Catch rates and demographics of loggerhead sea turtles (*Caretta caretta*) captured from the Charleston, South Carolina, shipping channel during the period of mandatory use of turtle excluder devices (TEDs)

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Abstract—Trawling was conducted in the Charleston, South Carolina, shipping channel between May and August during 2004–07 to evaluate loggerhead sea turtle (*Caretta caretta*) catch rates and demographic distributions. Two hundred and twenty individual loggerheads were captured in 432 trawling events during eight sampling periods lasting 2–10 days each. Catch was analyzed by using a generalized linear model. Data were fitted to a negative binomial distribution with the log of standardized sampling effort (i.e., an hour of sampling with a net head rope length standardized to 30.5 m) for each event treated as an offset term. Among 21 variables, factors, and interactions, five terms were significant in the final model, which accounted for 45% of model deviance. Highly significant differences in catch were noted among sampling periods and sampling locations within the channel, with greatest catch furthest seaward consistent with historical observations. Loggerhead sea turtle catch rates in 2004–07 were greater than in 1991–92 when mandatory use of turtle excluder devices was beginning to be phased in. Concurrent with increased catch rates, loggerheads captured in 2004–07 were larger than in 1991–92. Eighty-five percent of loggerheads captured were ≤75.0 cm straight-line carapace length (nuchal notch to tip of carapace) and there was a 3.9:1 female-to-male bias, consistent with limited data for this location two decades earlier. Only juvenile loggerheads ≤75.0 cm possessed haplotypes other than CC-A01 or CC-A02 that dominate in the region. Six rare and one un-described haplotype were predominantly found in June 2004.

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Fisheries interactions are the greatest perceived threat to sea turtles (Wallace et al., 2010a), with specific fisheries differentially afflicting various life history stages across most developmental and foraging habitats (Wallace et al., 2010b). Consequently, techniques to reduce sea turtle bycatch have been evaluated for multiple fisheries (Brewer et al., 1998; Watson et al., 2005; Gilman et al., 2010). Prevalent among such measures is the turtle excluder device (TED) which enables sea turtles to escape and return to the surface to breathe while bottom trawling continues. Because of the coastal nature of most trawl fisheries, Kemp's ridley (*Lepidochelys kempii*) and loggerhead (*Caretta caretta*) sea turtles foraging on benthic prey (Shaver, 1991; Plotkin et al., 1993; Seney and Musick, 2007) have likely benefited more from TEDs than herbivorous green sea turtles (*Chelonia mydas*) grazing in shallow, nearshore habitats (Seminoff et al., 2002) or leatherback sea turtles (*Dermochelys coriacea*) pursuing gelatinous prey near the water surface and offshore (Eckert et al., 1989) from where most coastal trawl fisheries operate.

Before implementing TEDs, sea turtle mortality in coastal trawl fisheries was estimated to exceed mortality from all other anthropogenic sources (NRC, 1990). Trawl-related mortality of loggerhead sea turtles remains a concern given that following an initial postpelagic settlement, juveniles predominantly forage in neritic habitats for approximately 19 years until they reach maturity, after which neritic habitats are used extensively (Conant et al., 2009). Because most loggerhead strandings before TED implementation were those of large juveniles with a high conservation value (Crouse et al., 1987), reducing mortality of large juveniles was a high priority. In the southeast United States, TEDs were mandated for most trawl fisheries in federal waters in 1987 (Federal Register, 52 FR 6179-6199); however, year-round use was not required for several more years and TED openings were not large enough to benefit large juveniles and adults until 2003 (Federal

Register, 2003). Consequently, loggerhead sea turtle cohorts during the past two decades have not uniformly benefited from TEDs.

Concurrent with improving benefits from TEDs since the late 1980s, loggerhead nesting in Florida, where 90% of loggerhead nesting in the Northwest Atlantic basin occurs, also increased between 1989 and 2000, after which a precipitous decline began (Witherington et al., 2009). As such, it is reasonable to anticipate that strong cohorts hatched between 1989 and 2000 should remain distinctly abundant given mandated use of appropriately sized TEDs in neritic habitats where these cohorts have likely occurred since 2003. Consistent with this assertion, statistically greater catches of small juvenile loggerheads were reported for estuarine habitats in North Carolina (Epperly et al., 2007) and Florida (Ehrhart et al., 2007) during the first decade of the 21st century. However, given the smaller sizes associated with loggerheads in estuaries (Lutcavage and Musick, 1985; Schmid, 1998) relative to coastal waters (Henwood, 1987; Schmid, 1995), loggerhead abundance in coastal habitats should also be monitored to evaluate the effectiveness of TEDs.

In the southeastern United States, shipping channels have been extensively surveyed to assess sea turtle abundance (Butler et al., 1987; Henwood, 1987; Van Dolah and Maier, 1993). Continued studies to monitor loggerhead abundance trends in shipping channels in the southeastern United States would provide some of the longest duration and most standardized observations for assessing temporal shifts in sea turtle distributions in this region. Because of their geographic configuration, commercial shipping channels throughout this region represent a "network of index in-water sites" that are ideal for long-term monitoring and for assessing demographic recovery criteria specified in the Northwest Atlantic Loggerhead Recovery Plan (NMFS and USFWS, 2008). Therefore, long-term monitoring at these index sites with a fixed-location (i.e., Eularian) sampling design has great potential for assessing, with high statistical confidence, temporal changes in catch rates in the water relative to stranding rates in the same region at the same time (NMFS and USFWS, 2008).

In order to gauge the utility of shipping channel data sets for monitoring regional loggerhead recovery efforts, we initiated a trawl survey in the Charleston, South Carolina, shipping channel (hereafter, "Charleston shipping channel") in 2004. Baseline catch and demographic data were not as abundant as data from Port Canaveral, Florida, shipping channel (Henwood, 1987), but they do date back to the early 1990s (Van Dolah and Maier, 1993; Dickerson et al.[1]) when TED use was beginning to be required. Our first objective was to document catch and recapture rates relative to 1991 (Van Dolah and Maier, 1993) and 1992 (Dickerson et al.[1]). The second objective was to document the demographic composition of loggerheads and compare the data to similar data collected in the early 1990s. Size-based sex and genetic assessments of loggerheads on foraging grounds (Braun-McNeill et al., 2007) are crucial for assessing whether loggerheads are likely to remain in the region upon reaching maturity (Sears et al., 1995; Encalada et al., 1998; Bowen et al., 2004; Roberts et al., 2005). As such, historical evaluation of these parameters is crucial for understanding what, if any, shifts in loggerhead foraging trends have occurred that may influence catch and recapture trends.

Materials and methods

Data collection

Trawling was conducted within the Charleston, SC, shipping channel (32°42′N, –79°48′W) in three (A, B, and D) of four blocks and at seven (A1–A3, B1, B3, D1, D3, Fig. 1) of twelve index stations previously established by Van Dolah and Maier (1993). Five stations (B2, D2, E1–E3) sampled by Van Dolah and Maier (1993) were not repeated in 2004–07 owing to bottom obstructions that precluded safe and effective trawling. Trawling (2–10 sea day cruises) occurred in May (2004–07), June (2004) and August (2004, 2005, 2007) with the same vessel as that used by Van Dolah and Maier (1993): the RV *Lady Lisa*, a 22.9-m trawler (except in May 2004 when the RV *Georgia Bulldog*, a 22.0 m trawler, was used). The sampling order of stations was randomly selected and stations were systematically sampled thereafter during 2004–06; however, in 2007, two stations (B3, D3) with high catch rates in 2004–06 were targeted to expedite loggerhead collections for satellite telemetry studies (Arendt et al., in press). Trawling was conducted with standardized National Marine Fisheries Service (NMFS) turtle nets: paired 18.3-m (head rope), 4-seam, 4-legged, 2-bridle nets; the net body consisted of a 10.2-cm bar and 20.3-cm stretch mesh, with tops and sides made of #36 twisted nylon and the net bottom of #84 braided nylon twine. Trawl bottom times ranged from six to 21 minutes.

Turtles were removed from nets and examined for general health status and injuries before being visually and electronically scanned for existing tags. Unique identification numbers were assigned to turtles when first encountered and subsequently re-used to denote recapture events. Body condition was evaluated and photographed before turtles were tagged externally with two Inconel 681 flipper tags (National Band and Tag Company, Newport, KY; distributed by the Archie Carr Center for Sea Turtle Research, Gainesville, FL) and internally with passive integrated transponder tags (TX1406L, 125 kHz, Biomark, Inc., Boise, ID). Standard morphometric data included five straight and six curved measurements and body mass; however, here we report only straight-line carapace length mea-

[1] Dickerson, D. D., K. J. Reine, D. A. Nelson, and C. E. Dickerson Jr. 1995. Assessment of sea turtle abundance in six South Atlantic U.S. Channels. U.S. Army Corps of Engineers Waterways Experiment Station Misc. Paper EL-95-5, 134 p. U.S. Army Corps of Engineers, Vicksburg, MS.

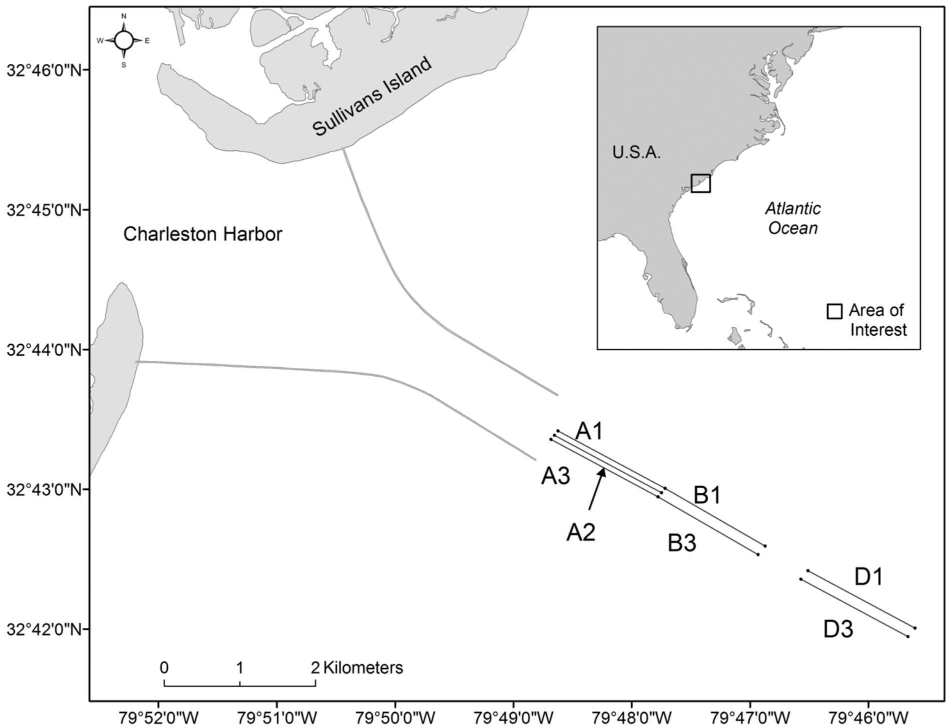

Figure 1

Trawling in the Charleston, South Carolina, shipping channel during 2004–2007 was completed at seven index stations (A1–A3; B1, B3; D1, D3) within three arbitrary blocks previously established by Van Dolah and Maier (1993).

sured from the nuchal notch to the posterior tip of the carapace (SCLnt, in cm). SCLnt for five loggerheads captured with healed posterior carapace amputations was estimated using the following relationship between carapace length and maximum straight-line carapace width (SCW) determined for 1497 loggerheads <80 cm SCLnt captured in our various studies between 2000 and 2010: $SCLnt = 0.496 + 1.23(SCW)$; coefficient of determination (r^2)=0.76.

Blood samples were collected from the dorsal cervical sinus (Owens and Ruiz, 1980) with a 21-gauge, 3.5-cm needle to measure three standard health metrics: blood glucose (mg/mL), hematocrit (%), and serum protein (g/dL) at sea. Blood samples were also analyzed in the laboratory to assess sex and genetic origin. Sex was assigned by using serum testosterone concentrations measured by radioimmunoassay, as described in Braun-McNeill et al. (2007) and considered reliable at water temperatures >23°C. Loggerheads with serum testosterone concentrations <450 pg/mL were identified as female, and those between 450 and 550 pg/mL, as undetermined, and those >550 pg/mL as male; however, two probable adult loggerheads >90 cm SCLnt with testosterone levels >1200 pg/mL were reclassified as female given tail length measurements consistent with adult females. Whole blood samples were prepped with lysis buffer solution before a 378 base-pair fragment of the mitochondrial DNA (mtDNA) control region was sequenced (see Roberts et al., 2005) to determine haplotypes for comparison with haplotypes reported for regional rookeries (Encalada et al., 1998; Bowen et al., 2004).

Station data consisted of towing speed (in knots, kn) at the start of each trawling event; surface water temperature (°C); wave height (m); wind speed (kn); wind direction (numeric); cloud cover (%); and barometric pressure (millibars, mb). Surface water temperature was recorded with a transducer located on each ship's hull approximately 1.5 m below the water surface. Wind direction was converted to a numeric value as follows: N (0°); NNE (22.5°); NE (45°); etc. Tide-stage data (15-min intervals) were obtained from the United States Geological Survey (USGS) for Fort Sumter, SC (station 02172100), which was located approximately 2 km directly inshore of the shoreward boundary of the shipping channel survey area. Three metrics corresponding to the start of each trawling event were subsequently computed: tide stage (ebb, flood); water level difference (m) between high and low tide; and the percentage of tide stage expired at the start of the trawling event.

Invertebrate and fish bycatch captured during each trawling event were identified to the lowest possible taxon and the actual or estimated counts for each taxon were also recorded. Total counts of potential invertebrate prey of turtles (Plotkin et al., 1993; Seney and Musick, 2007) per trawling event were included in multivariate analyses as follows: blue crab (*Callinectes* *sapidus*), horseshoe crabs (*Limulus polyphemus*), miscellaneous crabs, cannonball jellyfish (*Stomolophus meleagris*), and miscellaneous jellyfish. Loggerheads will consume finfish; however, such occurrences of finfish are thought to be dead fishery discards (Seney and Musick, 2007), and were excluded from multivariate analyses. Owing to the large-mesh webbing and streamlined body designs of finfish, we also suspected less efficient finfish capture relative to similar-size invertebrates that became entangled in or otherwise clung to the trawl webbing.

Data analyses

Loggerhead catch during 2004–07 was analyzed using a generalized linear model (GLM) with log-link function, with the log of the standardized sampling effort for each trawling event treated as an offset variable. Sampling effort was standardized to a net head rope length of 30.5 m calculated as follows: [2 nets×(18.3 m head rope)/30.5 m]×[(*tow time*, min)/60]. Loggerhead catch per trawling event best fitted the negative binomial distribution despite a significant *P*-value (χ^2=17.346, df=7, P=0.015) which resulted from infrequent capture of three or more loggerheads per trawling event.

Final model selection was accomplished in R software (vers. 2.10.1; R Core Team, Vienna, Austria) through backward elimination stepwise regression (α=0.05) that generated the lowest Akaike's information criterion (AIC) score. With chi-square analysis of deviance, we assessed the statistical significance of variables retained in the final model. Quantile residuals (Dunn and Smyth, 1996) were plotted against each variable to assess trends and model-assigned statistical significance of variables. Cumulative deviance attributed to final model variables was expressed as a percentage of the null deviance to characterize the extent to which the final model accounted for variation in catch in the data set. The adjusted loggerhead counts (mean ±95% confidence interval [CI]) per trawling event were used to examine catch rate trends among years and among blocks and size classes by year.

Twenty-one terms included in the null model consisted of hydrographic and meteorological variables (9), vessel towing speed, prey item groupings (5), sampling period (factor, 1 to 8), sampling block (factor, 1 to 3), hour of day, and three interaction (Pearson correlation coefficient r>0.4) terms between 1) barometric pressure and sampling period, 2) blue crabs and water temperature, and 3) miscellaneous jellyfish and water temperature. Twelve trawling events that were conducted at stations sampled only in May 2004 and 11 trawling events that were terminated early because of net hang ups or interference were not analyzed. Five stations missing vessel towing speed data were also excluded from the GLM. The wind direction for 38 trawling events with calm winds was assigned as the prevalent wind direction during trawling events immediately before or after (whichever was more robust) winds became calm. Cloud cover for five events and wave height for one event were populated by using the same approach.

Standardized effort enabled comparison of catch rates between this study and two historical data sets, one employing the same trawl gear as the current study (Dickerson et al.[1]) and another using 18-m mongoose-style nets with 10-cm stretch mesh webbing (Van Dolah and Maier, 1993). Effort and catch for daytime only trawling in 1991 were obtained from Van Dolah et al.[2] A negative binomial GLM with log-link function was used to compare loggerhead catch between study periods (1991–92 vs. 2004–07) with year and month as factors and the log of the sampling effort as an offset variable. Data for May were available in all years; however, data for August were absent in 1992 and 2006 and data for June were only available in 1991 and 2004.

Straight-line carapace length (nuchal notch to postmarginal scutes, SCLnt) was compared between 2004–07 and 1991–92 (Dickerson et al.[1]; Van Dolah et al.[2]). Size values were not normally distributed; therefore, data grouped by 10-cm size classes were analyzed with Kruskal-Wallis analysis of variance by ranks and Dunn-Bonferroni pairwise comparisons (Minitab 15®; Minitab, Inc., State College, PA). Sex and mtDNA data were evaluated by using chi-square analysis (Minitab 15®) to test for annual differences in the ratio of females to males and variations in haplotype frequencies between groups of interest. Owing to a high probability of error for determing the sex of pubescent loggerheads based on hormone levels alone, sex was not assigned for loggerheads from 75.1 to 85.0 cm SCLnt.

Results

Catch and recapture data

From the 432 trawling events conducted in the Charleston shipping channel between May 2004 and August 2007, 220 loggerhead sea turtles were captured (Table 1). Eight of 220 loggerheads (3.6%) were recaptured during the survey of which four were recaptured during the same cruise, one was recaptured during the same season, and three were recaptured in subsequent years 257, 453, and 705 days later. Two loggerheads captured by trawling <5 km from the Charleston shipping channel in 2001 by the South Carolina Department of Natural Resources (SCDNR) were recaptured in this channel 1066 and 1396 days after initial tag and release. Only two loggerheads tagged during this survey were reported as recaptured away from the channel: a 95.4-cm SCLnt female captured in May 2006 nested on Cumberland

[2] Van Dolah, R. F., P. P. Maier, S. R. Hopkins-Murphy, G. F. Ulrich, and D. M. Cupka. 1992. A survey of turtle populations in the Charleston Harbor entrance channel. SC Dept Natural Resources, Charleston, SC Final Report #14-16-0004-90-944 to USFWS. [Available from http://dnr.sc.gov/marine/turtles/Literature/Van%20Dolah%20CNHB%20Channel.pdf, accessed June 2011.]

Table 1

An overview of sampling effort (CPUE) and loggerhead sea turtle (*Caretta caretta*) catch (no. of loggerheads) in the Charleston, South Carolina, shipping channel between 2004 and 2007. Fate of turtles relative to original capture numbers is indicated in parentheses as follows: five within-year recaptures denoted by a W, three between-year recaptures denoted by a B, one loggerhead recaptured elsewhere denoted by RE, two loggerheads tagged elsewhere denoted by TE, and one loggerhead stranded near Charleston in a subsequent year denoted by an S. CI=confidence interval.

Year	Start	End	No. of events	"A"	"B"	"D"	"E"	*C. caretta*	Mean CPUE	95% CI
2004	05/11	05/19	48	15	13	14	6	49 (1W, 1TE, 1S)	1.55	0.66
2005	05/09	05/20	70	30	20	20		36 (1TE)	0.54	0.13
2006	05/15	05/26	69	29	20	20		43 (2W, 1B, 1RE)	0.63	0.12
2007	05/21	05/22	16	0	1	15		7	0.40	0.10
2004	06/14	06/25	71	31	20	20		55 (2W, 1B)	0.74	0.18
2004	08/23	09/01	43	14	15	14		16 (1B)	0.36	0.10
2005	08/08	08/19	92	39	26	27		11	0.13	0.03
2007	07/31	08/01	23	0	8	15		7	0.33	0.08
Total			432	158	123	145	6	224		

Island, GA, in June 2008 and an 81.2-cm SCLnt loggerhead (sex not determined) stranded approximately 25 km north of the channel in May 2005, 372 days after being tagged and released.

Forty percent (158 events) of trawling events during 2004–06 were completed in the "A" block (which included three stations) compared to 29% of sampling effort in the "B" (114 events) and "D" (115 events) blocks which had two stations apiece; however, these differences were not statistically significant among years (χ^2=0.785, df=4, P=0.940). Trawling in 2007 was conducted only in the "D" (93% in May, 65% in August) and "B" (all others) blocks.

Table 2

The importance of model terms (ordered by *P*-value) on loggerhead sea turtle (*Caretta caretta*) catch in the Charleston, South Carolina, shipping channel, 2004–07. Seven variables and three interaction terms (see *Materials and methods* section for description) were removed from the final model. The Akaike information criterion (AIC) score and the percentage of model variance accounted for are also included.

Model terms retained	*P*-value
Sampling period	<0.001
Sampling block	<0.001
Barometric pressure (mb)	0.004
Miscellaneous crabs (count)	0.009
Vessel speed (kn)	0.020
Horseshoe crabs (count)	0.056
Wind direction (degrees)	0.077
Cloud cover (%)	0.088
Tide stage (ebb, flood)	0.126
Miscellaneous jellyfish (count)	0.135
Surface temperature (°C)	0.171
AIC score	675.2
Null model deviance	523.8
Final model deviance	288.4
% of model deviance explained	44.9

Significant influences on loggerhead catch included sampling period, sampling block, barometric pressure (mean ±95%CI=1015.6 ±0.5 mb), vessel towing speed (2.8 ±0.02 kn), and miscellaneous crabs (586 specimens); 17 variables and factors were deemed nonsignificant or were dropped from the final model (Table 2). High adjusted loggerhead sea turtle catch in the "D" (and to a lesser extent the "B") block in May 2004 (mean ±95%CI=1.55 ±0.66 turtles per 30.5 m net-hour) and June 2004 (0.74 ±0.18 turtles per 30.5 m net-hour) contributed greatly to significant results (Fig. 2). Barometric pressure in May 2004 (median=1026 mb) was significantly greater (H=296.2, df=7, P<0.001) than all other sampling periods except May 2007 (median=1020 mb); however, miscellaneous crab counts (Fig. 3) in May 2004 (12.0 ±87.8 crabs/event) were not statistically different from other sampling periods (≤1.8 ±28 crabs/event). The GLM accounted for 45% of the model deviance in adjusted loggerhead catch.

The GLM (AIC=872.4) explained 17% of model deviance in adjusted loggerhead catch between the 1991–92 and 2004–07 study periods and both model terms (month and year) were significant (P<0.001). Greatest catch rates occurred in May (Fig. 4); however, catch rates in May 1991 and 1992 represented just one loggerhead in 12 trawling events and five loggerheads in 27 trawling events, respectively. Confidence intervals around mean adjusted loggerhead catch did not overlap between study periods for any month, and the greatest catch rate during 1991–92 only exceeded that of August 2005 in the present study (Fig. 4).

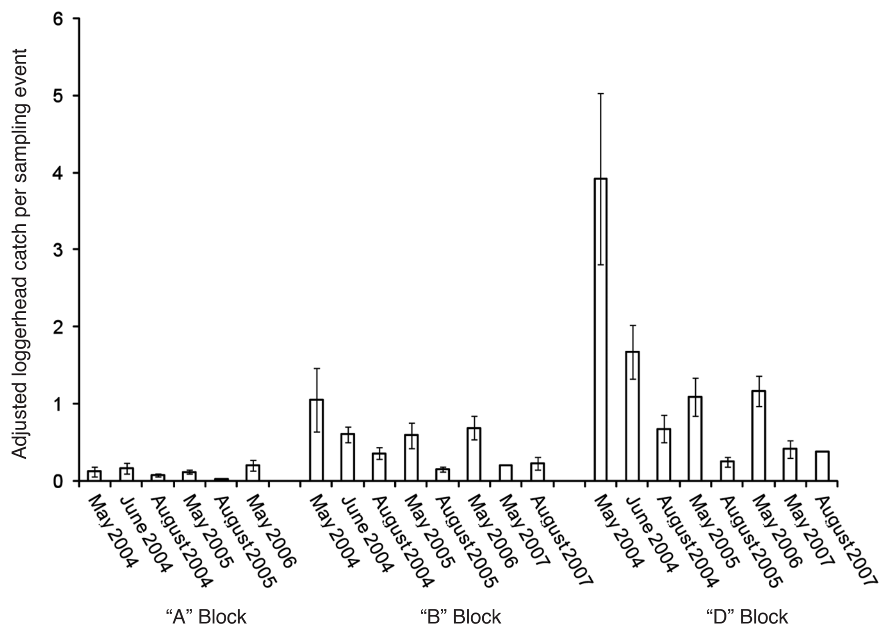

Figure 2

Model-adjusted loggerhead sea turtle (*Caretta caretta*) catch (mean ±95% confidence interval) per trawling event by sampling period and location within the Charleston, South Carolina, shipping channel during 2004–07.

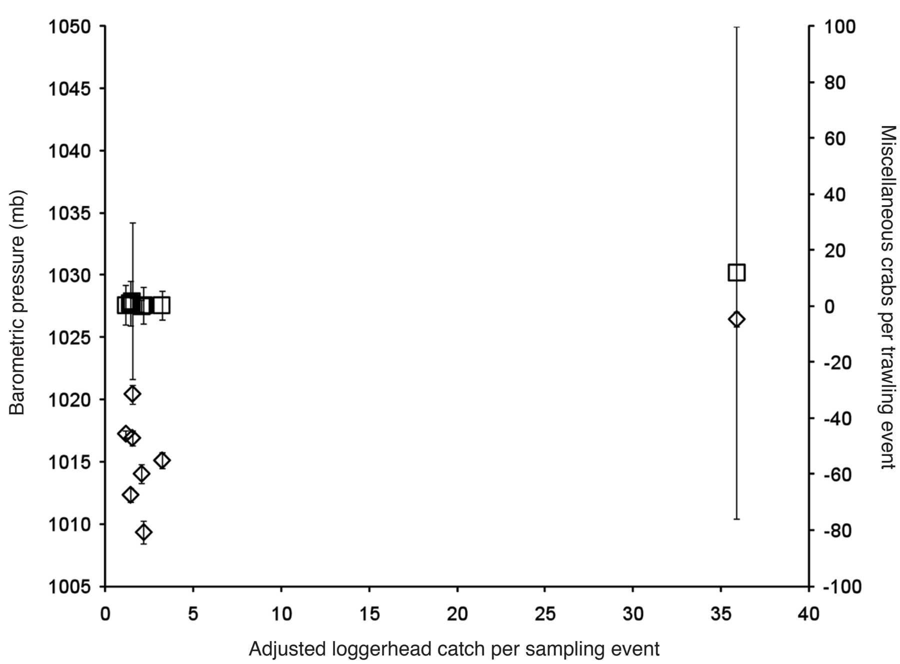

Figure 3

Distribution (mean ±95% confidence interval) of barometric pressure (diamonds) and miscellaneous crab count (squares) relative to mean model adjusted loggerhead sea turtle (*Caretta caretta*) catch in the Charleston, South Carolina, shipping channel during 2004–07.

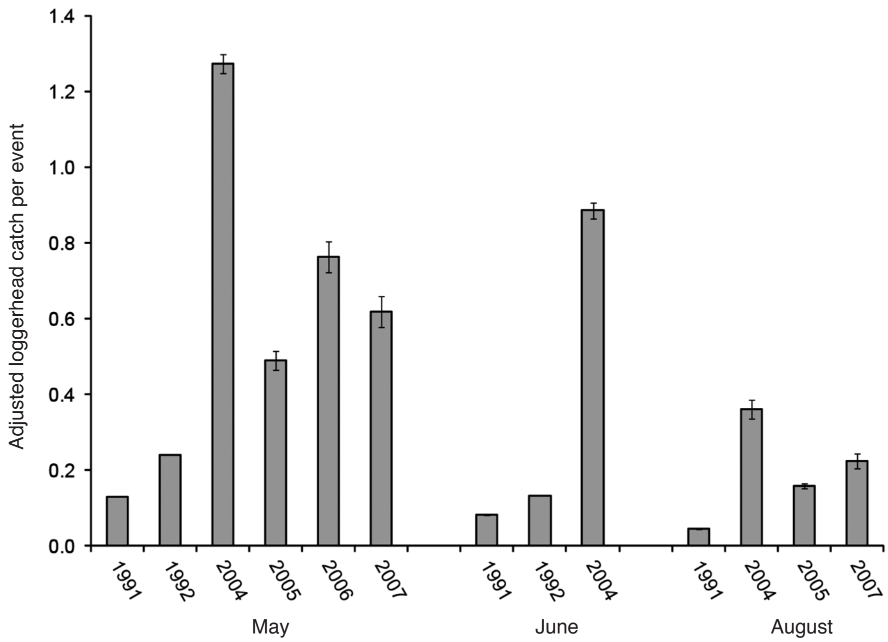

Figure 4

Model-adjusted loggerhead sea turtle (*Caretta caretta*) catch (mean ±95% confidence interval) per trawling event in the Charleston, South Carolina, shipping channel by year and month between 1991–92 and 2004–07.

Size, sex, and genetic distributions

Eighty-three percent (184 of 220) of loggerheads measured ≤75.0 cm SCLnt (Fig. 5). Size distribution at time of initial capture during 2004–07 was not significantly different by month (H=2.53, df=2, P=0.283) or by year (H=2.27, df=3, P=0.518). Loggerhead sea turtles captured between May and August in 2004–07 were larger (median=67.9 cm SCLnt) and exhibited a narrower size range (54.4–101.0 cm SCLnt) than loggerheads captured between May and August in 1991–92 (median=61.5 cm SCLnt; range=51.1–112.0cm SCLnt); however, size distributions were not statistically compared because only nine loggerheads were captured during daytime only trawling between May and August 1991–92.

Sex was determined for 176 loggerheads ≤75.0 cm SCLnt at the time of initial capture during 2004–07, which occurred with a sex ratio of 3.9 females per male and which was significantly different from a 1:1 ratio (χ^2=33.6, df=1, P<0.001). Sex ratio for loggerheads ≤75.0 cm SCLnt was not significantly different by month (χ^2=1.44, df=2, P=0.486). Annual sex ratios for loggerheads ≤75.0 cm SCLnt ranged from 2.9 females per male in 2004 (98) to 10.7 females per male in 2005 (35); however, sex ratios in 2004 were not significantly different from the pooled sex ratios between 2005 and 2007 (78; χ^2=3.47, df=2, P=0.062). Twice as many loggerheads ≥85.1 cm SCLnt captured during 2004–07 were female (11) than were male (6), but this ratio was not statistically different from a 1:1 sex ratio (χ^2=0.77, df=2, P=0.380). Seventy percent (12) of loggerheads ≥85.1 cm SCLnt were captured in May, 23% (4) in June, and only one in August, whereas loggerheads ≥85.1 cm SCLnt were captured in all years, except 2007. Sex was not able to be determined for eight loggerheads ≤75.0 cm.

mtDNA data were available for 213 of 220 loggerheads captured from the Charleston shipping channel between 2004 and 2007. Haplotypes other than CC-A01 or CC-A02 were possessed only by loggerheads ≤75.0 cm SCLnt (Table 3). The ratios of CC-A01 to CC-A02 were not statistically different (χ^2=0.654, df=2, P=0.721) among three loggerhead size classes (≤75.0 cm vs. 75.1 to 85.0 cm vs. ≥85.1 cm SCLnt). Eighty-nine percent of loggerheads ≤75.0 cm SCLnt had the CC-A01 (93; 52%) or the CC-A02 (65; 37%) haplotype. Eleven percent (20) of loggerheads ≤75.0 cm SCLnt possessed haplotypes other than CC-A01 or CC-A02 (Table 3), of which 16 were observed in 2004 (10 in June 2004) and two apiece were observed (in May) during 2005 and 2006. Haplotype CC-A01 was twice as common as CC-A02 among 19 loggerheads 75.1 to 85.0 cm SCLnt, but occurred with similar frequency among 16 loggerheads ≥85.1 cm SCLnt.

Discussion

Increased standardized catch rates of loggerheads in the Charleston shipping channel concurrent with expanded use of TEDs are encouraging for future species recov-

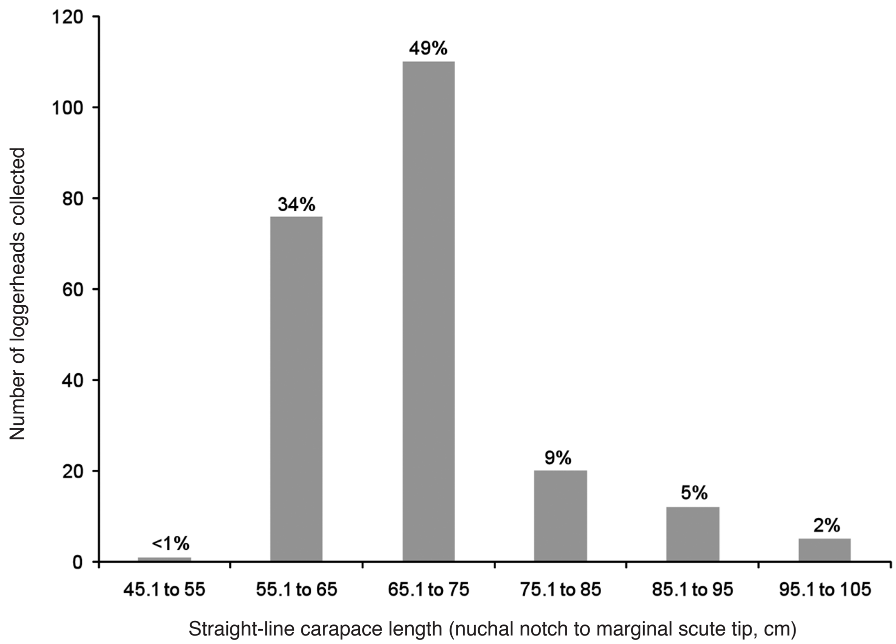

Figure 5

Size distribution of loggerhead sea turtles (*Caretta caretta*) captured in the Charleston, South Carolina, shipping channel during May, June, and August 2004–07.

Table 3

Haplotype distribution by straight-line carapace length (SCLnt) groupings among 213 loggerhead sea turtles (*Caretta caretta*) captured from the Charleston, South Carolina, shipping channel (2004–07). Only loggerheads ≤75.0 cm SCLnt possessed haplotype designations other than regionally dominant (CC-A01 and CC-A02) haplotypes. Additionally, one loggerhead possessed a new haplotype that was not previously described and is pending an official designation.

SCLnt	CC-A01	CC-A02	CC-A03	CC-A07	CC-A09	CC-A10	CC-A13	CC-A14	New	Total
≤75.0 cm	93	65	4	2	1	4	1	7	1	178
75.1 to 85.0 cm	12	7								19
≥85.1 cm	8	8								16

ery in the Northwest Atlantic provided that the trends reported here are indicative of a larger pattern and that these cohorts survive to maturity. Catch variability was noted within both study periods; however, between 2004 and 2007 only catch rates in August 2005 did not exceed 1991–92 levels. Comparison of loggerhead catch rates in the present study with loggerhead catch rates in 1991 (Van Dolah et al.[2]) suffered from low loggerhead catch rates (i.e., ≤1 loggerhead per month) as well as low monthly sampling effort (i.e., 11 to 12 daytime trawls per month). Furthermore, a peak daytime catch rate of six loggerheads occurred in July 1991 (Van Dolah et al.[2]), but these data were not analyzed because we did not sample in July during 2004–07. However, high catch rates in July 1991 represented an anomaly relative to other catch rates during 1991–92 and were analogous to high catch rates in May 2004 relative to other catch rates during 2004–07. Given limited overlap in catch rates between study periods we contend that loggerhead catch rates (and presumably abundance) in this shipping channel have increased since the early 1990s.

Lower recapture rates in 2004–07 relative to the two previous studies were also consistent with the suggestion that more loggerheads used the Charleston shipping channel in this study than in the early 1990s. During monthly trawl surveys that spanned 11 to 16 months each, Van Dolah and Maier (1993) recaptured seven of 53 (13%) loggerheads and Dickerson et al.[1] recaptured four of 45 (9%) loggerheads. Loggerhead recaptures during the two previous studies also occurred in pulses. For example, in September 1991 a loggerhead was recaptured in both studies that had been tagged and released by the other study during that same month. Additionally, three additional loggerheads that were previously tagged and released by Van Dolah and Maier (1993) were also recaptured in September 1991 by Dickerson et al.[1] In contrast, only eight (3.6%) of 220 loggerheads tagged after collection in the shipping channel during 2004–07 were recaptured during this study, four of which were recaptured within the same 2–10 day sampling period. During 2004–07, recaptures of loggerheads tagged in a previous year occurred in spring when total loggerhead catch was also greatest, similar to trends reported by Van Dolah and Maier (1993) and Dickerson et al.[1]

Significant variables accounted for 45% of model deviance, of which sampling period (outlier) and sampling block within the channel were most strongly associated with loggerhead catch. Loggerhead catch rates were greatest in the "D" sampling block (farthest offshore) and least in the "A" block (closest inshore). A clustered distribution with increasing catch farther seaward in the channel was consistent with aggregation of loggerheads in the "D" block throughout the Van Dolah and Maier (1993) survey; however, Dickerson et al.[1] did not report spatial clustering of catch during monthly trawl surveys in this channel between September 1991 and November 1992. Lack of spatial influence on catch reported by Dickerson et al.[1] may stem from sampling the center of the channel to avoid "edge effects," whereas channel edges were sampled by Van Dolah and Maier (1993) and the present study (2004–07). Dickerson et al.[1] also sampled fewer (3) and longer (3 km vs. 1.5 km) stations than Van Dolah and Maier (1993) and the present study; thus, fine-scale habitat differences may have been less discernible owing to overlap in station boundaries.

Among environmental variables, only barometric pressure was significantly associated with loggerhead catch rates, notably due to higher barometric pressure during May 2004. Barometric pressure in May 2004 was statistically similar to May 2007 when loggerhead catch rates were much lower despite targeted trawling in May 2007 at stations associated with high catch rates during the previous three years. Although some loggerheads foraging in oceanic habitats are reported to respond to changes in sea level height (Eckert et al., 2008), contrasting catch rates under similar barometric pressures between May 2004 and May 2007 suggest that higher barometric pressures in May 2004 were simply autocorrelated with anomalously high catch rates in May 2004. High loggerhead catch in May 2004 was more likely related to concurrent catches of horseshoe crabs, a known prey item (Plotkin et al., 1993; Seney and Musick, 2007), which was a marginally nonsignificant model term but that also occurred at high and potentially under reported levels because of high loggerhead catch (J. Byrd, personal observ.).

Intensive trawling in the Charleston shipping channel during a four-month window associated with peak annual catch (Van Dolah and Maier, 1993) revealed a consistent decline in catch rate between May and August, but there was no interannual change except for catch rate in May 2004, which was an outlier. Relatively stable catch rates during the present study may explain why most variables were deemed nonsignificant in (or were dropped from) the final GLM equation. In contrast, significant increases in catch rates were reported for juvenile loggerheads in estuarine study sites in Florida (Ehrhart et al., 2007) and North Carolina (Epperly et al., 2007) during the first half of the same decade. Catch rate increases in Florida and North Carolina were attributed to smaller (and presumably younger) loggerheads than those captured during the present study and are noteworthy for at least two reasons. First, annual survival (Conant et al., 2009) systematically reduces cohort abundance with age. Second, given compensatory growth in the pelagic phase (Bjorndal et al., 2003) and initial neritic settlement at a fairly consistent size and age (Conant et al., 2009), younger cohorts should provide a more direct reflection of nesting success than older cohorts with greater exposure to natural and anthropogenic sources of mortality. As such, increases in catch rates in Florida and North Carolina during the early 2000s likely reflect strong year classes hatched between 1989 and 2000 (Witherington et al., 2009), with larger loggerheads sampled in the present survey representing older (and initially less abundant) cohorts whose abundance was further reduced with time. Therefore, increased catch rates for similar sizes (and presumably similar ages) of loggerheads in the present study between 1991–92 and 2004–07 suggest great potential for sustained increases in nesting in the region during the next 10–20 years, assuming stable survival rates. However, we caution that indefinite increases are unrealistic, given multidecadal fluctuations in Northwest Atlantic loggerhead nesting which may be climate induced (Van Houtan and Halley, 2011).

Ninety-one percent of all loggerheads possessed one of two dominant haplotypes, consistent with previous genetic studies with loggerheads captured from our study location (Sears et al., 1995) and elsewhere along the U.S. East Coast (Rankin-Baransky et al., 2001; Bass et al., 2004; Roberts et al., 2005). Three distinct nesting "populations" in the southeast United States are also dominated by these two haplotypes (Encalada et al., 1998), but with different relative distributions of CC-A01 and CC-A02 between northeast Florida and North Carolina (0.79; 0.09), south Florida (0.44; 0.48), and northwest Florida (0.93; 0.06). In the present study only juvenile loggerheads ≤75.0 cm SCLnt possessed haplotypes other than CC-A01 or CC-A02 and were predominantly observed in May and June 2004, when greatest catch rates also occurred. Concentration of six rare (and one new) haplotypes in June 2004 was statistically unique, but given the time of year and the rare occurrence of these haplotypes from nesting beach and foraging ground surveys throughout the Northwest Atlantic (Bowen et al., 2004), high catch rates in May and June 2004 did not likely result from an influx of transients (Sasso et al., 2006). Instead, we suggest that primarily local sea turtles aggregate in shipping channels each spring, coincident with some transient use. For example, a female loggerhead collected and tagged during this study nested on Cumberland Island, Georgia, two years later. Shipping channels in the southeast United States may also be important stops for juvenile loggerheads migrating between foraging and overwintering areas (Morreale, 1999; McClellan and Read, 2007; Mansfield et al., 2009; Arendt et al., in press).

Juvenile female loggerheads were captured four times as frequently as males—a rate that is double that reported for pelagic juveniles collected from the Madeira Archipelago (Delgado et al., 2010) and for neritic juveniles from estuarine and coastal waters from Florida to North Carolina (Wibbels et al., 1991; Shoop et al., 1998; Braun-McNeill et al., 2007). Sex ratios (two females per male) reported for neritic loggerheads in U.S. waters also differ, however, from sex ratios determined by direct gonadal observation for (predominantly pelagic phase) loggerheads in the Mediterranean Sea, where a 1:1 ratio is reported (Casale et al., 2006). Hopkins-Murphy et al. (2003) suggested that female-biased foraging grounds may exist in the poorly surveyed tropics; however, fine-scale habitat partitioning by sex among juveniles within a geographic area is perplexing and to the best of our knowledge has not been previously reported. The four-to-one female bias for juvenile loggerheads captured in this channel (the same ratio as 12 females and three males of similar size collected from the same location between May and November 1991, NOAA[3]) and higher injury rates among loggerheads collected from this channel than from adjacent shoals (Alderson, 2009) indicate that mortality of developing females may disproportionately occur in shipping channels if the data reported here are representative of larger trends in the region.

Conclusions

Seasonal occurrence of loggerheads in shipping channels and the distribution of shipping channels along a latitudinal gradient in the southeastern United States are ideal for assessing catch rates of loggerheads at a network of index sites, a high priority action of the Northwest Atlantic loggerhead recovery plan (NMFS and USFWS, 2008). Temporal and spatial variables appeared to exert the most influence on loggerhead catch rates and accounted for nearly half of model deviance in the present study. Within-channel spatial influences on catch in the present study were consistent with those from historic data and, as such, represent important sampling design considerations for future studies at this location, and likely at other shipping channels as well. Peak within-season catch in the present study contrasted with monthly data reported for this location in 1991 (Van Dolah and Maier, 1993) and 1992 (Dickerson et al.[1]). Satellite telemetry data collected for a subset of loggerheads tagged and released during the present study revealed greatest affinity for adjacent shoals and fidelity to the channel itself during spring (Arendt et al., in press)—an affinity consistent with *in situ* tracking at this location during spring (Keinath et al.[4]) and summer (Maier et al.[5]). As such, there exists a high probability of being able to assess and account for "detectability" (Anderson, 2001) in shipping channels with spatial and temporal factors, which in turn should enhance the statistical confidence of using shipping channels as index sites for long-term trends assessments. Fine-scale influences on detectability of loggerheads within shipping channels will likely require continuous and concurrent monitoring of loggerhead occurrence and a suite of environmental variables and should be included in future research efforts to study sea turtle distributions in shipping channels. In addition to strengthening statistical confidence, such data sets could also potentially help identify mechanisms to reduce anthropogenic mortality rates, which are a continued conservation need, and that were the original premise for evaluating sea turtle occurrence in shipping channels.

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[3] NOAA (National Oceanographic and Atmospheric Administration). Unpubl. data. Sex determination from testosterone radioimmunoassay conducted by David Owens, Texas A&M University. Data maintained by Kathy Moore, National Ocean Service, 219 Fort Johnson Road, Charleston, SC 29412, and available from Kathy.Moore@noaa.gov.

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