in deviance per degree of freedom) was added to the base model if addition of the factor explained significantly more of the observed variability than did the null model (χ^2 test: $P < 0.05$) and if the deviance per degree of freedom explained by the factor was ≥1%. This model then became the base model, and the process was repeated, adding factors and interactions individually until no factor or interaction met the criteria for incorporation into the final model.

Because only hook type had a significant effect on hooking location for each species, Pearson chi-square tests were used to test for differences in hooking location among hook types. Multiple comparisons were then conducted using pairwise Pearson chi-square tests using the Bonferroni adjustment to correct the experiment-wise error rate for multiple tests.

A Kolmogorov-Smirnov (KS) test was run to compare size distributions between oceanic and coastal regions for measured turtles; size data were not available for all loggerheads, particularly for those too large to be brought aboard and measured. Because few leatherbacks are brought onboard pelagic longline vessels, leatherback lengths are generally estimated by observers, and size distributions are not available.

Proportional frequencies of all interaction types (entangled, external, mouth/beak, and swallowed) by hook type for each species were obtained from frequency tables generated for hooking location by hook type using the PROC FREQ procedure in SAS (Version 9.2 of the SAS System for Windows ©2002–2008. SAS Institute, Inc., Cary, NC, USA).

Table 1. Deviance tables from the stepwise regression procedure used to construct a model of hook location in pelagic longline–loggerhead sea turtle (*Caretta caretta*) interactions. df = degrees of freedom, DEV/df = deviance per degree of freedom, % reduction = the percent reduction in deviance per degree of freedom explained by each factor. CCL = curved carapace length.

A. Base model containing no explanatory factors. Each factor was examined separately, but factors are shown in a single table for comparison. Hook style accounted for the largest reduction in deviance per degree of freedom.

Factor	df	Deviance	DEV/df	% reduction	Chi-square	*P* value
Base	230	306.023	1.33053	n/a	n/a	n/a
Hook style	226	264.807	1.17171	11.937	41.22	< 0.0001
Bait type	229	297.570	1.29943	2.338	8.45	0.0036
Region	229	303.357	1.32470	0.438	2.67	0.1025
Temperature	182	241.646	1.32772	0.211	0.76	0.3818
CCL	171	229.712	1.34334	–0.963	0.31	0.5794

B. Base model containing the factor hook style. No additional factors met the criteria for inclusion in the model.

Factor	df	Deviance	DEV/df	% reduction	Chi-square	*P* value
Hook style (base)	226	264.807	1.17171	n/a	n/a	n/a
Temperature	178	197.303	1.10844	5.400	1.55	0.2124
Bait type	225	262.739	1.16773	0.340	2.07	0.1505
Region	225	264.660	1.17626	–0.389	0.15	0.7013
CCL	167	199.574	1.19505	–1.992	2.22	0.1359

Results

GLM results indicated that hook type was the only factor that met our criteria for inclusion (i.e., explained a significant portion of the observed variability and accounted for ≥1% of the deviance per degree of freedom) when modeling hooking location of mouth/beak vs swallowed in loggerheads (Table 1) and mouth vs external hooking in leatherbacks (Table 2). Subsequent Pearson chi-square analyses revealed significant differences in hooking location among hook types existed when comparing mouth/beak vs swallowed hooking locations in loggerheads [χ^2 (3, n = 217) = 34.93, P < 0.001] and when comparing external vs mouth locations in leatherbacks [χ^2 (3, n = 288) = 13.98, P = 0.003]. Multiple pairwise comparisons revealed that for loggerheads, J-20° hooks were swallowed more often than mouth/beak hooked when compared to C-0°, J-0°, or C-10° hooks (Table 3). Multiple pairwise comparisons indicated that leatherbacks were hooked in the mouth significantly more often on C-0° and J-0° hooks than on C-10° hooks (Table 4).

Loggerhead size distributions (Fig. 4) differed significantly between oceanic (n = 86, mean CCL 63.8 ± 8.1 cm, range 39.8–82.1 cm) and coastal regions (n = 100, mean CCL 70.4 ± 7.3 cm, range 52.0–95.2 cm; n = 198, KS test = 2.63, P < 0.001). However, sea turtle size was not a significant factor in explaining differences among hooking location in the GLM analyses.

An examination of the data including all hooking locations (entangled, external, mouth/beak, and swallowed) revealed that loggerheads (n = 241) were hooked most often in the mouth or beak on C-0° and C-10° offset circle hooks (66%) and J-0° hooks (71%), while they swallowed 66% of J-20° hooks when considering the frequency of hooking location by hook types (Fig. 5). In a closer examination of offset within the

Table 2. Deviance tables from the stepwise regression procedure used to construct a model of hook location in pelagic longline–leatherback sea turtle (*Dermochelys coriacea*) interactions. df = degrees of freedom, DEV/df = deviance per degree of freedom, % reduction = the percent reduction in deviance per degree of freedom explained by each factor.

A. Base model containing no explanatory factors. Each factor was examined separately, but factors are shown in a single table for comparison. Hook style accounted for the largest reduction in deviance per degree of freedom.

Factor	df	Deviance	DEV/df	% reduction	Chi-square	*P* value
Base	242	193.073	0.79782	n/a	n/a	n/a
Hook style	239	182.423	0.76328	4.330	10.65	0.0138
Bait type	241	191.307	0.79381	0.504	1.77	0.1839
Region	241	192.892	0.80038	–0.321	0.18	0.6706
Temperature	241	193.003	0.80084	–0.378	0.07	0.7906

B. Base model containing the factor hook style. No additional factors met the criteria for inclusion in the model.

Factor	df	Deviance	DEV/df	% reduction	Chi-square	*P* value
Hook style (base)	239	182.423	0.76328	n/a	n/a	n/a
Temperature	238	180.516	0.75847	0.629	1.91	0.1673
Region	238	182.252	0.76577	–0.326	0.17	0.6797
Bait type	238	182.265	0.76582	–0.333	0.16	0.6909

Table 3. Pearson chi-square results testing for differences in hooking location (mouth/beak vs swallowed) by hook style for loggerheads (*Caretta caretta*). *P* values <0.05 were considered to be significant, as indicated with an asterisk (*).

Hook style comparisons	Hooking location (% mouth/beak:% swallowed)	*n*	df	Chi-square	*P* value
C-0°	80.5:19.5	41	1	1.117	0.292
C-10°	72.1:27.9	111			
C-0°	80.5:19.5	41	1	0.002	0.968
J-0°	80.0:20.0	15			
C-0°	80.5:19.5	41	1	23.039	< 0.001*
J-20°	30.0:70.0	50			
C-10°	72.1:27.9	111	1	0.422	0.516
J-0°	80.0:20.0	15			
C-10°	72.1:27.9	111	1	25.226	< 0.001*
J-20°	30.0:70.0	50			
J-0°	80.0:20.0	15	1	11.879	0.001*
J-20°	30.0:70.0	50			

J-20° hook category, the majority (76%) had offsets of 20°–30°, and of those, 68% were swallowed, while of those with a 10° offset (LPSWOBL), 58% were swallowed. Leatherbacks (*n* = 328) were most often externally hooked on C-0° (75%), C-10° (77%), J-0° (67%), and J-20° hooks (89%) when considering the frequency of hooking location by hook type (Fig. 5). No leatherbacks were entangled but not hooked when J-20° hooks were used, and very few (1%–4%) swallowed hooks.

Table 4. Pearson chi-square results testing for differences in hooking location (external vs mouth) by hook style for leatherbacks (*Dermochelys coriacea*). *P* values < 0.05 were considered to be significant, as indicated with an asterisk (*).

Hook style comparisons	Hooking location (% external:% mouth/beak)	*n*	df	Chi-square	*P* value
C-0°	83.9:16.1	137	1	7.877	0.005*
C-10°	97.1:2.9	70			
C-0°	83.9:16.1	137	1	2.085	0.149
J-0°	74.5:25.5	47			
C-0°	83.9:16.1	137	1	1.142	0.285
J-20°	91.2:8.8	34			
C-10°	97.1:2.9	70	1	13.725	< 0.001*
J-0°	74.5:25.5	47			
C-10°	97.1:2.9	70	1	1.780	0.182
J-20°	91.2:8.8	34			
J-0°	74.5:25.5	47	1	3.650	0.056
J-20°	91.2:8.8	34			

Discussion

Hooking location may have important ramifications for serious injury and mortality in incidentally captured sea turtles (Ryder et al. 2006). The results here demonstrate that the 2004 NMFS regulatory switch from J-hooks to non-offset or minimal offset circle hooks (USDOC 2004) has resulted in a shift in hooking location in incidentally captured loggerheads. Our loggerhead data show that prior to 2004, the majority of J-20° hooks were swallowed; however, after the regulatory changes the majority of sea turtles were likely to get hooked in the mouth or beak on C-0° and C-10° hooks. This shift in hooking location may facilitate easier gear removal and potentially increase survival odds of incidentally captured loggerheads and other hard-shelled sea turtles in the western North Atlantic Ocean.

Estimating post-interaction survival is controversial and difficult given the variety of factors involved with each unique interaction. It is generally agreed, however, that lightly hooked sea turtles (external and mouth/beak hooked) have a higher chance of survival than sea turtles that swallow the hook, particularly when all gear is removed before release (Ryder et al. 2006, Swimmer et al. 2006). Results from satellite telemetry research generally support the hypothesis that deeply hooked turtles (Chaloupka et al. 2004) have a higher probability of mortality than lightly hooked turtles when all gear is removed (Swimmer et al. 2006, Sasso and Epperly 2007). Necropsies conducted on loggerheads incidentally captured on longline gear have demonstrated that deeply ingested hooks can cause traumatic perforation to the heart, blood vessels, or gastrointestinal tract, or ulcerative and fibrinous esophagitis (Orós et al. 2005, Valente et al. 2007, Casale et al. 2008). Live stranded turtles were more likely to die if they were injured by deeply ingested hooks (Aguilar et al. 1995, Casale et al. 2008). However, some studies have documented long term survival of turtles with deeply ingested hooks when held in captive rehabilitation facilities (Aguilar et al. 2005,

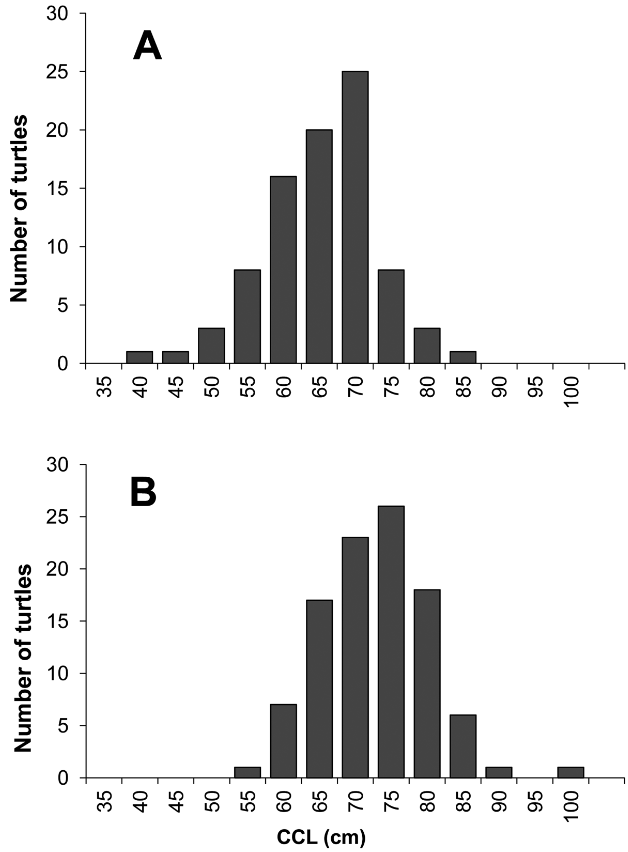

Figure 4. Observed loggerhead (*Caretta caretta*) size frequency distribution (curved carapace length, CCL, in cm) in the (A) oceanic region (n = 86) and (B) coastal region (n = 100), as defined in Figure 3 by Statistical Reporting Areas.

Alegre et al. 2006, Piovanno et al. 2009), suggesting that caution should be applied when making generalized assumptions of post-hooking mortality estimates based on hooking location alone. Those cases involved active rehabilitation, under supervised veterinary care in some instances, and those observed survivorship rates cannot be directly compared with rates of survival in incidentally captured turtles released immediately after interaction with fishing gear. More research is needed to determine the fate of incidentally captured turtles for which hooking location and other gear interaction details are known.

Many factors will influence the survival of a hooked turtle, including the hook position, length of remaining monofilament line, and amount of tension or traction applied to the hook during the interaction (Valente et al. 2007). However, there is general agreement that reducing the amount of line remaining on the hook is critical to maximizing the probability of survival (Casale et al. 2007, Piovano et al. 2009). Hooks can be more easily removed from the mouth/beak or external hooking locations, but deeply swallowed hooks cannot be removed safely, and the gangion is sometimes cut with several inches or feet of line remaining. However, shifting hooking location to a more favorable location for gear removal alone is not enough to

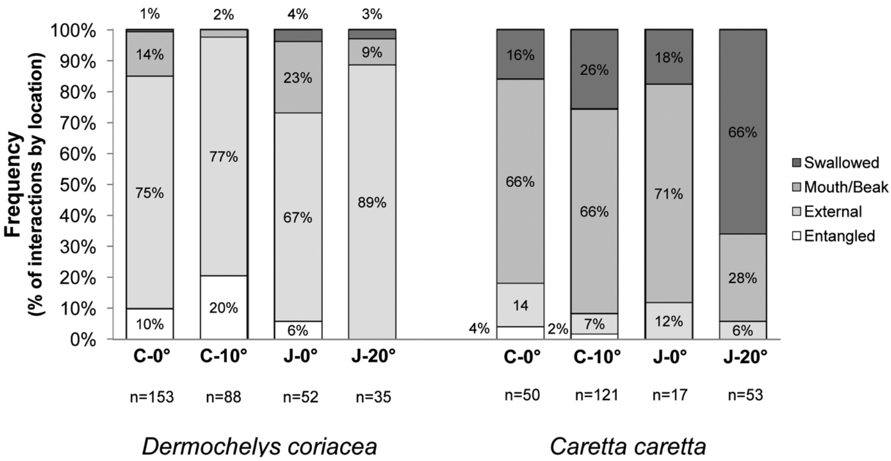

Figure 5. Frequency of leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) hooking locations (entangled, external, mouth/beak, swallowed) within each hook type: circle hook with 0° offset (C-0°), circle hook with 10° offset (C-10°), J-hook with 0° offset (J-0°), and J-hook with 10°–30° offset (J-20°).

increase survival odds, as not all fleets or individual fishers actively remove fishing gear from incidentally caught turtles. Careful release tools and protocols, including outreach and education to encourage safe gear removal, are critical components of reducing serious injury and mortality (Ryder et al. 2006, NMFS 2008). In addition, longline fisheries that set gear deeper (e.g., bottom longline fisheries) have a greater likelihood of incidental mortalities because of the risk of forced submergence and drowning.

Controlled laboratory experiments have demonstrated a relationship between bait type (squid vs fish) and the ability of loggerhead turtles to swallow hooks (Stokes et al. 2011). Our results suggest that under normal fishing conditions, bait type may not influence hooking location. The use of finfish as bait has been proven to be an effective bycatch mitigation measure, however, by reducing overall loggerhead and leatherback bycatch numbers (Watson et al. 2005, Yokota et al. 2007). Use of finfish as bait in the pelagic longline fishery remains an important conservation measure.

There may be a direct relationship between a sea turtle's size and its ability to ingest large hooks, and regional differences in size classes potentially could affect hooking location. Stokes et al. (2011) showed a relationship between the size of loggerhead sea turtles [in the 45–65 cm straight carapace length (SCL in cm) size classes] and their ability to swallow large circle hooks. Oceanic stage loggerheads are generally smaller than coastal/benthic stage loggerheads, and our data from turtles captured on longline gear confirm this. However, sea turtle size did not meet the criteria for inclusion in the model constructed to explain differences in hooking location. It is likely that sea turtles observed and measured in this fishery were sufficiently large to swallow all hook sizes, possibly explaining why hook size did not meet the criteria for inclusion in the model. In laboratory trials, once the sea turtles reached 65 cm SCL, they were able to swallow hooks up to 18/0 with little difficulty, and turtle size became less of a factor in predicting the ability of a sea turtle to swallow a hook (Stokes et al. 2011). The measurements taken by observers also may represent a bias in data toward the smallest sea turtles encountered by the fleet, as vessel crews are more likely to bring smaller sea turtles on board due to weight constraints of dip nets and the difficulty in handling the largest sea turtles. The size distribution of the population may be larger than our data demonstrate, particularly in the coastal region where sea turtles too large to bring onboard are more likely to be encountered. In areas such as waters near the Grand Banks in the northwest Atlantic, loggerheads (generally within the 40–60 cm SCL size range; Watson et al. 2005, Brazner and McMillan 2008) are smaller than those found in benthic/coastal regions, and hook size may play a larger role in reducing the number and severity of interactions.

Fishing methods and directed target may mask the effects of hook size as well. Most commonly used J-hooks (7/0, 8/0, and 9/0) are slightly smaller than 16/0 and 18/0 circle hooks, confounding comparisons of hook type with a potential hook size effect. In addition, there are differences in hook selection based on directed target species, as vessels targeting tuna are most likely to use 16/0 0° offset hooks, while those targeting swordfish generally use 18/0 10° offset hooks. Other setting and gear characteristics also differ by target species. These issues highlight the need for regional and fishery-specific bycatch mitigation strategies.

Several studies have demonstrated the conservation benefits of using circle hooks for loggerhead sea turtles (Watson et al. 2005, Gilman et al. 2007, Brazner and McMillan 2008). For example, catch rates of loggerheads were decreased by approximately 90% when circle hooks and mackerel were used relative to 9/0 J-hooks baited with squid (Watson et al. 2005). Our results are consistent with a growing body of evidence (Watson et al. 2005, Gilman et al. 2006, Brazner and McMillian 2008, Piovano et al. 2009) that suggests significantly more loggerheads are mouth hooked than gut hooked with circle hooks than with J-hooks.

Our findings highlight the importance of hook offset in hooks that are swallowed and become lodged internally. Greater degrees of offset for circle hooks increase mortality in billfish due to internal damage caused by the barb (Prince et al. 2002). Note that there was no significant difference between loggerhead hooking locations when comparing J-0° hooks with C-0° and C-10° hooks, suggesting that non-offset J-hooks and minimal offset (≤10°) circle hooks perform in a similar manner with regard to hooking location, although the sample size for J-0° interactions was low in our study. However, minimal offset J-hooks (10°) do not appear to afford the same protection from gut hooking, likely due to the difference in hook shape and the shielding that the circle provides due to its geometry. A significantly higher percentage of loggerheads swallowed J-20° offset hooks than C-0° and C-10° hooks and J-0° hooks. It is likely that loggerheads were able to swallow all of these hooks, but that offset J-hooks became lodged in the gastrointestinal tract, while non-offset J-hooks and minimal offset and non-offset circle hooks may have been pulled back out of the esophagus and ultimately become lodged in the mouth or beak. If so, minimizing offset may play as important a role in reducing deeply ingested hooks. These results are consistent with those of other studies, which found no significant differences in anatomical hooking location between olive ridleys, *Lepidochelys olivacea* (Eschscholtz, 1829), caught on 14/0 circle hooks with a 10° offset and with no offset (Swimmer et al. 2010), or in the incidence of gut hooking of loggerheads caught on 16/0 circle hooks (Bolten et al. 2002) with and without a 10° offset. In contrast, Carruthers et al. (2009) found no significant difference in hooking location among 16/0 circle hooks, non-offset

J-hooks, and offset (20°–30°) J-hooks, although the sample size for offset J-hooks in that study was low.

The effect of hook type is less clear when considering leatherback hooking location, as leatherbacks were primarily externally hooked (in almost 90% of interactions) with a similar proportional frequency across hook types. More leatherbacks were mouth-hooked on non-offset hooks (C-0° and J-0°) than the C-10° offset hooks. We speculate that offset may play some role in leatherbacks becoming externally hooked before they are able to ingest baited hooks because the offset barb is exposed and more likely to engage the skin. Although leatherbacks are most often hooked externally, the existence of mouth-hooked and swallowed hook locations in our data demonstrates that leatherbacks indeed do ingest baited hooks.

Understanding factors that affect post-hooking mortality rates remains an important component when evaluating the population-level impact of fishery interactions. Our results demonstrate the efficacy of using large circle hooks with minimal offset (0°–10°) rather than 10°–30° offset J-hooks to reduce the incidence of deep hook ingestion in loggerheads. In addition, we found a relationship between offset and deep ingestion rates regardless of hook type. This is an important observation when considering the effect of hook offset on injury and mortality. By reducing the number of deeply ingested hooks, the potential to maximize gear removal success may be one of the most critical benefits of using circle hooks as a mitigation method. However, this strategy will only work if vessel crews are well trained and diligent in gear removal efforts. Therefore, outreach and education on careful release protocols remain critical components to maximizing the conservation benefit of using circle hooks to reduce sea turtle mortality.

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Addresses: *National Marine Fisheries Service, Southeast Fisheries Science Center, Miami, Florida 33149.* Corresponding Author: (LWS) *Email: <Lesley.Stokes@noaa.gov>.*