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Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 5(5) : 281-290

Published By: American Fisheries Society

URL: https://doi.org/10.1080/19425120.2013.829143

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 5:281–290, 2013

ISSN: 1942-5120 online
DOI: 10.1080/19425120.2013.829143

ARTICLE

Assessment of Management Scenarios to Reduce Loggerhead Turtle Interactions with Shrimp Trawlers in Georgia

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Abstract
Recovery of loggerhead turtle *Caretta caretta* populations depends on many factors, including reducing anthropogenic mortality of adult turtles. Shrimp trawls are considered a major source of mortality for adult loggerhead turtles despite the mandatory use of turtle excluder devices. We modeled scenarios for reducing the likelihood of interaction between nesting adult loggerhead turtles and shrimp trawlers operating off the coast of Georgia during the nesting season (May–August). We used satellite telemetry and aerial surveys to describe the distribution patterns of nesting adult female turtles (2004–2005; $n = 22$) and shrimp trawls (1999–2005), respectively, across waters adjacent to the Georgia shoreline. Adult female turtles and shrimp trawlers both occupied state waters extensively during the nesting season. Turtles tended to have long, narrow home ranges that were located parallel to shore and that overlapped with the shrimp trawl distribution, which showed a slight grouping around deep channels. We modeled the efficacy of fleet reductions and spatial closures (accounting for fleet redistribution) in reducing shrimp trawler activity around loggerhead turtles. A comparison of spatial closures indicated that a large closure of state waters (∼200 km^2) east of Sapelo and Blackbeard islands would reduce mean trawler activity levels in turtle home ranges. We also found that fleet reductions of 50% or more reduced potential interactions between turtles and trawlers. Although spatial closures produced a net total reduction in turtle–trawler interactions, fleet reductions yielded a reduction in such interactions across the study area. We recommend that to reduce loggerhead turtle–trawler interactions, state agencies should consider a limited-entry system or some other means to limit the number of vessels operating within state waters.

Five recovery units have been established for the Northwest Atlantic population of loggerhead turtles *Caretta caretta*; the Northern Recovery Unit extends from the Florida–Georgia border to the northern extent of the nesting range in Virginia. The Northern Recovery Unit is the second-largest nesting aggregation, but the number of nests has declined at a rate of 1.3% annually since 1983 (NMFS and USFWS 2008). Declines have continued despite comprehensive nest protection efforts

Subject editor: Debra J. Murie, University of Florida, Gainesville

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Received October 2, 2012; accepted July 17, 2013

spanning more than three decades and despite the mandatory use of turtle excluder devices (TEDs) in all commercial shrimp trawl nets since the 1990s. Even with the use of TEDs, bottom trawls like those used in the commercial shrimp fishery are listed as one of several highest priority threats that limit the species' recovery. Noncompliance with proper TED installation regulations, lack of adequate enforcement, and repeated sequential captures of loggerhead turtles have been identified as potential sources of mortality (Turtle Expert Working Group 1998; Lewison et al. 2004; NMFS and USFWS 2008). Adult female loggerhead turtles are especially important for recovery of the species (Crouse et al. 1987) but may be susceptible to incidental capture by shrimp trawls during the nesting season. A better understanding of in-water movement patterns by nesting females is needed to effectively evaluate alternative management approaches that aim to limit interactions between shrimp trawls and loggerhead turtles (Hawkes et al. 2011).

The nesting season for loggerhead turtles in the Northern Recovery Unit begins in early May and continues through mid-August (Richardson 1980). Females may lay up to seven or eight clutches during a nesting season (Talbert et al. 1980; Lenarz et al. 1981; Tucker 2010), with estimated means of 4.1 (Murphy and Hopkins 1984) and 5.4 nests/female per season (Tucker 2010). The internesting interval (number of days between consecutively laid nests by a single individual) is approximately 14 d (Richardson 1980). The distribution and movement behavior of loggerhead turtles between nesting events are poorly understood for the Northern Recovery Unit, although anecdotal evidence suggests that the turtles stay within 10 km of shore and sometimes enter estuarine habitats behind barrier islands (Stoneburner 1982; Hopkins-Murphy et al. 2003). Some turtles associate with areas of high relief, such as shipping channels or shoals (Hopkins-Murphy et al. 2003).

Reducing the interactions between the commercial shrimp trawl fishery and loggerhead turtles of the northern subpopulation is a priority action necessary to recover the species (NMFS and USFWS 2008). The South Atlantic Fishery Management Council (SAFMC 2002) stated that possible management options could encompass an overall reduction in fishing effort or temporal and spatial closures. Detailed information on movements and habitat use is critical for assessing the efficacy of proposed management strategies for reducing shrimp trawler-related mortality in the northern subpopulation of loggerhead turtles, yet much of this information is lacking. Considerable effort has been spent describing loggerhead turtle movements during critical life history stages, with suggestions for using the data to improve management and aid conservation (Sakamoto et al. 1997; Mansfield et al. 2009; Marcovaldi et al. 2010; Tucker 2010; Hawkes et al. 2011; Kobayashi et al. 2011; Arendt et al. 2012). However, habitat models and movement data are most useful when they are used to make predictions about consequences of management actions (Conroy and Moore 2002). Use of loggerhead turtle movement data to forecast the outcomes of proposed management actions has not been attempted.

Our goal was to demonstrate the use of loggerhead turtle movement data in forecasting the results of proposed management actions prior to implementation. Specifically, we used movement patterns of loggerhead turtles to evaluate the efficacy of different management scenarios in reducing the potential for interaction between shrimp trawls and loggerhead turtles during the nesting season in waters adjacent to the Georgia coast. We established an index of trawler activity occurring around loggerhead turtle use areas; we then modeled the expected change in the trawler activity index (TAI) after the implementation of different spatial closure and shrimp trawl fleet reduction scenarios.

METHODS

Distribution Patterns

Nesting loggerhead turtles ($n = 24$) were captured and tagged during night patrols on four Georgia barrier islands (Figure 1) during the 2004 and 2005 nesting seasons ($n = 12$ turtles/year). Patrols began in mid-May during each season and continued until all transmitters were deployed (July 7 in 2004; May 31 in

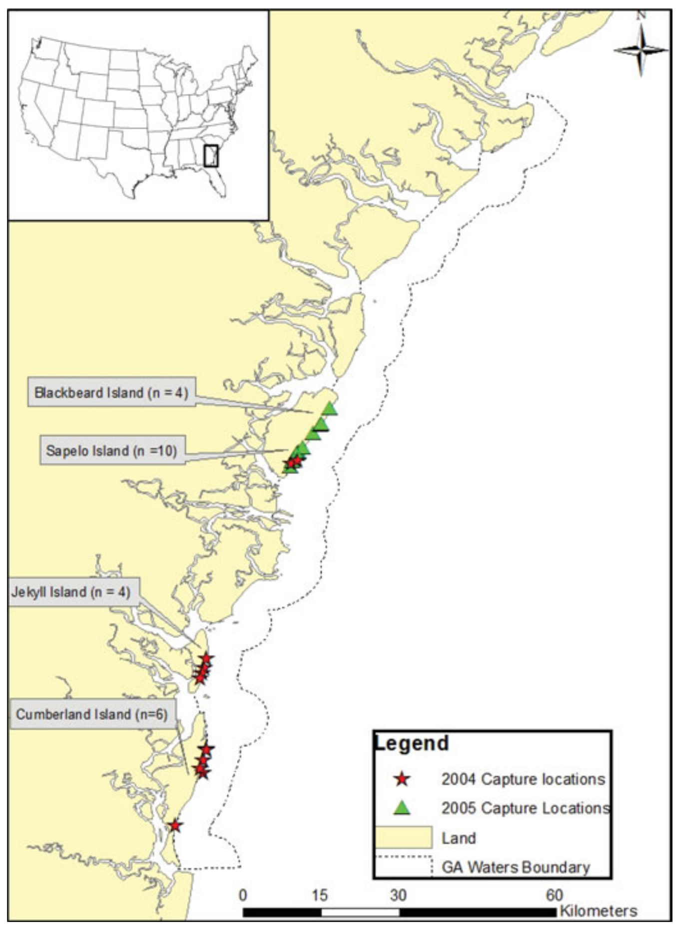

FIGURE 1. Capture locations of loggerhead turtles ($n = 24$) during the 2004 and 2005 nesting seasons on four barrier islands in Georgia.

2005). Females that were encountered on the beach were fitted with platform terminal transponders (Model ST-20; Telonics, Inc.), sonic transmitters (modified Model CHP-87-S; Sonotronics), and (in 2005 only) very high frequency (VHF) radio transmitters (MOD-305; Telonics). Attachment methods followed those detailed by Mitchell (2000).

Upon release of the turtles, Geostationary Operational Environmental Satellites (National Oceanic and Atmospheric Administration) monitored the platform terminal transponder signals on a continuous duty cycle (CLS 1996). Only fixes from satellite transmitters of location classes 3, 2, 1, and A were used. Location classes 0 and B were excluded due to excessive error (Hays et al. 2001; Vincent et al. 2002; Scott 2006). Manual tracking by boat using VHF and sonic telemetry occurred during daylight hours. Loggerhead turtle locations from manual tracking efforts were visually confirmed by waiting for the turtle to surface (Collazo and Epperly 1995). Location coordinates for each manually located turtle were recorded with a handheld GPS unit.

Prior to analyzing the distribution and movement patterns of marked loggerhead turtles, the satellite telemetry location database and manual tracking database were combined and subjected to censoring processes to eliminate duplicate entries, outliers based on liberal swim speed restrictions (i.e., a distance greater than would be expected for a turtle swimming 10 km/h between point locations), and locations appearing on land beyond the error range. A 2-h minimum time period between points was also imposed on the combined database to reduce serial autocorrelation between successive points while maintaining adequate sample sizes (De Solla et al. 1999). For cases in which elimination of a location was required due to autocorrelation, the location with the highest quality level was retained. Location quality was ranked from highest to lowest as visual observation, followed by satellite location classes 3, 2, 1, and A, respectively. If quality levels were identical, the earliest location was kept.

Loggerhead turtle home ranges were estimated using fixed kernel densities (FKDs) at the 95% use level and 50% core area level (Worton 1989), with least-squares cross validation as the smoothing factor (Blundell et al. 2001). Only loggerhead turtles that yielded 15 or more locations during the internesting interval were included (Blundell et al. 2001). Portions of home ranges that overlapped with land were eliminated.

Bi-monthly aerial surveys of shrimp trawlers were conducted by the Georgia Department of Natural Resources during daylight hours over state and federal jurisdictional waters off the Georgia coast for seven consecutive years (1999–2005), with standardized methods used across all flights. Location coordinates for every shrimp trawl vessel observed during the surveys were recorded by using handheld GPS units. The trawler location database was filtered to include only locations of actively trawling vessels while eliminating locations of trawlers that were hauling in nets, anchored, or traveling. Furthermore, these analyses only included flights that occurred between May and August (i.e., coinciding with loggerhead turtle observations during the nesting season).

Baseline Trawler Activity

To evaluate the merits of management scenarios, we first established a baseline estimate of observed trawler activity levels around loggerhead turtle use areas. The turtle use areas were defined by 95% and 50% FKD home range contours. Within each home range, observed trawling activity was calculated as the mean density of trawlers (trawlers/km^2) observed per flight within each home range. We used the density of trawlers per flight as the observed TAI value. The TAI essentially described the 7-year average daily trawler density that occurred within the area of each home range during the nesting season. We assumed that loggerhead turtles occupying areas with consistently high trawler activity over the 7-year period had a higher probability of interaction with trawls than turtles occupying areas with consistently low trawler activity.

A null distribution of trawlers was created to identify patterns in the observed trawler distribution relative to loggerhead turtle use areas. To produce the null trawler distribution, a random point generator extension in ArcMap version 9.2 (ESRI 2008) assigned new latitude and longitude coordinates to each trawler location. Random trawler locations were restricted to within 9.6 km from shore, were excluded from estuaries, and occurred in equal proportion to how they were originally distributed relative to state and federal water boundaries (i.e., 87.5% in state waters). For each loggerhead turtle, 10 iterations of the random redistribution of trawlers for the null model were conducted, with a new TAI calculated each time. The 10 new TAI values for each turtle were then averaged to provide an estimated null TAI value. Comparisons between the observed and null distributions were made by dividing the null TAI by the observed TAI for each loggerhead turtle. A TAI ratio (null TAI/observed TAI) equal to 1.0 indicated that the observed trawler distribution occurred in a random pattern—that is, the TAI did not change when the trawler locations were randomized multiple times. If the TAI ratio was greater than 1.0, the observed trawler distribution would be best described as "clumped" but in areas that were not heavily used by loggerhead turtles (i.e., the randomized null distribution created a higher TAI than originally observed). If the TAI ratio was less than 1.0, the observed trawler distribution would be best described as clumped in areas that were also used heavily by loggerhead turtles (i.e., the randomized trawler distribution reduced the TAI around the turtles in comparison with the baseline observations).

Management Scenarios

Management scenarios were created by following conceptual formats outlined by the South Atlantic Fishery Management Council (SAFMC 2002). Options that were considered included spatial closures—either a single large closure or configurations of several small closures—and variable levels of fleet reduction. Potential utility of the different management scenarios was

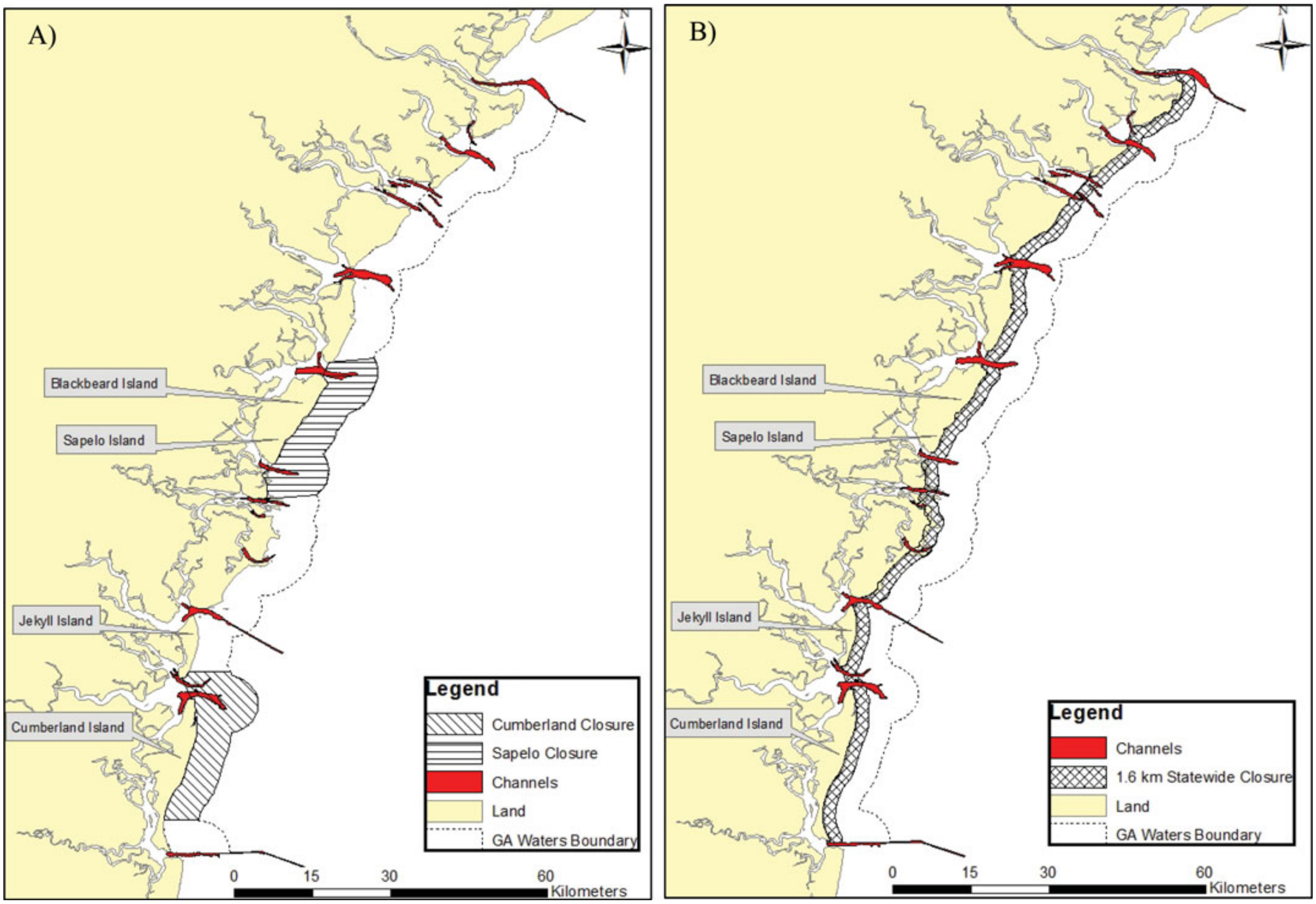

FIGURE 2. Shapes and locations of the three single large area closure scenarios evaluated for Georgia: **(A)** the Cumberland Island (Cumberland) and Sapelo Island–Blackbeard Island (Sapelo) closure scenarios; and **(B)** the statewide 1.6-km closure scenario. Maps show the 4.8-km state jurisdictional boundary and the locations of deep channels maintained between barrier islands.

evaluated by simulating the redistribution patterns of the commercial shrimp trawler fleet to create new trawler distributions. The new predicted distributions of trawlers were then used to calculate new TAI values for each loggerhead turtle, thereby allowing direct comparison with baseline values.

Spatial closures.—Preliminary analyses of loggerhead turtle and shrimp trawler distributions were used to identify boundaries of potential spatial closures. Areas of high overlap between the two distributions were identified and used to delineate the boundaries of the potential closure areas. We developed three scenarios involving a single large closure area and one scenario that involved several small closures. One management scenario was a single large closure from the eastern shore of Cumberland Island (Cumberland closure) to the state water boundary 4.8 km offshore (Figure 2A). Cumberland Island is considered a major nesting beach in Georgia (Georgia Department of Natural Resources, unpublished data). A single large closure east of the Sapelo Island–Blackbeard Island complex (Sapelo closure) was also delineated (Figure 2A). Like the Cumberland closure, the Sapelo closure's boundary extended from the shore to the state water jurisdiction line 4.8 km offshore. Sapelo and Blackbeard islands are also considered major nesting beaches (NMFS and USFWS 2008). The third single large closure scenario was a statewide closure that encompassed the waters within 1.6 km (1 mi) of shore (statewide 1.6-km closure), thus leaving 3.2 km (2 mi) of state waters open to commercial shrimp trawling (Figure 2B). A statewide 1.6-km closure was developed because both trawlers and loggerhead turtles tended to locate close to shore. The final closure scenario established several smaller protected areas focused around deep channel locations (channel closure) identified across coastal Georgia (Figure 3). The closure boundary for each channel was delineated by placing a 1-km buffer around the channel area.

New TAI values were calculated for each loggerhead turtle under each spatial closure scenario. Trawler locations within the spatial closure boundaries were counted and removed from the database, thus simulating the exclusion of trawlers from those areas. Because displaced trawlers likely would continue to fish,

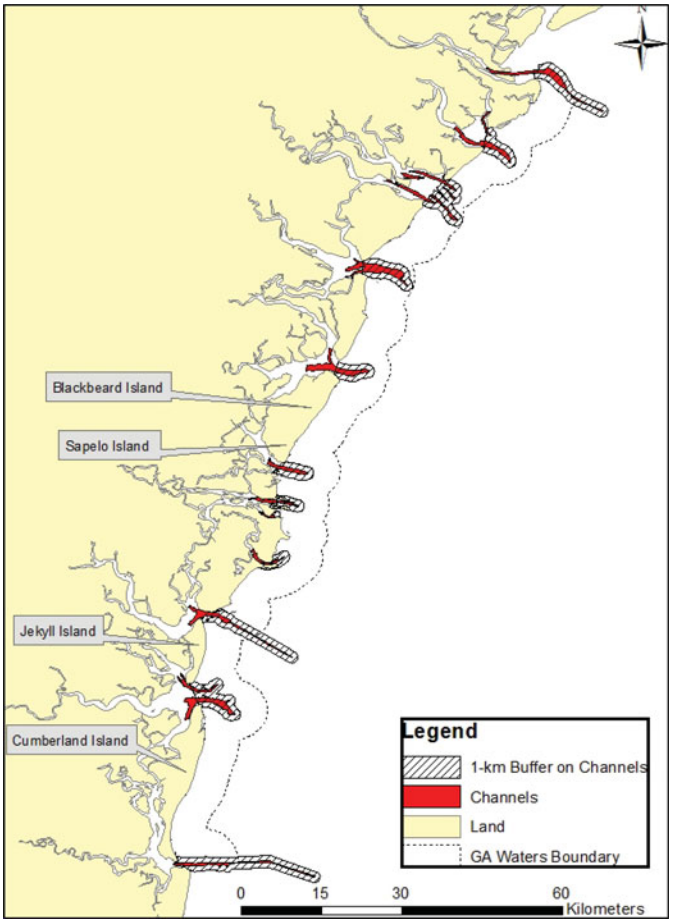

FIGURE 3. Shapes and locations of the several small closure areas delineated for the channel closure scenario in Georgia.

an equal number of trawler locations were redistributed across the extent of trawler use as determined from the aerial surveys. Uncertainty existed as to how the displaced trawlers would redistribute when faced with a closure around an area in which they previously operated (Stelzenmüller et al. 2008; Greenstreet et al. 2009). Thus, three competing hypotheses that described potential trawler redistribution patterns were evaluated. The first hypothesis was that trawlers would relocate randomly within a 2-km buffer along the outside edge of the closure boundary (Sweeting and Polunin 2005). The premise behind this prediction was twofold: (1) shrimp boat captains would want to stay near areas they previously fished (Mason et al. 2012) and (2) the captains would view the sanctuary as a source population of shrimp and would concentrate operation around closure edges, gleaning shrimp outflow from the unexploited sanctuary area (Mason et al. 2012). The second hypothesis was that trawlers would relocate randomly across the study area but would do so in equal proportion to their pre-closure distribution within state and federal jurisdictional waters (Hiddink et al. 2006). The third hypothesis was that trawlers would redistribute randomly across the study area but would remain in equal proportion to the pre-closure distribution of low-density (0.001–2.5 trawlers/km^2), medium-density (2.501–5.0 trawlers/km^2), and high-density (>5.0 trawlers/km^2) areas (Hiddink et al. 2006; Hunter et al. 2006). Homogeneity in displaced trawlers' responses to a closure was considered unlikely due to individual human choice and the many influencing factors driving that choice (Stelzenmüller et al. 2008). Any single trawler redistribution hypothesis would not be a clear predictor of how all trawler captains would respond to closures (Hiddink et al. 2006). Belief in the different redistribution hypotheses was considered equal, so consecutive TAI values predicted for individual loggerhead turtles under each of the three hypotheses were averaged to produce a new mean TAI value for each turtle. Ten iterations of the three-hypothesis trawler redistribution model were run, producing a mean estimated TAI value for each loggerhead turtle under each spatial closure management scenario.

Fleet reductions.—Potential management scenarios representing 10, 30, 50, 70, and 90% fleet reductions were simulated. New TAI values were calculated for each loggerhead turtle under each fleet reduction scenario. To simulate fleet reductions, the corresponding proportions of trawler locations were randomly eliminated from the trawler database. Remaining trawler locations were used to recalculate the new TAI for each loggerhead turtle. Ten iterations of each trawler reduction model were performed, producing a mean estimated TAI value for each loggerhead turtle under each fleet reduction scenario.

Model Evaluation

Paired *t*-tests were performed to compare baseline TAI values among loggerhead turtles to the TAI values produced from each management scenario. Potential impacts of the management scenarios on mean trawler activity within each measure of home range or core use area (95% and 50% contours) were tested separately. We defined a meaningful reduction in turtle–trawler interaction as one for which the TAI after implementation of the management scenario differed significantly from the baseline TAI value ($\alpha = 0.05$).

RESULTS

Distribution Patterns

We were unable to obtain sufficient tracking data for two of our tagged loggerhead turtles. For the data from the other 22 turtles, the censoring process reduced the total number of usable locations by 26.7% to 955 locations. The 22 turtles provided adequate sample size for inclusion in analyses, with a mean of 43.4 usable locations/turtle (SE = 9.8; range = 16–107 locations/turtle). The turtles for which there were adequate data were tracked for an average of 42.6 d (SE = 4.0; range = 24–65 d). Loggerhead turtles exhibited wide variability in estimated 95% FKD home range size, averaging 206.5 km^2 (SE = 173.8) and ranging from 7.0 to 1,750.0 km^2. Similar variability was observed for the 50% core area sizes, which averaged 25.2 km^2 (SE = 22.9) and ranged from 0.3 to 244.8 km^2. Tracked

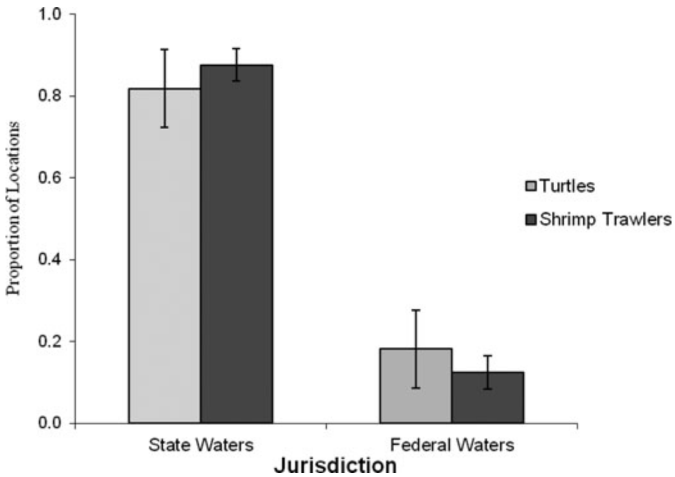

FIGURE 4. Mean proportion of loggerhead turtle locations (2004–2005) and shrimp trawler locations (1999–2005) occurring in state and federal jurisdictional waters. Error bars represent 95% CI around the means.

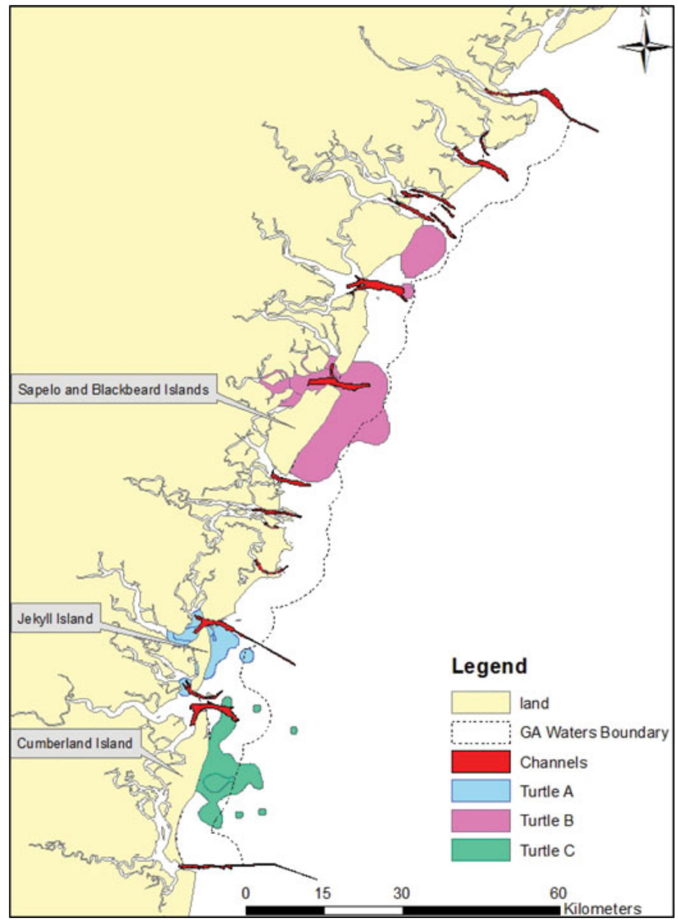

FIGURE 5. Three representative 95% fixed kernel density home ranges estimated for female loggerhead turtles that were tagged while nesting on Georgia barrier islands in 2004 and 2005.

loggerhead turtles were observed to extensively use state jurisdictional waters (mean percentage of observations; Figure 4), with the majority of the turtles (n = 20), termed "nearshore turtles," located on average 2.7 km (SE = 0.7) from shore (Figure 5). The other two individuals, termed "offshore turtles," were located on average 26.0 km (SE = 12.2) from shore. In addition, locations for each loggerhead turtle tended to be distributed parallel to shore (Figure 5). Half of the sample population (n = 11) used less than 40 km of shoreline each during their respective in-water movements over the duration of the nesting season (mean = 71.4 km; SE = 29.3; range = 15.3–286.6 km). Home ranges of individual turtles overlapped extensively.

During the 7 years of trawler activity monitoring, 43 flights occurred between May and August, recording 3,221 trawler locations (mean = 81.6 trawlers/flight). Of those trawler locations, 87.5% occurred in Georgia state jurisdictional waters, and the remaining trawler locations occurred within the first 4.8 km of federal water jurisdiction (Figure 6). Shrimp trawlers also tended to locate close to shore, with just over 40% of the observations occurring within the first 2.1 km from shore. Over one-quarter (27.6%) of the observed trawler locations were positioned within 1 km of deep channels, an area that makes up just 13.8% of the available seascape within 9.6 km of shore (excluding estuaries, which are closed to trawlers).

The general distribution pattern observed in trawler locations within 9.6 km of shore was best described as being random relative to loggerhead turtle distribution (Figure 6). The TAI ratio was less than 1.0 (0.85), indicating a clustering of trawler locations around specific areas that were also used by loggerhead turtles.

Management Scenarios

Spatial closures.—There was no discernible relationship between the impact of a spatial closure on the TAI and the number of trawlers that were displaced by the different spatial closures (Table 1). The scenarios of a single large spatial closure generally reduced mean TAI values more than the channel closure scenario, regardless of the home range contour evaluated (95% or 50%; Table 2). Mean TAI values produced by the channel closure scenario appeared to be nearly unchanged from the baseline TAI values after accounting for trawler redistribution. Only the Sapelo closure consistently resulted in predicted TAI reductions (P < 0.05) relative to the baseline TAI calculated from observed trawler locations (Table 2). Although similar in size to the Sapelo closure, the Cumberland closure did not produce a significant reduction in overall trawler activity in the study area. The statewide 1.6-km closure displaced more trawlers (Table 1), but there was no evidence that this closure would reduce trawl interactions with loggerhead turtles.

Fleet reductions.—The TAI values for loggerhead turtle use areas decreased as the level of trawler fleet reduction increased. A significant reduction in TAI within the 95% home ranges was observed after a 30% fleet reduction, but the trend was not repeated for the turtle core use areas (Table 2). A 50% fleet reduction (~42 active trawlers/d) was required before a

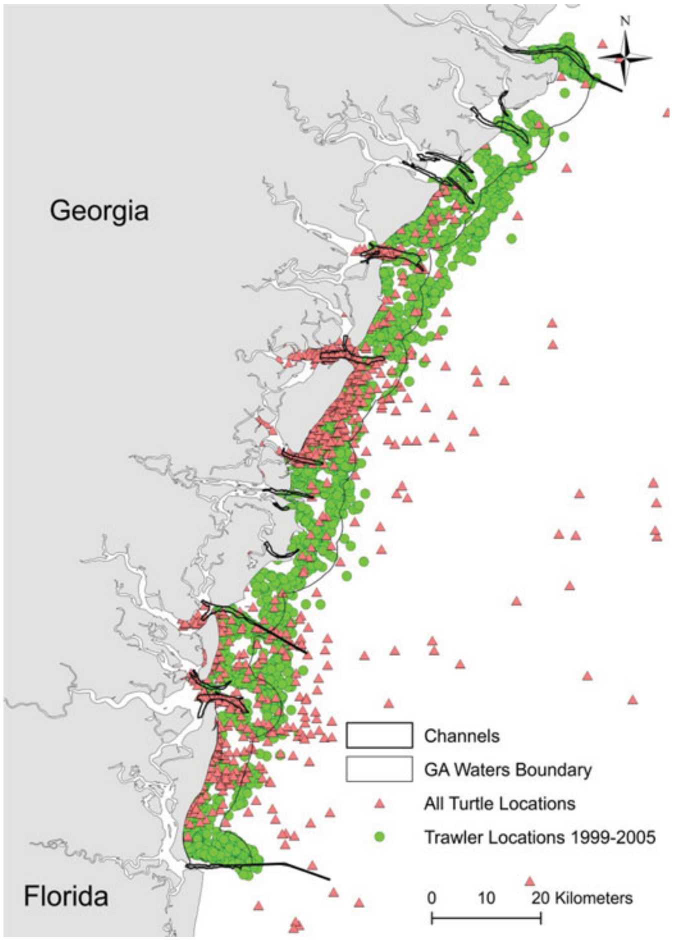

FIGURE 6. Locations of shrimp trawlers (1999–2005) and loggerhead turtles (2004–2005) in waters adjacent to the Georgia coast.

significant decrease in TAI was observed in both the 95% home ranges and 50% core use areas of tracked turtles (Table 2).

DISCUSSION

Our results indicated that only the Sapelo closure or a 50% or greater reduction in the shrimp trawl fleet would generate meaningful reductions in trawler activity around female loggerhead turtles in waters adjacent to the Georgia coast. Despite the apparent benefits of the Sapelo closure, fleet reduction would likely provide the greatest overall reduction in turtle interactions with trawlers. Fleet reductions would reduce the probability of trawler interaction for all female turtles regardless of home range distribution, whereas closure of limited areas would only benefit turtles that have home ranges overlapping the closure area. Although all of the spatial closures showed reductions in TAI for turtle home ranges that overlapped heavily with the closure area, redistribution of trawler activity outside of the boundaries actually resulted in an increased probability of trawl interaction for turtles outside of the closure areas. Given uncertainty about the distribution of the total nesting turtle population and shrimp trawler displacement after spatial closures, the observed consistency of fleet reduction in reducing turtle–trawler interactions supports its merit as the most effective management strategy.

The Sapelo closure scenario was the only spatial closure option that offered a potentially meaningful reduction in trawler activity around loggerhead turtles. The Cumberland closure was similar in size and shape to the Sapelo closure, but fewer trawlers were displaced and fewer turtle home ranges overlapped with the closure area (Table 1), which appeared to limit the Cumberland closure's effectiveness in reducing turtle–trawl interactions. This result supports the idea that the distribution and movements of both turtles and trawlers relative to the closure area are primary considerations for spatial closures (Murawski et al. 2000; Meyer and Holland 2005). Although the statewide 1.6-km closure displaced more trawlers and was nearly double in total area than the Sapelo closure, it produced little decrease in trawler activity around loggerhead turtles. The shape of the statewide 1.6-km closure area (i.e., narrow and parallel to shore) meant that the area bisected many loggerhead turtle home ranges but did not encompass any home range completely. In our simulations, trawlers that were displaced by the statewide 1.6-km closure redistributed back into loggerhead turtle home ranges, thus negating the potential effectiveness of the closure. Similarly, our channel closure management scenario resulted in displaced trawlers relocating back into turtle home ranges despite the large overall closure area and the large number of

TABLE 1. Characteristics of shrimp trawling spatial closure scenarios (see Methods) that were evaluated for their potential impacts on adult female loggerhead turtles during the nesting season off the Georgia coast.

Closure scenario	Closure type	Closure area (km^2)	Percent of total area[a]	Number of trawlers[b]	Trawler density[c]	Closure overlap (%)[d]
Statewide 1.6-km closure	Single large	357.0	17.8	1,083	3.0	100
Cumberland closure	Single large	200.8	10.0	362	1.8	55
Sapelo closure	Single large	201.4	10.0	612	3.0	68
Channel closure	Several small	270.0	13.5	853	3.2	95

[a]Percentage of the closure area relative to the total area (2,006.6 km^2) of waters used by shrimp trawlers (0.0–9.6 km from shore).
[b]Total number of trawler positions recorded within each closure boundary during aerial surveys ($n = 43$) between 1999 and 2005.
[c]Trawler observations/km^2.
[d]Percentage of tracked turtles ($n = 22$) with home ranges (95% fixed kernel densities) that completely or partially overlapped with the closure area.

TABLE 2. Predicted mean trawler activity index (TAI) values estimated within the 95% and 50% fixed kernel density (FKD) home ranges of 22 adult female loggerhead turtles that were tagged during the 2004 and 2005 nesting seasons on Georgia barrier islands. The *P*-values represent results from paired *t*-tests comparing post-management-scenario mean TAI values with baseline TAI values (bold italics indicate significance: $P < 0.05$). See Methods for definition of the management scenarios.

	95% FKD contour			50% FKD contour		
Management scenario	Mean TAI[a]	SE	*P*-value	Mean TAI	SE	*P*-value
Baseline	0.335	0.033		0.414	0.061	
Statewide 1.6-km closure	0.267	0.027	0.120	0.302	0.051	0.166
Cumberland closure	0.293	0.042	0.437	0.362	0.072	0.582
Sapelo closure	0.223	0.033	***0.022***	0.219	0.049	***0.016***
Channel closure	0.330	0.032	0.924	0.365	0.064	0.582
10% fleet reduction	0.302	0.030	0.462	0.372	0.055	0.612
30% fleet reduction	0.234	0.023	***0.017***	0.290	0.042	0.101
50% fleet reduction	0.167	0.016	***<0.0001***	0.207	0.030	***0.004***
70% fleet reduction	0.100	0.010	***<0.0001***	0.122	0.018	***<0.0001***
90% fleet reduction	0.033	0.003	***<0.0001***	0.041	0.006	***<0.0001***

[a]Mean TAI value calculated across all turtles.

trawlers that were displaced. Based on our results, single large spatial closures that cover areas of maximum overlap between high trawler activity and high loggerhead turtle activity would be most likely to produce a significant decline in trawler activity around turtles.

Our study was based on a comparison of loggerhead turtle and shrimp trawler distributions to identify potential areas of overlap. The evaluation of concurrent commercial fishery and species distributional data to identify potential management options is a relatively new concept for sea turtle management (e.g., Kobayashi and Polovina 2005) but has been frequently applied in fisheries management systems (Goodyear 1999; Sweeting and Polunin 2005; Hunter et al. 2006). Such modeling approaches necessitate a simplification of the study system and often require assumptions that cannot be explicitly tested. We used a 7-year average of trawler activity observed within areas that were inhabited by loggerhead turtles as a proxy for the risk of interaction between turtles and trawlers. Although trawler activity in areas with turtles present is likely to increase the risk of interaction, the outcome of an interaction is based on multiple factors (e.g., behavior of individual trawlers and turtles) that could not be incorporated into our models. We also incorporated assumptions about how trawl captains would react to spatial closures. Because we did not have observational data describing trawl fishing behavior after an actual closure, we averaged the results of the three redistribution hypotheses, effectively giving each hypothesis equal weight. Despite these simplifications, our models offer promise for evaluating potential management actions prior to implementation and provide guidance for data requirements in future studies to increase model reliability.

The in-water management of loggerhead turtles during nesting-season movements falls heavily on state resource managers. Based on our results from Georgia, the best management option for decreasing the likelihood of interactions between shrimp trawlers and loggerhead turtles during the nesting season is a 50% reduction in the fleet. Heavier reductions of trawler activity were more effective in reducing interactions but would have greater economic impacts on the state's commercial shrimp trawl fishery. Although one spatial closure scenario showed promise for reducing turtle–trawl interactions, spatial closures generally did not offer consistent reductions due to the displacement of trawlers out of the closure area and into areas used by other turtles.

The impetus of our study was to determine effective options for managing loggerhead turtles in Georgia waters and directly adjacent federal waters. However, our study provides a predictive mechanism that can be more broadly applied. The majority of nesting loggerhead turtles in the Northwest Atlantic population occur in the Northern Recovery Unit and the Peninsular Florida Recovery Unit (NMFS and USFWS 2008). Because the threat from commercial shrimp fishing exists throughout these two units, our approach to evaluating the effect of management scenarios can be applied to both units, potentially benefiting the majority of the Northwest Atlantic nesting population of loggerhead turtles. If improved management is the primary goal for research, future loggerhead turtle tracking studies could be conducted under a similar framework to evaluate management options prior to implementation.

ACKNOWLEDGMENTS

Funding for this research was provided by the Protected Species Cooperative Conservation Grant Program of the National Oceanic and Atmospheric Administration; additional funding and local support were provided by the Georgia Department of Natural Resources' Nongame Conservation Fund. We thank G. Martin, M. McElroy, K. Sparks, and S. Truesdell for field assistance and J. Carroll and A. Fisk for providing manuscript reviews.

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