# GIS ANALYSIS OF INTER-NESTING HABITAT, MIGRATORY CORRIDORS, AND RESIDENT FORAGING AREAS OF THE LOGGERHEAD SEA TURTLE (*CARETTA CARETTA*) ALONG THE SOUTHEAST COAST

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by

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**GIS ANALYSIS OF INTER-NESTING HABITAT, MIGRATORY CORRIDORS, AND RESIDENT FORAGING AREAS OF THE LOGGERHEAD SEA TURTLE (*CARETTA CARETTA*) ALONG THE SOUTHEAST COAST**

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## ABSTRACT

The internship project used satellite-tracking data from five female loggerhead sea turtles to characterize the inter-nesting, migratory, and resident foraging habitats using geographic information systems (GIS) and remote sensing applications. This information was used to determine if loggerheads' inter-nesting habitat, migratory corridors, and resident foraging areas coincide with commercial fisheries, such as shrimp trawling and longline fishing, which capture and or kill marine turtles. This will help identify which anthropogenic activities are endangering the survival of loggerhead sea turtles and where conservation efforts should be focused. Five adult female loggerhead turtles were instrumented with Telonics ST-14 satellite transmitters on Cape Island, Cape Romain National Wildlife Refuge, South Carolina in 1998. From this work, the following results were obtained: **Inter-nesting habitat**: Four turtles remained in the inter-nesting habitat for 12 days. Most turtles remained near the nesting beach in water depths of 0.5 to 18.7 m. These data are compared to results of a previous study in 1979; **Migration corridors**: Three turtles migrated south and two migrated north. Turtles traveling south took between 5 to 17 days to reach resident foraging areas with speeds ranging from 1.43 to 2.63 km/hr. Distance traveled ranged from 285 to 871 km. One turtle that migrated north, migrated south to a second resident foraging area when sea surface temperatures declined to 15.9ºC. Limited signals from the other northern turtle indicated similar behavior; **Resident foraging areas**: Home ranges determined by minimum convex polygons ranged from 204 to 1342 $km^2$. Kernel density estimator core areas ranged from 17 to 202 $km^2$, with home ranges between 87 and 1468 $km^2$. Mean water depth for the four turtles ranged from 26 to 81 m. Sea surface temperatures ranged from 18.2 to 30.2ºC; transmitter temperatures ranged from 14.4 to 31.1ºC. Results show considerable overlap between shrimp trawlers in South Carolina state waters and the 1979 and 1998 internesting habitats. Results also show overlap between longline fishing on the outer Continental Shelf and the 1998 resident foraging areas.

## DEDICATION

This manuscript is dedicated to those individuals who still continue to ask the question:

**"Now explain to me again why we want to save the sea turtles?"**

and of course, a most humble dedication to:

**the turtles.**

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# INTRODUCTION

Circumglobally, marine turtles are an integral part of marine communities. Marine turtles occur throughout temperate and tropical regions including open ocean waters, continental shelves, bays, lagoons, and estuaries. Currently, there are seven extant species belonging to two families: Leatherback, *Dermochelys coriacea*, Loggerhead, *Caretta caretta*, Green, *Chelonia mydas*, Hawksbill, *Eretmochelys imbricata*, Olive Ridley, *Lepidochelys olivacea*, Kemp's Ridley, *Lepidochelys kempii*, and Flatback, *Natator depressus*. The Green, Leatherback, Hawksbill, Loggerhead, Olive Ridley, and Kemp's Ridley spend part of their lives in the Atlantic Ocean and Gulf of Mexico (Pritchard, 1997).

The loggerhead is distinct in that the size of its head is disproportionate to its body (hence the name) with a reddish brown carapace and yellow plastron. Loggerheads rarely exceed 122 cm and 227 kg in straight carapace length (SCL) and weight, respectively. Loggerheads forage on invertebrates from eight phyla, including coelenterates and cephalopod mollusks, as well as scavenge fish (Dodd, 1988).

The loggerhead's life cycle begins with hatchlings emerging from their nests and heading to the ocean. For 10 to 12 years, they lead a pelagic existence in the North Atlantic Gyre and are found in and around the Azores, Madeira, Canary Islands, and the western Mediterranean Sea. When the pelagic immatures reach 40 to 60 cm in SCL, they head to the continental shelf and progress to benthic feeding. They utilize coastal and offshore feeding habitats for approximately 10 to 15 years. When reaching adulthood, they begin their first reproductive migration to the courtship areas and nesting beaches. Throughout their life cycle, females continue to migrate between the resident foraging areas (RFAs), courtship areas, and nesting beaches on a two or three-year cycle (TEWG, 1998).

Nesting loggerheads in the northwest Atlantic comprise about 35 to 40 percent of the global nesting activity (TEWG, 2000). The southeastern U.S. comprises one of the largest loggerhead nesting assemblages in the world. Estimations of this population by Murphy and Hopkins (1984) state there to be 14,150 females from Cape Hatteras to Key Biscayne. More recent data estimate the mean total U.S. nesting female loggerhead population, including the west coast of Florida, to be 17,224 and 17,988 in 1998 and 2000, respectively (TEWG, 1998; TEWG, 2000).

The loggerhead sea turtle (*Caretta caretta*) is of special interest because not only is it the state reptile, but it is the most common marine turtle nesting on the coast of South Carolina. Both natural and anthropogenic factors threaten this species' existence. Therefore, determining their inter-nesting habitat, migratory corridors, and resident foraging areas has become essential to the loggerhead sea turtle's survival. This knowledge will provide decision-makers with additional information needed to protect both the turtles and their critical habitat areas (NMFS and USFWS, 1991).

The internship project used satellite-tracking data from five female loggerhead sea turtles (provided to me by the South Carolina Department of Natural Resources) to characterize the inter-nesting, migratory, and resident foraging habitats using geographic information systems (GIS) and remote sensing applications. This information will help determine if loggerheads' inter-nesting habitat, migratory corridors, and resident foraging areas coincide with commercial fisheries, such as shrimp trawling and longline fishing, which capture and kill marine turtles. This will help identify anthropogenic activities, which may be endangering the survival of loggerhead sea turtles and where conservation efforts should be focused.

## LITERATURE REVIEW

The loggerhead turtle, *Caretta caretta,* was listed as a threatened species under the Endangered Species Act in 1978. It is considered “endangered” by the World Conservation Union (IUCN) and listed in Appendix 1 of the Convention on International Trade in Endangered Species of Flora and Fauna (CITES) (TEWG, 1998). “Eighty-eight percent of loggerhead nesting occurs in the southeastern United States, Oman, and Australia” (NMFS and USFWS, 1991, p.2). Along the south Atlantic and Gulf coasts, this species of marine turtle is thought to have three genetically distinct subpopulations based on nesting females as determined by mtDNA (Bowen et al., 1993). They are: the Northern Subpopulation, nesting from North Carolina to northeast Florida; the South Florida Subpopulation, nesting from 29 degrees North on the east coast to Sarasota on the west coast of Florida; and the Florida Panhandle Subpopulation, nesting at Eglin Air Force Base and the beaches near Panama City, Florida. The Northern Subpopulation comprises nine percent of the loggerheads that nest in the United States (TEWG, 1998). Of this nine percent, fifty-six percent of the nesting effort is on South Carolina beaches (Hopkins-Murphy et al., 2001). Recent data indicate that the Northern Subpopulation is declining and mortality reduction is critical (Plotkin and Spotila, in press).

Causes of marine turtle mortality include both natural and anthropogenic factors. Natural mortality may result from predation and inundation of nests. Anthropogenic mortality includes disorientation from lights, incidental take by commercial fisheries and hopper dredges, boat collisions, oil platform construction/disposal, and oceanic debris. The primary identifiable source of mortality for loggerhead turtles in southeastern coastal waters is the incidental take by shrimp trawls. An analysis by the National Research Council found that for juveniles, subadults, and breeders, shrimp trawls account for more deaths than all other anthropogenic-induced mortality combined (National Research Council, 1990).

Recovery of the loggerhead turtle cannot be one hundred percent successful without protecting all stages of the life cycle. However, research shows that reducing mortality in juveniles, subadults, and breeders has a greater influence on population growth than increasing the survivorship of eggs or hatchlings (Crouse et al., 1987). If the survivorship of these older stages is increased, a greater number of turtles is likely to reach maturity and therefore increase productivity in the stages of eggs and hatchlings. Conservation measures directed at the larger (older) life stages are critical to the success of marine turtle conservation. Until migratory corridors, resident foraging areas, and courtship areas are identified, conservation measures to protect the juveniles, subadults, and breeders will be difficult to implement (National Research Council, 1990).

Studying the migratory behavior of turtles in the marine environment is extremely challenging. Early attempts at remote sensing were restricted to waters adjacent to the nesting beach. Carr (1967) used helium balloons attached to the carapace of loggerhead turtles to track their movements in the Gulf of Mexico off of Cedar Key, Florida. Mortimer and Porter (1989) used floats with a mast and light to monitor nighttime movements of nesting green turtles at Ascension Island located in the mid-south Atlantic Ocean between Brazil and Africa.

The use of sonic and radio transmitters enabled researchers to monitor turtles farther out at sea. Murphy and Hopkins (1981) used sonic and radio transmitters to 1) determine the habitat used by adult loggerheads during their inter-nesting period, 2) evaluate disturbance to nesting females, and 3) determine if translocated females would "home" to their preferred nesting beach.

The introduction of satellite telemetry for wildlife by ARGOS made it possible to monitor movements and behaviors of turtles in their marine environment (Eckert, 1999). "Satellite telemetry provides a superior means of monitoring long distance movement, as well as various behavioral parameters, and has been used successfully by a number of researchers" (Eckert, 1999, p.89).

Currently, ARGOS is the only satellite that can collect daily global positions from transmitters that have been placed on wildlife. Satellite telemetry allows researchers to track marine turtles hundreds and thousands of kilometers at sea, which was limited with the other methods. The transmitters are also able to collect and transmit other types of data such as water temperature, water depth, and dive time. Being able to track marine turtles helps researchers answer questions about the life history and ecology of these animals, which has, prior to this technology, been unavailable (Eckert, 1999).

Stoneburner (1982) obtained useful data on two of eight female loggerheads in the Georgia Bight using the NASA Nimbus 6 Satellite. This research clearly indicated that satellite telemetry is an efficient means for monitoring marine turtle movement in the ocean. Keinath et al. (1989), using the polar orbiting ARGOS system, tracked marine turtles using satellite telemetry off of Oregon Inlet, North Carolina. Results of this study posed two questions concerning turtle movements: is oceanic movement typical and is movement related to sexual maturity, mating, and/or feeding? Another study by Renaud and Gitschlag tracked seven marine turtles using satellite telemetry to explain “movement and dive patterns” as well as develop “a biological model to be able to predict these patterns and explain interactions between turtles and gas/oil structures offshore” (Renaud and Gitschlag, 1992, p. 100).

To further illustrate the role of satellite telemetry in the study of marine turtles, scientists at Gray’s Reef National Marine Sanctuary (GRNMS) use satellite telemetry to monitor juvenile and adult loggerhead migrations and behavior in the declining population of marine turtles off of the coast of Georgia (Fioravanti-Score et al., 2000). More recent tracking studies by Hickerson and Peccini (2000), Plotkin and Spotila (in press), and Schroeder et al. (in press) have demonstrated the success and importance of satellite tracking studies to monitor marine turtles away from the nesting environment. This technology has greatly increased the understanding of inter-nesting habitats, migratory corridors, and resident foraging areas. However, specific habitat characterization of these areas is needed (Schroeder et al., in press).

With the improvement of the ARGOS satellite system to meet users needs (Roche, 1996), satellite tracking of turtles (and other wildlife) has developed into a reliable and feasible way to study animals in their marine environments. Geographic Information Systems (GIS) have become researchers' primary tool for analyzing data to identify biological and migratory patterns of behavior. GIS allows graphical representation and analysis with minimal error (Mosier and Leary, 1998).

# METHODS

## Sea turtle captures and transmitter attachment

The beach selected for this study was Cape Island in the Cape Romain National Wildlife Refuge (CRNWR) because it is the beach with the most nesting activity of the Northern Subpopulation. Cape Island is nine kilometers long and is located at 33.02' N by 79.21' W. South Carolina Department of Natural Resources biologists and technicians attached satellite transmitters to five adult females on the night of 14 July 1998. The platform terminal transmitters (PTT), developed for use on sea turtles by Telonics Incorporated, weigh approximately 800 grams and represent less than three percent of the turtle's body weight. They are linked to the ARGOS satellite system, which consists of four satellites in polar orbit. Data from the satellites were received daily via electronic mail. Each turtle was assigned a five-digit PTT number by ARGOS.

A box was placed around each turtle to restrict movement while the transmitter was affixed. Each turtle was measured and tagged on both front flippers. The carapace was prepared for the attachment of the transmitter by removing barnacles and other organisms with a paint scraper and wire brush. A roll of 1.0 cm diameter Sonic Weld was placed around the bottom edge of the transmitter to form a well. Fast Foil epoxy was then applied to the entire bottom surface within the well with a glue gun. The transmitter was placed on the second vertebral scute and allowed to harden for 20 minutes. The turtle was then released to the ocean. The transmitter was expected to fall off of the turtle in a harmless manner in 12 to 24 months.

**Satellite telemetry**

Each of the five turtles was fitted with an ST-14 PTT built to last 12 months. The duty cycle was set to 24 hours on, 12 hours off with a saltwater switch that activated the transmission of data at 401.650 MHz. The repetition period was 40 seconds.

ARGOS instruments are flown on board the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES). The PTT transmits data to one of four NOAA Tiros-N satellites. The satellites transmit data to ground receiving stations that process and distribute it to users.

Processing assigns distance accuracy to each satellite location data point. The locations are calculated using the Doppler shift on the PTT. The Doppler shift in frequency is used to calculate the global position of the transmitter. Distance accuracy is placed into seven location classes (LC) (Table 1).

Table 1. ARGOS location classes.

| CLASS | ESTIMATED ACCURACY OF LATITUDE AND LONGITUDE |
|---|---|
| 3 | ≤150 meters |
| 2 | ≥150 meters and ≤ 350 meters |
| 1 | ≥ 350 meters and ≤ 1000 meters |
| 0 | > 1000 meters |
| A | No estimate of location accuracy |
| B | No estimate of location accuracy |
| Z | Invalid locations |

## Geographic Information System analysis

ArcView 3.2, (including Spatial Analyst, Animal Movement, Grid Analyst, Chart Viewer, and Spatial Tools extensions), was used to analyze the data. Layering of data provided information for analysis of inter-nesting habitat, migratory corridors, and resident foraging areas.

## Location data

Location data (latitude/longitude) for each turtle were acquired daily from ARGOS via electronic mail. Location data were classified according to accuracy (Table 1). Location data for each turtle were divided between location points with estimated known accuracy and location points with no estimate of accuracy. Estimated location points were labeled as numbers and included LC = 3, 2, or 1. Non-estimated location points were labeled as letters and included LC = 0, A, or B. LC = Z was not used.

The numbers and letters for each turtle were compiled into an Excel tab-delimited file. Therefore, for each turtle there were two tab-delimited files (number file and letter file). Each file was then imported as a table into ArcView. An ArcView shape file was created from each table. Satellite data (according to location) were divided into three habitats: inter-nesting, migratory, and foraging habitats.

## Bathymetry

CDROM bathymetry data obtained from the National Geophysical Data Center (NGDC) Coastal Relief Model volumes one and two were imported into ArcView as grid files. The original NGDC data format was converted to an ArcView grid file using the Geophysical Data System (GEODAS) "Grid Translator" utility program. This bathymetry data allowed for the water depth at specific geographic locations to be determined.

## Site fidelity and home range

Using the ArcView Animal Movement extension, site fidelity tests were performed on the resident foraging area data for each turtle. To determine site fidelity within the resident foraging areas, 1000 "random walks" were generated from the arithmetic mean of the geographic locations within the foraging area**.** Before the site fidelity test was performed, geographic boundaries were placed along the Atlantic coast to restrict the random walks to the ocean.

Home range area (size) of the resident foraging areas was calculated with the Animal Movement extension using both the Minimum Convex Polygon area (MCP) and probabilistic Kernel Density Estimator methods (KDE). The MCP represents the space that the animal uses and traverses. The 50% and 95% KDE represent core area and home range, respectively. Home range is considered to be the area that the turtle actually uses, while the core area is the center of activity. Core area size is the best estimator to use when comparing

RFAs (Hooge et al., unpubl).

## Nautical charts, Continental Shelf, and the Gulf Stream

NOAA nautical charts of the western Atlantic Ocean were imported into ArcView using the Chart Viewer extension. From the nautical charts, the three following shapefiles were constructed in ArcView: continental shelf, center of the Gulf Stream, and the approximate western edge of the Gulf Stream. Using these shapefiles, the width of the Continental Shelf, distance to the continental shelf edge, and distance to the Gulf Stream were calculated. Given the meanders and eddies associated with the Gulf Stream, the measurements are approximations.

## Sea Surface Temperature

Retrospective Sea Surface Temperature (SST) data were obtained from the NOAA Coastwatch website. Advanced Very High Resolution Radiometer (AVHRR) image files from the NOAA POES with a 1.1 x 1.1 km spatial resolution were used. The image products are validated monthly by comparing satellite measurements to buoy in situ measurements. Products are within 0.2ºC (NOAA 2001). Image files were downloaded in the Coastwatch format. Using the "Coastwatch to ArcView Format" utility program, the images were rewritten as a binary file and then imported into ArcView as a grid file. Temperatures at specific geographic locations were determined from SST data.

**Transmitter temperature**

The ambient temperature of the transmitter was reported with every location transmission. The ambient temperature was recorded as a temperature count value that had to be converted by the user to degrees Celsius. The temperature count value was converted to degrees Celsius with the aid of a temperature curve (provided by ARGOS) for each transmitter. The curve plotted temperature count versus degrees Celsius. To determine degrees Celsius from the curve, the slope of the line was calculated. Then using the slope of the line and a set of *x,y* points, a standard formula for the temperature curve was determined, for example $f(x) = 0.3529x - 37.8756$. Each transmitter had its own temperature curve and formula for determining degrees Celsius.

**Inter-nesting habitat, migratory corridors, and resident foraging areas**

The inter-nesting habitat for each turtle was characterized as to: duration of inter-nesting interval, longshore distance from nesting beach, distance from shore, and water depths. Migratory corridors were determined using both location numbers and letters to map out the most probable migratory route utilized by each turtle. After each migratory route was mapped, it was characterized as to: duration and final location, direction, distance from Atlantic coast, distance traveled, distance traveled per day (distance traveled divided by the number of days to destination), speed, potential distance per day, water depth, sea surface temperature (SST), and transmitter temperature (TT).

The resident foraging areas for each turtle were characterized as to: duration, minimum convex polygon area (MCP), core area (CA), home range area (HR), width of Continental Shelf, distance to the Continental Shelf edge, distance to Gulf Stream, water depth, SST, and TT.

**Commercial fishery data**

Locations for the South Carolina shrimp trawlers were obtained from T. Murphy (unpublished data). The data were imported into ArcView as dBase files and converted to shapefiles.

Observer logbook data from the longline fishery, including vessel locations and loggerhead capture data were obtained from the National Marine Fisheries Service from 1992 to 2000 (NMFS, unpublished data). The data were imported into ArcView as Excel tab-delimited files and converted to shapefiles. The data were used to determine overlap between the fishery and loggerhead habitat.

# RESULTS/DISCUSSION

## Inter-nesting Habitat

Dates and Activity

All five turtles were instrumented on the night of 14 July 1998. Four of the five turtles made a non-nesting emergence (false crawl); turtle 07993 nested. The high number of false crawl (FC) turtles was due in part to the lack of nesting habitat on that section of the beach at Cape Island. Also, the human activity associated with the research could have contributed, since all the turtles emerged within 100 meters of each other. Although turtle 07992 false crawled the night she was tagged, she must have laid her final clutch the next night because she began her migration on 16 July 1998. The other four turtles, including the one that had nested, remained in the vicinity of the nesting beach for approximately one inter-nesting interval before beginning their migration (Table 2).

Table 2. Inter-nesting data from the 1998 telemetry study.

| Data | 07992 Flag | 07993 Jackie | 07994 Flora | 08003 Caroline | 08004 Virginia |
|---|---|---|---|---|---|
| **Dates** | N/D | 7/15/98 to 7/27/98 | 7/15/98 to 7/26/98 | 7/15/98 to 8/01/98 | 7/15/98 to 7/26/98 |
| **Days in Inter-nesting Habitat** | 0 | 12 | 12 | 17 | 12 |
| **Activity at Tagging** | False Crawl | Nested | False Crawl | False Crawl | False Crawl |
| **Inter-nesting** | NO | YES | YES | YES | YES |
| **Longshore Distance From Nesting Beach (km)** | N/D | 12.01 | 47.75 | 9.15 | 15.86 |
| **Distance from Shore (km)** | N/D | $\mu$ = 5.40 n=21 Range 1.14-24.70 | $\mu$ = 15.28 n=9 Range 0.67-34.05 | $\mu$ = 3.91 n=14 Range 0.34-10.36 | $\mu$ = 7.33 n=17 Range 1.28-15.49 |
| **Water Depth (m)** | N/D | $\mu$ = 6.0 n=21 Range 1.8-18.7 | $\mu$ = 11.2 n=9 Range 1.2-18.4 | $\mu$ = 5.0 n=14 Range 0.5-12.2 | $\mu$ = 7.7 n=17 Range 2.0-12.6 |

Longshore Dispersal

In 1979, Murphy and Hopkins (1981) placed sonic transmitters on 29 loggerhead turtles to document inter-nesting habitat use (Hopkins-Murphy et al., in press). We compared our results with that earlier study. In their study, the tagging beach was South Island, which is 20.50 km north of our tagging beach at Cape Island. Inter-nesting turtle locations from both studies were in the same area between Raccoon Key and North Island (Figure 1-All figures are located in Appendix A). The 1998 turtles remained within 47.75 km (maximum northern or southern distance) of their nesting beach (Table 2). This compares to 34.07 km reported by Murphy and Hopkins (1981). Both this study and the one by Murphy and Hopkins are comparable to results reported by Tucker et al. (1994) indicating that movements were longshore oriented, north or south of the nesting beach.

Distance from Shore

The turtles' distances from shore ranged from 0.34 to 34.05 km with a mean of 7.06 km (n = 61) (Table 2). This compares to a range of 0.37 to 15.59 km with a mean of 4.39 km (n = 67) reported by Murphy and Hopkins (1981). The two means were found to be significantly different (Welch's ANOVA; p = 0.0058). The mean distance from shore in the 1998 study was significantly farther than the mean from 1979. There are several possible explanations. Accurate satellite location data are dependent on the time the transmitter is above the ocean surface, which is dependent on the turtle's surface time. Therefore, the accuracy of the satellite data is highly variable based on surface time, which could result in an erroneous data point that is farther from shore than its true location, especially if based on A and B location classes.

Sampling effort is also a possible cause of variability between the means. The satellite is able to cover all areas in which the turtle may be found. However, the study done by Murphy and Hopkins in 1979 was based on a grid sampling effort with vessel surveys. The sampling effort in their study could not cover all areas simultaneously, including those farther from shore.

Water Depth

Water depths ranged from 0.5 to 18.7 m with a mean of 7.02 m (n = 61) (Table 2). This compares to a range from 0.7 to 13.3 m with a mean of 5.89 m (n = 67) reported by Murphy and Hopkins (1981). The two means do not differ significantly (Welch's ANOVA; p = 0.0974). In comparing water depth with distance from shore, the statistics indicate that the turtles are selecting locations based on water depth rather than distance from shore. These results support Murphy and Hopkins' observations in their study.

> "Shoals and areas of high relief were found to receive concentrated use by turtles during the inter-nesting period. The movements were also found to parallel high relief contour lines …" (Hopkins-Murphy et al., in press).

Summary

It is noteworthy that the inter-nesting habitat used by the four loggerheads in 1998 is strikingly similar to the inter-nesting habitat of the 29 loggerheads in the 1979 study by Murphy and Hopkins, i.e. Raccoon Key to North Island. Limpus and Reed (1985) noted the possibility of strong inter-nesting habitat site fixity that overrides the natural instinct to avoid disturbance. This is extremely relevant to our turtles whose inter-nesting habitat coincides with shrimp trawling grounds along the coast of South Carolina (Figure 1).

## Migration Corridors

Travel Dates

Turtles 07993, 07994, 08003, and 08004 remained in coastal waters after tagging to re-nest one additional time and then immediately began their migration. Turtle 07992 began her migration two days after she was tagged. This is consistent with post-nesting observations by Tucker et al. (1994) off the coast of Queensland, Australia, indicating that after the final nest is laid, females immediately depart with a directional movement different from inter-nesting movements. The initial migration dates for the four turtles that re-nested were within one week of each other (Table 3).

Table 3. Migration data from the 1998 telemetry study.

| Data | 07992 Flag | 07993 Jackie | 07994 Flora | 08003 Caroline | 08004 Virginia (N) | 08004 Virginia (S) |
|---|---|---|---|---|---|---|
| **Travel Dates** | 7/16/98 to 7/28/98 | 7/28/98 to N/D | 7/27/98 to 8/12/98 | 8/2/98 to 8/6/98 | 7/27/98 to 8/17/98 | 11/2/98 to 12/3/98 |
| **Location (km east of)** | 56.00 Flagler Beach, FL | 26.80 Cape May, NJ | 25.60 Vero Beach, FL | 92.80 Cumberland Island, GA | 62.40 NC/VA border | 142.40 St. Catherine's Island, GA |
| **Direction** | South | North | South | South | North | South |
| **Mean Dist. from Atl. Coast (km)** | 74.74 | 53.09 | 48.25 | 76.87 | 49.34 | 51.42 |
| **Distance (km)** | 458.30 | 871.17 | 669.10 | 285.26 | 597.58 | 650.23 |
| **Days to Destination** | 13 | N/D | 17 | 5 | 22 | 31 |
| **Distance (km/day)** | 35.25 | N/D | 39.36 | 57.05 | 27.16 | 20.98 |
| **Speed (km/hr)** | μ = 1.43 n = 3 Range 1.11 - 1.73 | μ = 1.82 n = 2 Range 1.48 - 2.16 | μ = 1.64 n = 7 Range 1.12 - 2.31 | μ = 2.63 n = 5 Range 1.58 - 3.01 | μ = 1.38 n = 4 Range 0.89 - 1.74 | μ= 1.07 n = 4 Range 0.50 - 1.88 |
| **Potential Distance (km/day)** | 34.32 | N/D | 39.36 | 63.12 | 33.12 | 25.68 |
| **Mean Water Depth (m)** | 32.2 | 29.1 | 26.5 | 39.8 | 27.8 | 39.1 |
| **SST (ºC)** | μ = 29.1 n = 3 Range 28.6 - 29.9 | μ = 27.8 n = 12 Range 26.0 - 29.2 | μ = 28.8 n = 5 Range 28.6 - 29.2 | μ = 28.8 n = 1 | μ = 27.9 n = 6 Range 27.5 - 28.7 | μ = 19.5 n = 5 Range 15.9 - 25.3 |
| **TT (ºC)** | μ = 19.9 n = 3 Range 16.2 - 23.0 | μ = 21.3 n = 12 Range 17.2 - 24.3 | μ = 24.4 n = 5 Range 23.0 - 26.0 | μ = 26.4 n = 1 | μ = 25.7 n = 6 Range 17.5 - 31.1 | μ = 21.15 n = 5 Range 17.5 - 25.8 |

Destination and Direction

Turtles 07993 and 08004 migrated to areas 26.80 km east of Cape May, New Jersey and 62.40 km east of the North Carolina/Virginia line, respectively (Figures 2 and 3). In conjunction with cooling water temperatures, turtle 08004 had a second southward migration to an area 142.40 km east of St. Catherine's Island, Georgia (Figure 3). Turtle 07993 had a final signal off of the North Carolina coast possibly indicating that this turtle also had a second southward migration. Turtles 07992, 07994, and 08003 migrated to areas 56.00 km east of Flagler Beach, Florida; 25.60 km east of Vero Beach, Florida; and 92.80 km miles east of Cumberland Island, Georgia, respectively (Table 3) (Figures 4, 5, and 6).

Flipper tag returns by Bell and Richardson (1978) and satellite tracking by Plotkin and Spotila (in press) indicate that post-nesting loggerheads from Georgia migrate northward beyond Cape Hatteras. Turtles in the Plotkin and Spotila study (in press) showed a southward migration in the fall when water temperatures dropped, which is similar to turtles 07993 and 08004. The three turtles from our study that migrated south were surprising in that they were inconsistent with these prior studies. However, post-nesting tag recoveries of loggerheads from Melbourne Beach, Florida, were recovered both north and south of the nesting beach (Meylan et al., 1983).

Turtles that swam south generally followed the depth contour of the Continental Shelf, while northern migrating turtles swam in a straight line to Cape

Hatteras and did not follow the more scalloped contour of North Carolina (Figures 7 and 8). Unlike the loggerheads in South Africa (Papi et al., 1997), our turtles did not take a coastal route but were more than 48.00 km from shore (Table 3). Morreale et al. (1996) when describing the migratory routes of eight leatherback turtles, *Dermochelys coriacea*, in the eastern Pacific, reported:

> "the most striking feature of the post-nesting migratory behaviour was the related movement among individuals. Turtles within the same seasons traveled along similar, and in some cases virtually identical pathways" (Morreale, 1996, p. 319).

We see this same pattern in our five loggerhead turtles. The three southern turtles were within 20.00 to 50.00 km of each other. The two northern turtles were even closer, being no more than 20.00 km apart, especially as they neared Cape Hatteras, North Carolina (Figures 7 and 8).

<u>Distance and Speed</u>

Distance traveled for all migrations ranged from 285.26 to 871.17 km and distance traveled per day ranged from 20.98 to 57.05 km (Table 3). Similar to our results, post-nesting tag recovery studies by Hughes (1974) had distances per day that ranged from 14 to 40 km. Bell and Richardson (1978) reported a maximum distance per day of 40 km with maximum distance traveled of 1352 km.

Mean speed ranged from 1.07 to 2.63 km per hour (Table 3). Migration speed was subject to error from satellite locations with unknown accuracy, undeterminable actual straight-line path of the turtle, and unknown effects of water currents.

Potential distance per day was calculated to determine if travel was steady over twenty-four hours or whether the turtle stopped or slowed along the way. There was very little difference between potential and actual distances per day indicating that the turtles did not stop during their migration. Slight differences occurred because the mean speed was used to calculate the potential distance traveled. The turtle might not maintain the mean speed at all times, but rather there could be intervals of slower and faster migration speeds (Hays et al., 2001) (Table 3).

When comparing kilometers per day and speed, our five turtles were extremely similar to those in several other studies. A nesting loggerhead in Japan traveled a mean distance of 32.67 km per day at 1.40 km per hour (Sakamoto et al., 1997). Limpus et al. (1992) reported that two Queensland (Australia) loggerheads traveled a mean distance of 32.97 km per day at 1.38 km per hour. Papi et al. (1997), studying the migration of loggerheads in South Africa, reported a mean of 31.80 km per day at 1.33 km per hour. Likewise, our loggerheads migrated a mean of 35.95 km per day at 1.66 km per hour (Table 3).

Water Depth

Water depth throughout the loggerheads' migrations ranged from 26.5 to 39.8 m (Table 3). Water depth is dependent on the turtle's distance from shore and the proximity to the shelf edge. This narrow range in water depth is consistent with the relative close proximity of turtles during migration.

Temperature

Sea surface temperature was consistently warmer than the transmitter temperature (excluding turtle 08004(S)) (Table 3). In an experiment by Col Limpus, he reported:

> "Caretta in Queensland, migrating from feeding areas in the southern Great Barrier Reef to Mon Repos, were fitted with temp-depth data loggers about one month or more before migration began and the gear was recovered when the turtles came up to nest about two or three months later. The individual dives were not logged. The data loggers were set to take readings every half hour. The results indicated that the turtles did not migrate at the surface. Rather they used the full range of depth available to them across the Continental Shelf as they migrated. Without knowing exactly where they were and hence the bottom depth, it is conjecture to say more than they migrated at or near the bottom, obviously surfacing for breath and did not spend extended periods at or near the surface" (Limpus, pers. comm.).

The cooler transmitter temperature indicates that our loggerheads may also have been migrating near the ocean floor. Turtle 08004's southern migration does not show this same relationship because the mean SSTs are cooler due to declines in water temperature at the start of her seasonal migration.

Summary

It is interesting that the paths and water depths of the individual migrations were similar. Turtles appear to be using northern and southern migration corridors (Figures 7 and 8). Water depth along northern routes differed by 1.3 m, while southern routes differed by 13.3 m. Cooler transmitter temperatures (relative to sea surface temperatures) indicate that turtles may be migrating at or near the bottom (Table 3).

## Resident Foraging Areas

Site Fidelity

Four of the five turtles provided data on resident foraging areas and exhibited site fidelity. Turtle 08004(S) did not show site fidelity because her RFA was linear in shape and the Animal Movement extension in ArcView is currently not designed to function with linear habitats. However, we believe that this turtle did exhibit site fidelity (Figure 9).

The southern RFA of turtle 08004 also differed from the other four RFAs in that it was 142.40 km east of St. Catherine's Island, Georgia, only 11.50 km from the Continental Shelf edge, and 3.29 km from the western edge of the Gulf Stream. At this location, the water is much deeper ranging from 64.6 to 110.0 m within the home range (Table 4). If turtle 08004 were feeding on the bottom, the mean transmitter temperature would be much lower than the mean SST. However, the mean transmitter temperature and SST are within 0.4ºC (Table 4).

This indicates that the turtle was probably feeding near the surface on prey items concentrated at the western edge of the Gulf Stream. Food resources would include floating prey as well as organisms attached to floating objects such as recorded for immature loggerheads at fronts in the central North Pacific (Polovina et al., 2000). The turtle's movement within her RFA indicates that she moved both south against the current and north with the current, thus creating the linear configuration of the RFA. This linearity precludes the relationships seen among the other RFAs (Figure 9).

Table 4. Resident foraging area data from the 1998 telemetry study.

| Data | 07992 Flag | 07994 Flora | 003 Caroline | 08004 Virginia (N) | 08004 Virginia (S) |
|---|---|---|---|---|---|
| Dates | 7/31/98 to 1/29/99 | 8/26/98 to 8/28/99 | 8/23/98 to 5/28/99 | 8/18/98 to 11/1/98 | 12/6/98 to 2/6/99 |
| Duration (days) | 182 | 367 | 278 | 75 | 62 |
| MCP ($km^2$) | 244.86 | 204.14 | 550.07 | 1342.45 | 469.83 |
| CA ($km^2$) | 34.80 | 17.42 | 120.09 | 168.53 | 201.77 |
| HR ($km^2$) | 219.82 | 86.76 | 1130.20 | 871.58 | 1467.98 |
| Continental Shelf Width (km) | 91.18 | 39.68 | 134.83 | 99.44 | 126.81 |
| Core Area to Continental Shelf (km) | 39.20 | 16.72 | 41.51 | 38.00 | 11.50 |
| Core Area to Western Edge of Gulf Stream (km) | 1.54 | 0.00 | 32.67 | 75.23 | 3.29 |
| Water Depth (m) | μ = 25.5<br>n = 30<br>Range<br>21.7 - 33.4 | μ = 28.6<br>n = 42<br>Range<br>19.2 - 60.1 | μ = 37.6<br>n = 9<br>Range<br>34.7 - 40.0 | μ = 30.0<br>n = 138<br>Range<br>24.9 - 41.0 | μ = 81.0<br>n = 29<br>Range<br>64.6 - 110.0 |
| SST (ºC) | μ = 26.5<br>n = 30<br>Range<br>23.1 - 28.9 | μ = 26.7<br>n = 42<br>Range<br>23.3 - 29.7 | μ = 23.6<br>n = 9<br>Range<br>18.4 - 30.2 | μ = 22.2<br>n = 138<br>Range<br>18.2 - 26.9 | μ = 24.3<br>n = 29<br>Range<br>22.8 - 24.9 |
| TT (ºC) | μ = 21.6<br>n = 30<br>Range<br>17.7 - 24.2 | μ = 19.0<br>n = 42<br>Range<br>14.4 - 25.6 | μ = 22.4<br>n = 9<br>Range<br>18.6 - 28.1 | μ = 23.7<br>n = 137<br>Range<br>17.9 - 31.1 | μ = 23.9<br>n = 29<br>Range<br>20.8 - 26.2 |

Home Range

The MCP is the most basic home range estimator but is skewed by outliers and actually overestimates the area that the animal actually uses. Although the MCP data are presented in Table 4 for information, they were not used in the comparisons. The more reliable method is the probabilistic kernel density estimator based on 95% (home range) and 50% (core area) contours (Hooge et al., unpubl). Core areas for our four turtles ranged in size from 17.42 to 201.77 $km^2$. The home ranges were between 86.76 and 1467.98 $km^2$ (Table 4) (Figures 9, 10, 11, 12, and 13). Since there are no published data on home range and core area size for nesting loggerheads, we compared our data to two studies in the Gulf of Mexico on mostly juvenile loggerheads (Table 5). The two studies had somewhat larger core areas and home ranges, but this might be a function of food resources in the Gulf of Mexico versus the Atlantic Continental Shelf or the age of the individuals.

Table 5. Resident foraging area comparisons of the 1998 telemetry study and two studies in the Gulf of Mexico.

| **Data** | **Adult Females Continental Shelf Atlantic Ocean n = 5** | **Juveniles Natural Reef Gulf of Mexico[1] n = 5** | **Juvenile/Adult Oil/Gas Structures Gulf of Mexico[2] n = 3** |
|---|---|---|---|
| **Mean Size of Core Area ($km^2$)** | 108.52 | 133.60 | 165.60 |
| **Mean Size of Home Range ($km^2$)** | 755.27 | 1054.94 | 1599.00 |

1. Hickerson, 2000.
2. Renaud and Carpenter, 1994.

When comparing resident foraging areas of the turtles in this study, the core area size decreases in a north to south gradient (excluding turtle 08004(S)) (Table 4) (Figure 14). The core areas' north to south gradient may be related to available food resources and the width of the continental shelf, which also decreases in a north to south gradient. This may allow for more concentrated food resources; therefore, the turtle does not require a larger core area size because food is readily available within a smaller area.

It is also interesting that our turtles off the coast of Florida (07992 and 07994) are within 1.54 km of the western edge of the Gulf Stream (Table 4). Their locations are consistent with observations by Hoffman and Fritts (1982) during aerial surveys of Florida waters. They noted a patterned distribution that indicated turtles were concentrated just west of the Gulf Stream.

Turtle 07992 and Goody (a nesting loggerhead from Melbourne Beach, Florida) (Schroeder, unpubl.) had home ranges and core areas of almost identical size. These were animals with like energy requirements in similar habitat. Although their RFAs were adjacent, they were not overlapping (Figure 15). This begs the question: Do adult female loggerheads defend a feeding area? If so, would this result in a contiguous mosaic of loggerhead territories covering the Continental Shelf?

Turtle 07993's satellite transmitter malfunctioned soon after she rounded Cape Hatteras, North Carolina, therefore providing no useful data on her resident foraging area. We received one location off of the coast of New Jersey in September (Figure 2). This location is consistent with data suggesting that loggerheads from Georgia migrate north to New Jersey (Bell and Richardson, 1998; Plotkin and Spotila, in press). A final signal was received from this turtle in

November near Cape Lookout, North Carolina (Figure 2). This location is also consistent with the Plotkin and Spotila study (in press) and the seasonal movements of turtle 08004 (Figure 3) in this study.

Water Depth

The four turtles resided in water depths ranging from approximately 25.0 to 60.0 m. These data (excluding turtle 08004(S)) are consistent with Fritts et al. (1983) aerial survey results and Byles and Dodd (1989) satellite tracking study where loggerheads were recorded in water less than 50.0 and 60.0 m, respectively. Turtles 07992, 08003, and 08004(N) had similar mean water depths and ranges; this may be related to the distance from their core area to the Continental Shelf edge, which are also extremely similar (39.20, 41.51, and 38.00 km, respectively). Turtle 07994 located on a narrower section of the Continental Shelf had a greater range of water depth because the shelf drops off closer to shore at this location (Table 4).

Temperature

Turtles 07992, 07994, and 08003 had mean transmitter temperatures that were cooler than mean SSTs. Cooler temperatures recorded during diving could explain turtle 07992's cooler transmitter temperatures since the SST temperatures remained warm even during mid-winter months. Cool water upwellings onto the shelf in the Florida Keys can drop temperatures to as low as

13ºC for several days (Leichter and Miller, 1999). These upwellings appear to be produced through several mechanisms including variability of the Gulf Stream. These same mechanisms along the shelf at the RFA of turtle 07994 could explain the low temperatures recorded for this turtle even in south Florida waters. Transmitter and SSTs are consistent for turtle 08003 indicating that seasonal declines in temperature are responsible for the cooler recorded temperatures (Table 4).

Turtle 08004 had a warmer mean transmitter temperature relative to the mean SST. Located 75.23 km from the Gulf Stream and north of Cape Hatteras, North Carolina, SSTs would be expected to be cooler. In cooler waters, turtles will tend to bask on the surface to raise body temperatures, indicated by the quality and quantity of the satellite transmissions (Hays et al., 2001; Plotkin, 1998) (Table 4) (Figure 13).

Comparisons of SST and loggerheads sighted during aerial surveys off the North Carolina coast (Coles and Musick 2000), suggest sea turtles have a preferred temperature regime ranging from 13.3 to 28.0ºC. We are comparing this regime with our transmitter temperatures because loggerheads spend very little time at the surface. Our transmitter temperatures range from 14.4 to 31.1ºC. With the exception of the 31.1ºC (which was possibly the result of basking), our temperatures are consistent with Coles and Musick (2000).

## Summary

Turtles 07994 and 08004(S) are in close proximity to longliners located near the outer Continental Shelf (Figures 16, 17, and 18). The longline fishing data presented in this paper under represents the true longline fishing effort in the western Atlantic Ocean. The presented U.S. fleet observer data (1992-2000) is only five percent of the U.S. effort and the U.S. effort is only five to eight percent of the total international effort in the western Atlantic Ocean (NMFS-SEFSC, 2001). Noting the small sample size of turtles (n = 5) in this study, the close proximity of two of the five turtles indicates the possible overlap between resident foraging areas and the longline fishery.

# CONCLUSIONS

## Inter-nesting Habitat

From the inter-nesting habitat analysis the following conclusions are presented: the inter-nesting habitat used by loggerheads from South Island in 1979 and Cape Island in 1998 overlapped; during the inter-nesting period, nesting loggerheads appeared to be selecting for water depth rather than distance from shore; and shrimp trawling in South Carolina state waters coincides with the inter-nesting habitat from both the 1979 and 1998 studies (Figure 1).

## Migration Corridors

Analysis of the 1998 loggerhead migrations indicates that corridors were not coastal, but were at least 48 kilometers from shore (Figures 7 and 8); individual migration routes were in relatively close proximity to each other, especially near Cape Hatteras, North Carolina (Figures 7 and 8); transmitter temperatures relative to sea surface temperatures indicate that the turtles were not traveling at or near the surface, but more likely near the bottom; southern migration corridors followed the contour of the Continental Shelf, while northern ones were direct to Cape Hatteras, North Carolina (Figures 7 and 8); turtles swam continuously until they reached their resident foraging areas as shown by similarity between actual and potential kilometers traveled per day (Table 3); and migration speed and travel distance per day are similar to nesting loggerheads in Australia, Japan, and South Africa.

### Resident Foraging Areas

Characterization of the resident foraging areas presents the following conclusions: South Carolina loggerheads migrated to resident foraging areas both north and south of their nesting beach (Figures 7 and 8); resident foraging areas were on the middle to outer Continental Shelf and tended to be near the western edge of the Gulf Stream (Figure 16); core areas decreased in size from north to south, but turtles in similar habitat had similar-sized core areas. This may be related to food resources (Figures 14 and 15); the mean size of core areas is similar to those of juvenile loggerheads in the Gulf of Mexico at natural and artificial sites (Table 5); turtles with a northern resident foraging area moved to a southern one in the fall in response to falling water temperatures (Figure 3); the difference between mean SST and TT was less than 3ºC; however the range was 16.7ºC indicating that turtles possibly foraged in deep cold water in the south and basked in the north (Table 4); and longline fishing effort and loggerhead captures are in close proximity to resident foraging areas near the outer Continental Shelf (Figures 16, 17, and 18).

## Limitations of the study

<u>Satellite Telemetry</u>

Telemetry limitations of the project include: the cost per turtle (transmitter, satellite time, and processing fees), which results in a small sample size of turtles; plausibility error of the satellite data, which decreases the sample size of accurate data points; ground truth methods are lacking to test accuracy of the data; and the study was compromised by battery life and durability of the transmitter once attached to the turtle.

<u>Geographic Information Systems</u>

Computer analysis limitations of the project include: lack of live bottom and ocean currents data; accuracy of the data layers that were used for analysis; limitations of the Animal Movement extension; and the accuracy of the georeferencing and measuring capabilities of ArcView.

## Recommendations

From this study, it is recommended that a larger sample size is needed to determine the extent of the areas used by South Carolina's nesting loggerheads. With a larger sample size, a more complete habitat analysis will be possible to further characterize and delineate the resident foraging areas. Better oceanographic data for GIS in the marine environment need to be developed. More extensive data are needed on live bottom areas to better understand the size relationship of resident foraging areas. The Animal Movement extension needs updating for linear environments. Transmitters are needed that will operate for several years to document remigration and withstand harsh marine conditions associated with sea turtles, and the longevity of the epoxy used for transmitter attachment needs to be determined.

Between 1992 and 2000, 136 loggerheads were incidentally taken by longliners as reported by NMFS observers. Observer data represents only 5% of the total fishing effort; therefore over the eight-year period, possibly 2,720 loggerheads were taken. Assuming 50% mortality, the number of loggerheads taken annually by the U.S. longline fleet in the western Atlantic is 170 turtles.

The northern nesting loggerhead subpopulation is estimated to be 1,524 and is currently declining 5% annually. Studies determining the index of the loggerheads in the western Atlantic report a mix of the subpopulations and over represent the northern subpopulation relative to the respective nesting population. This indicates that the northern subpopulation, which is in decline, is more prevalent in the western Atlantic Ocean. Therefore, measures should be taken to protect critical habitat and more importantly, protect loggerheads. These measures could include relisting the loggerhead northern subpopulation as endangered (currently threatened); expanding current and establishing new marine sanctuaries to protect critical habitat (with an increased sample size identifying resident foraging areas), and restricting the U.S. longline fishery to areas beyond the Continental Shelf edge to protect loggerheads.

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# APPENDIX A

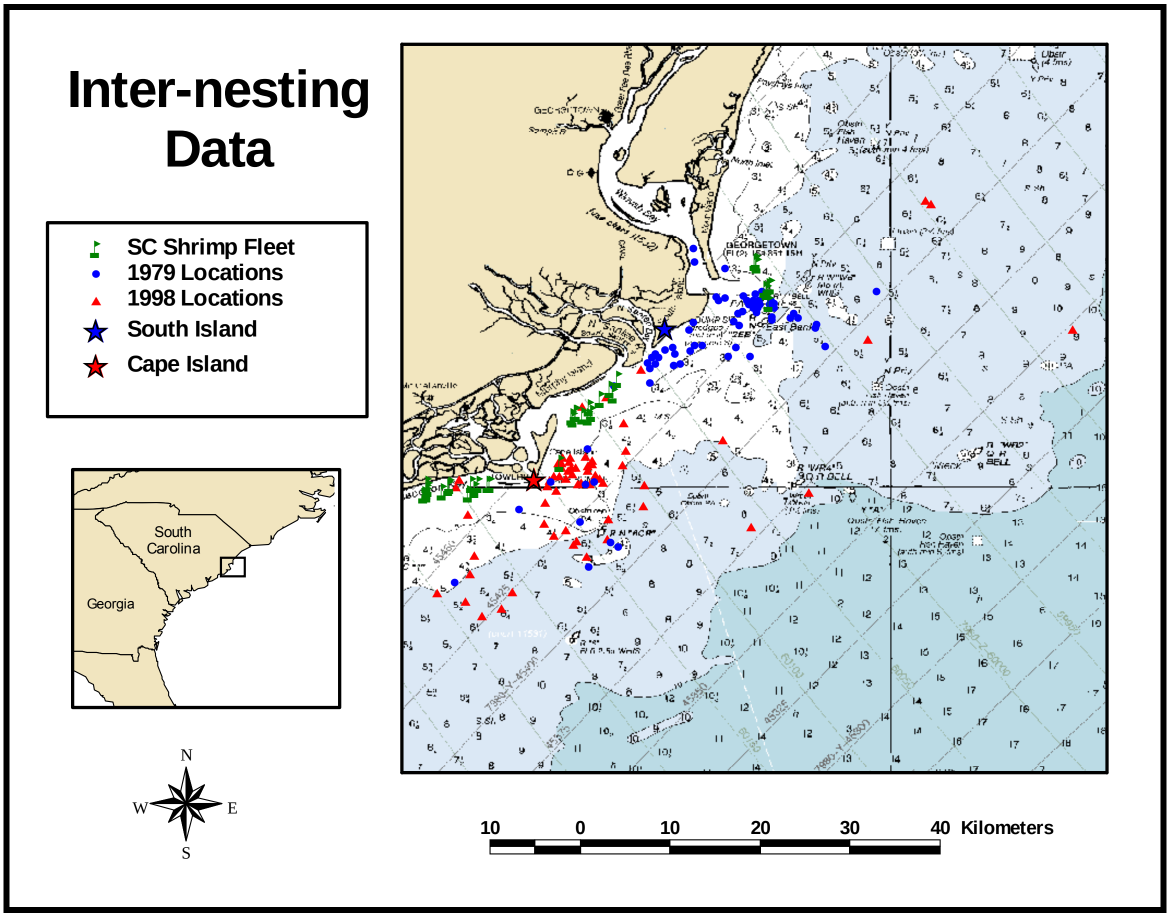


Figure 1. Overlay of SC shrimp fleet with the 1979 and 1998 inter-nesting habitats.

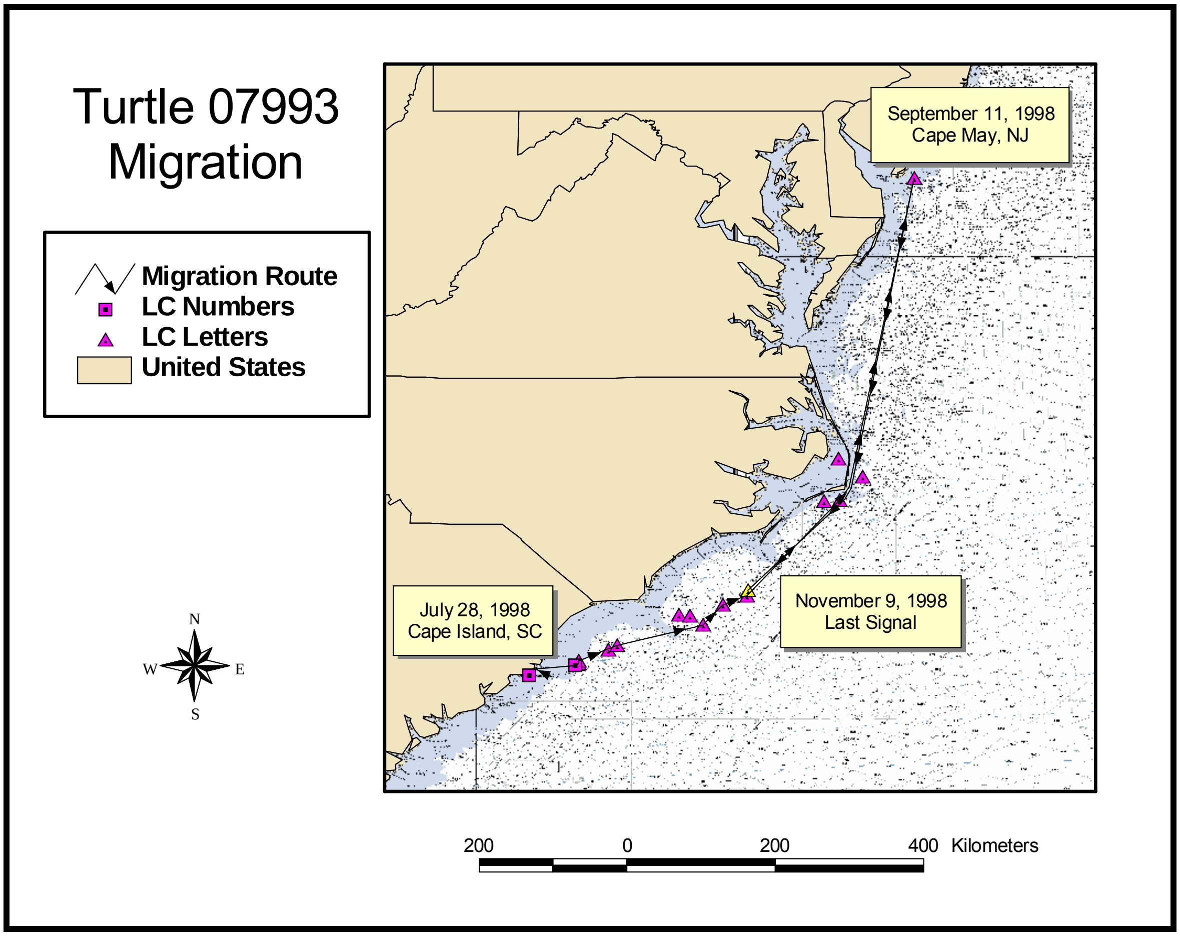


Figure 2. Turtle 07993's migration.

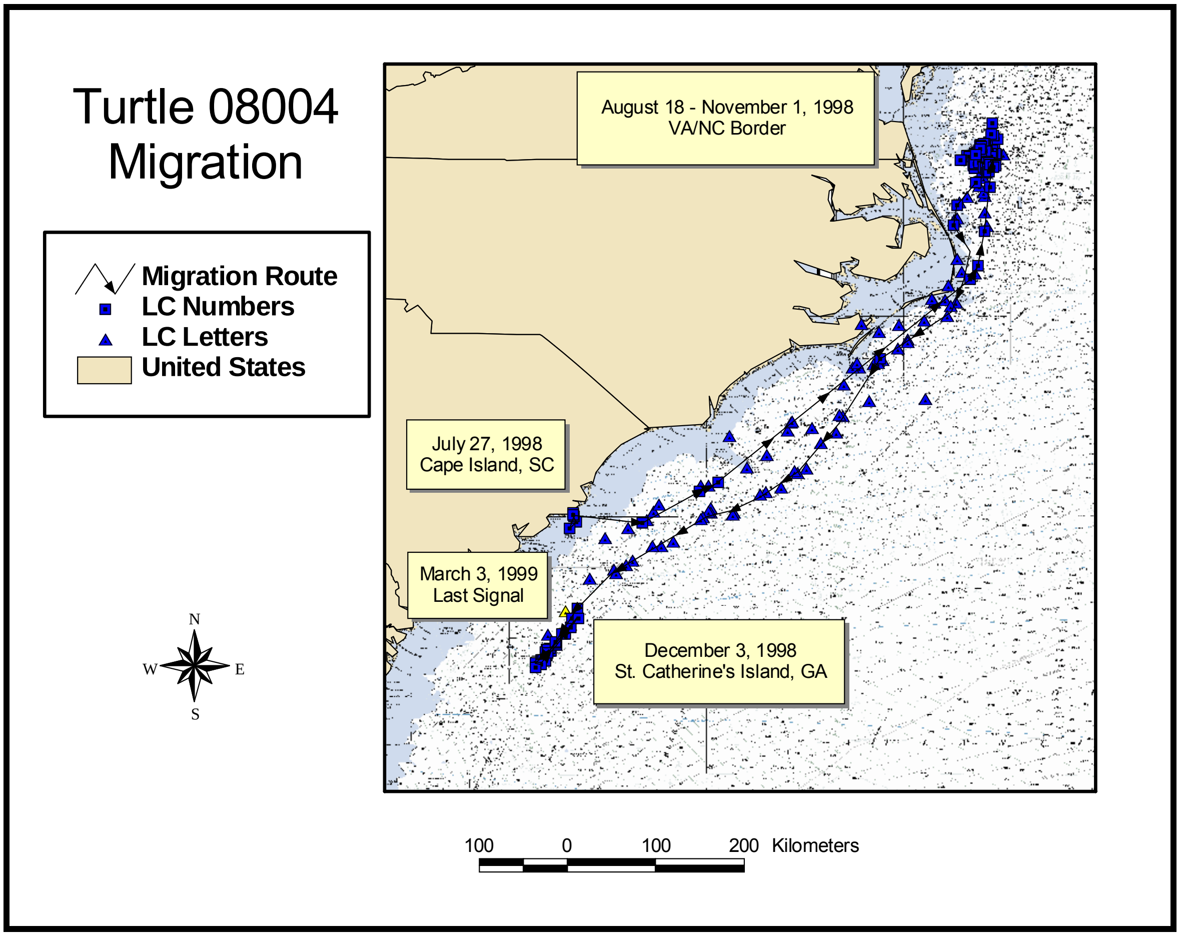


Figure 3. Turtle 08004's migration.

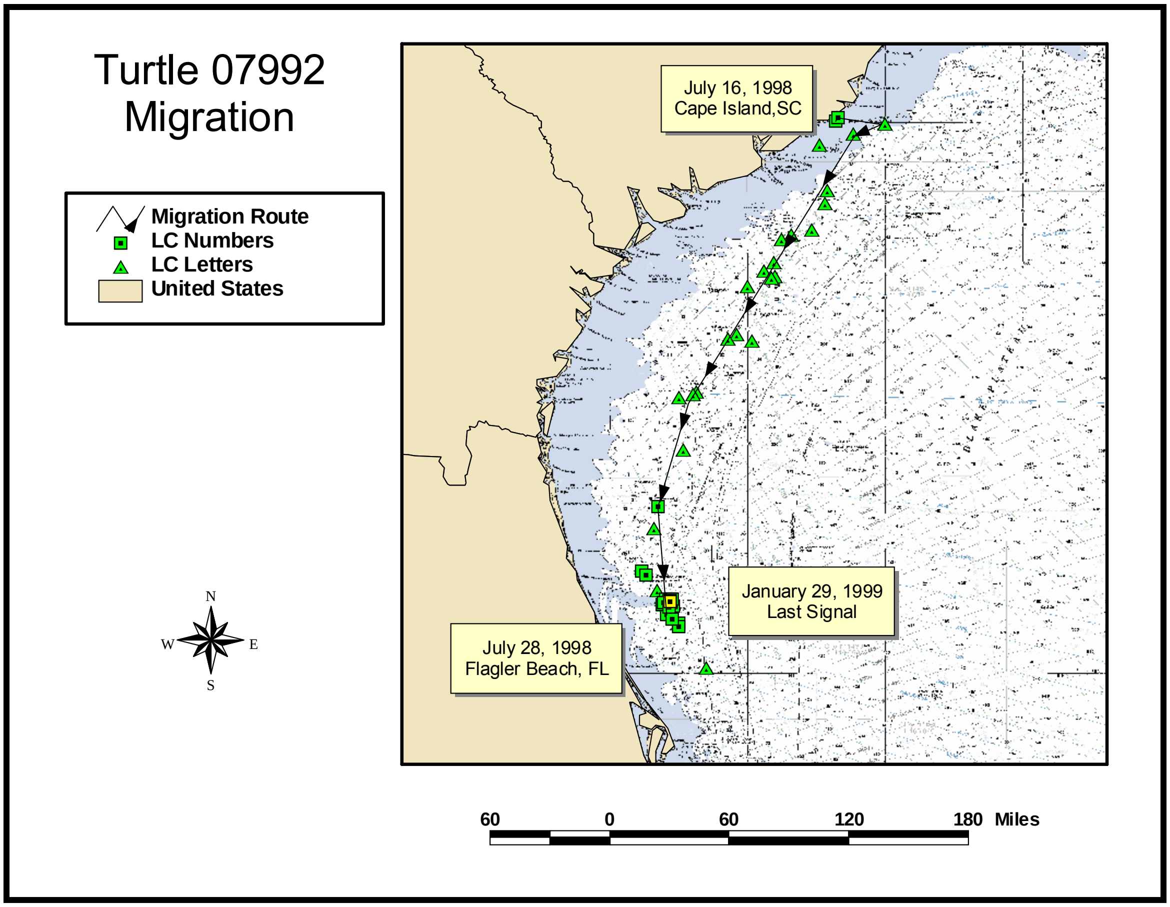

Figure 4. Turtle 07992's migration.

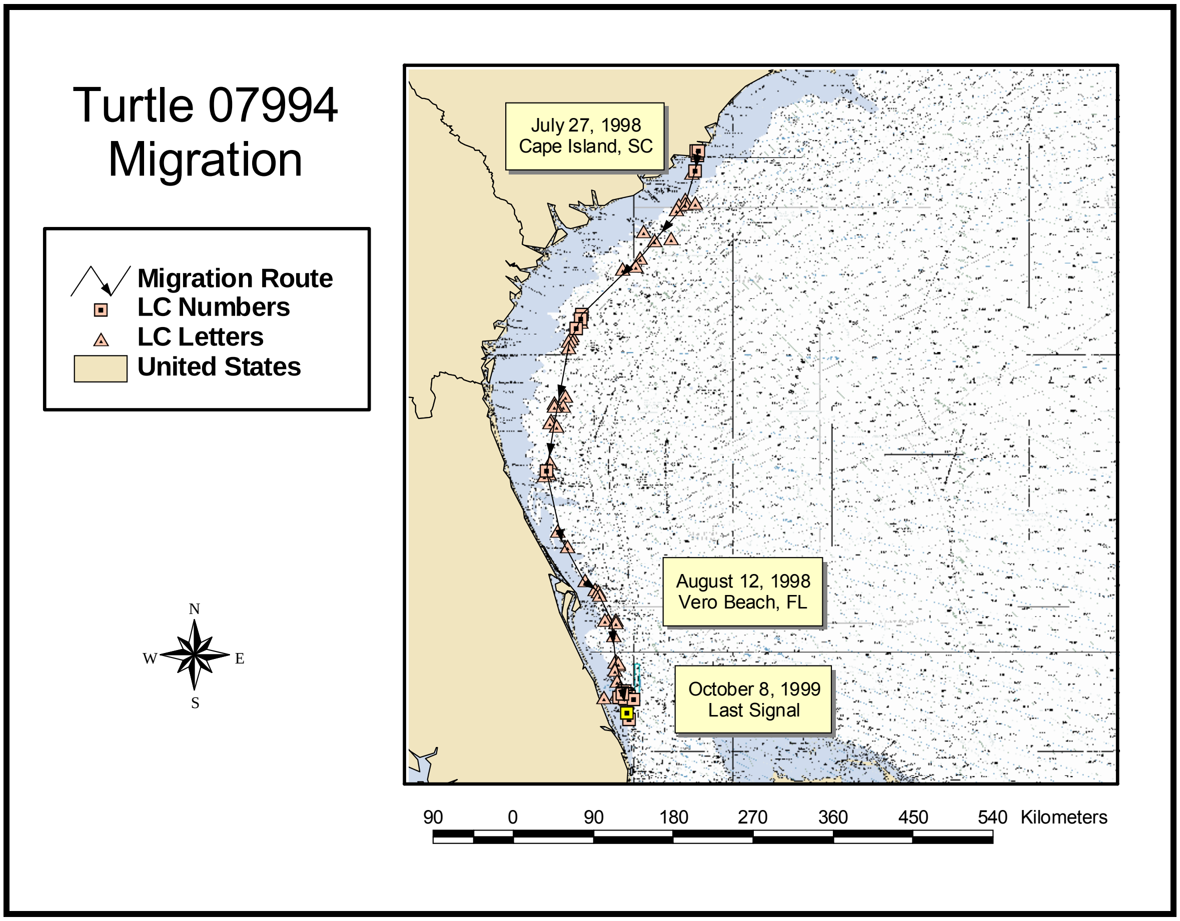


Figure 5. Turtle 07994's migration.

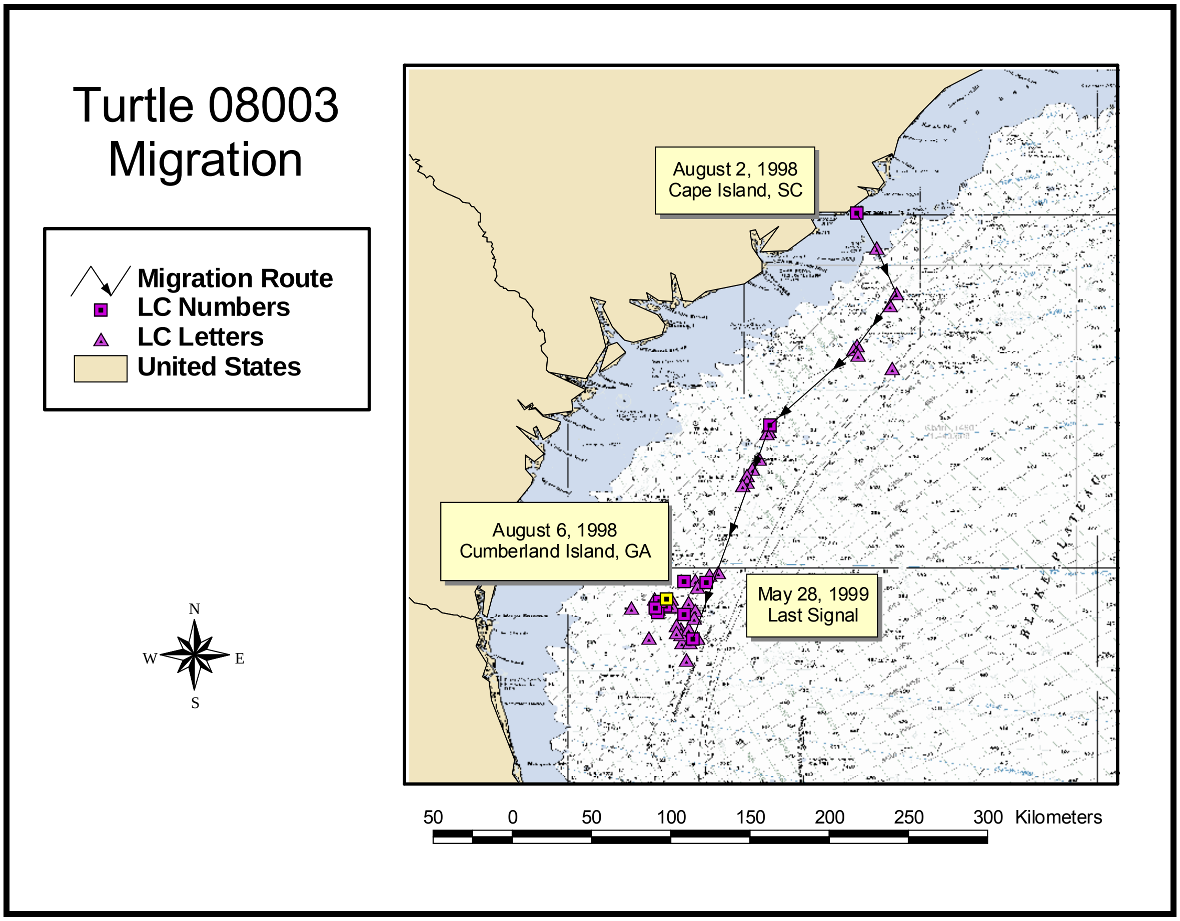


Figure 6. Turtle 08003's migration.

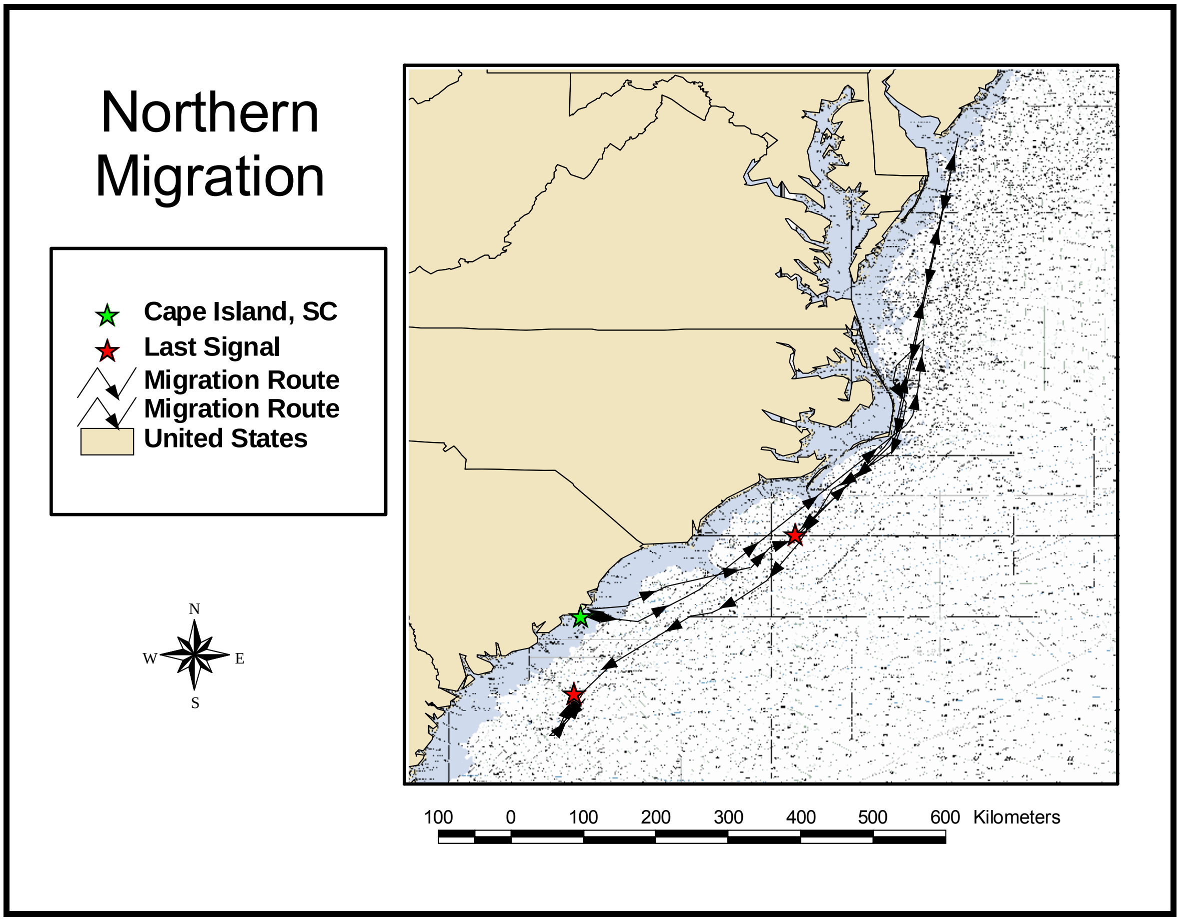


Figure 7. Northern migrations.

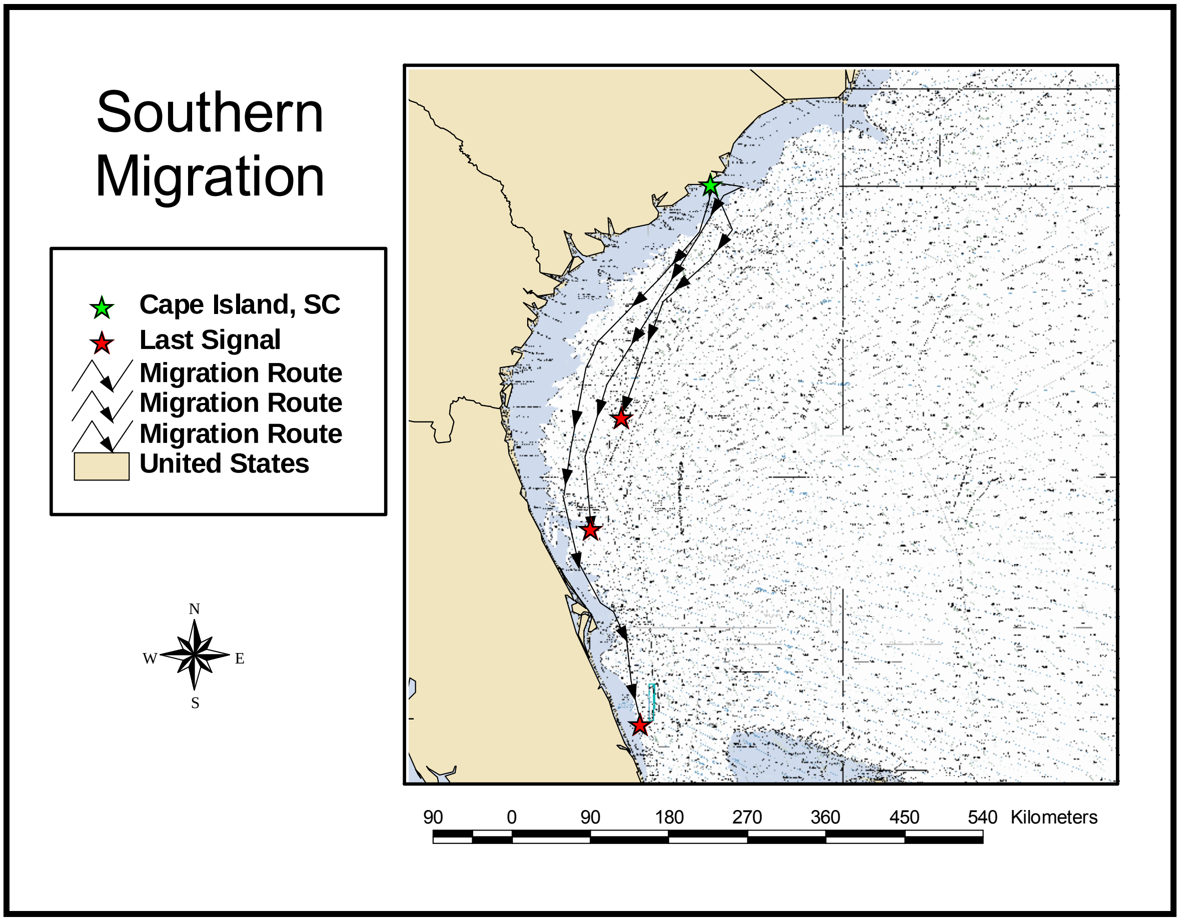

Figure 8. Southern migrations.

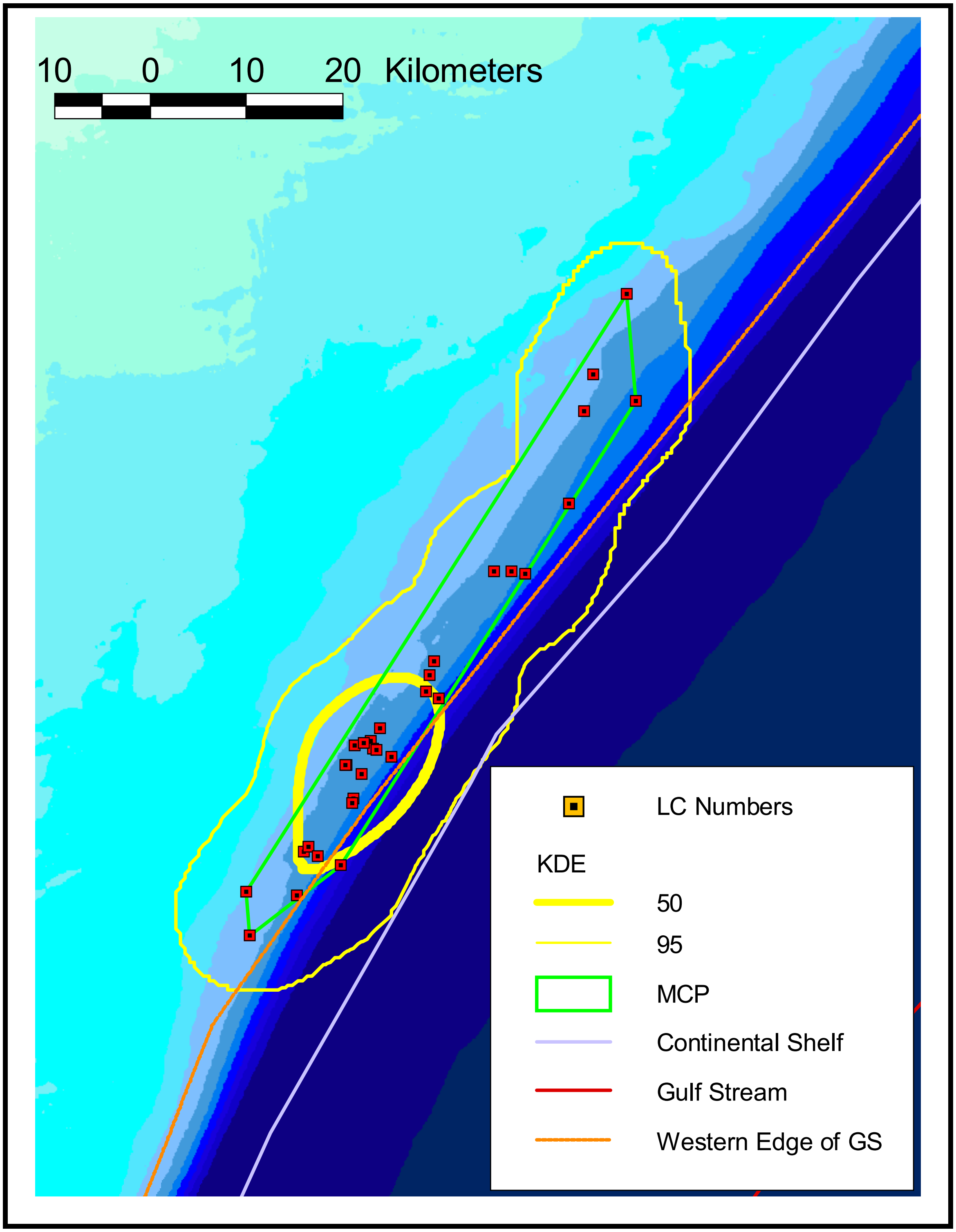

Figure 9. Turtle 08004's southern resident foraging area.

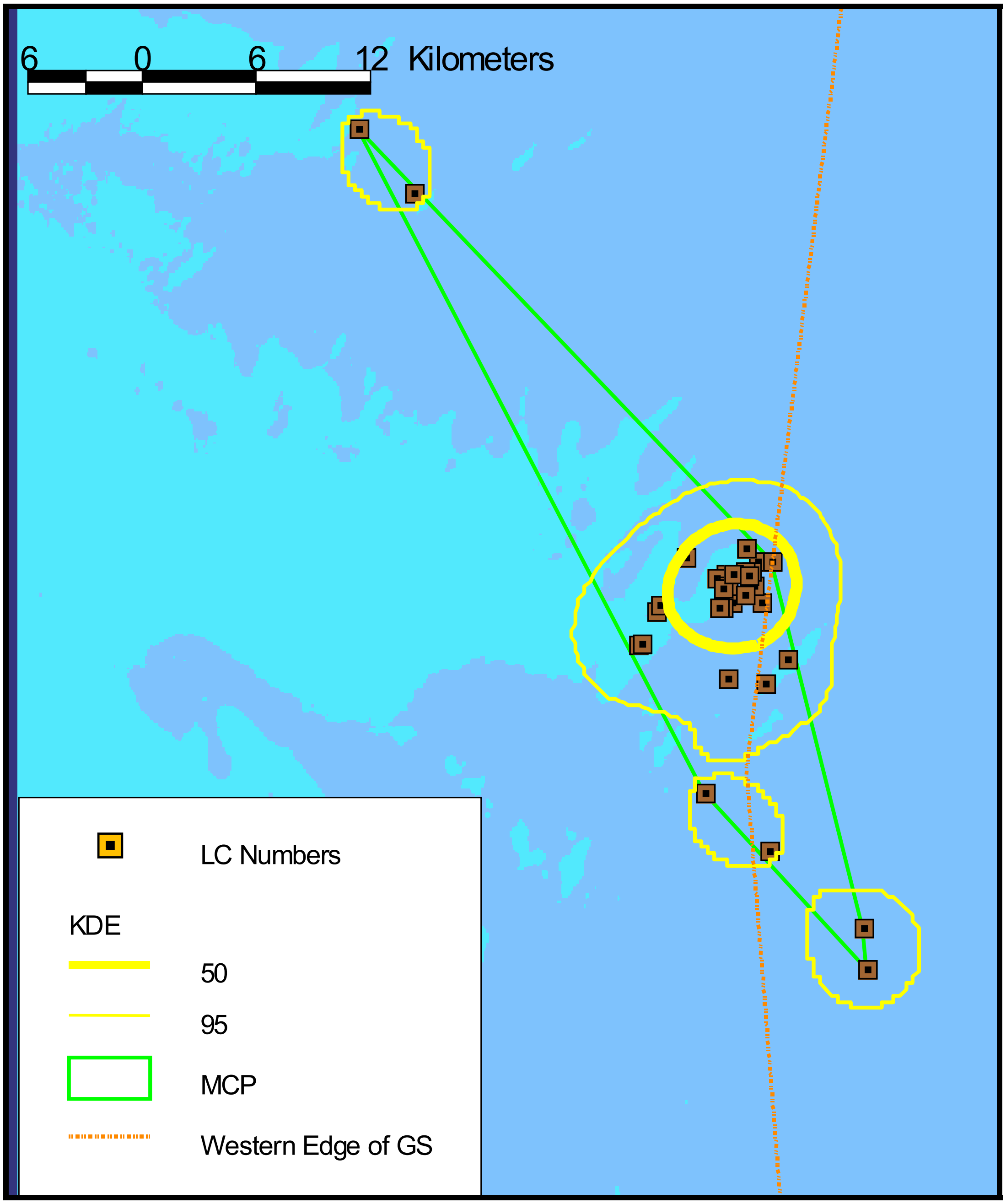

Figure 10. Turtle 07992's resident foraging area.

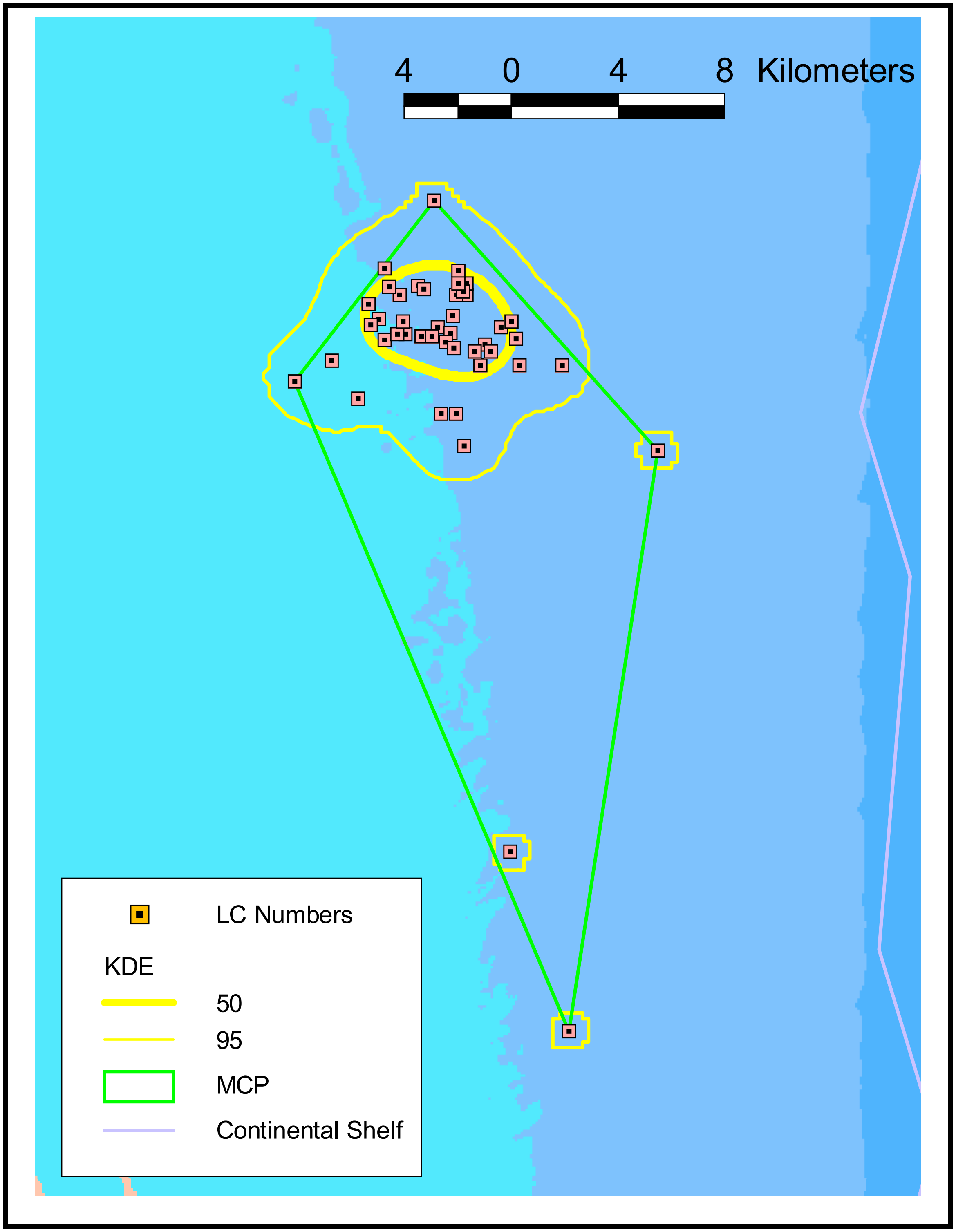

Figure 11. Turtle 07994's resident foraging area.

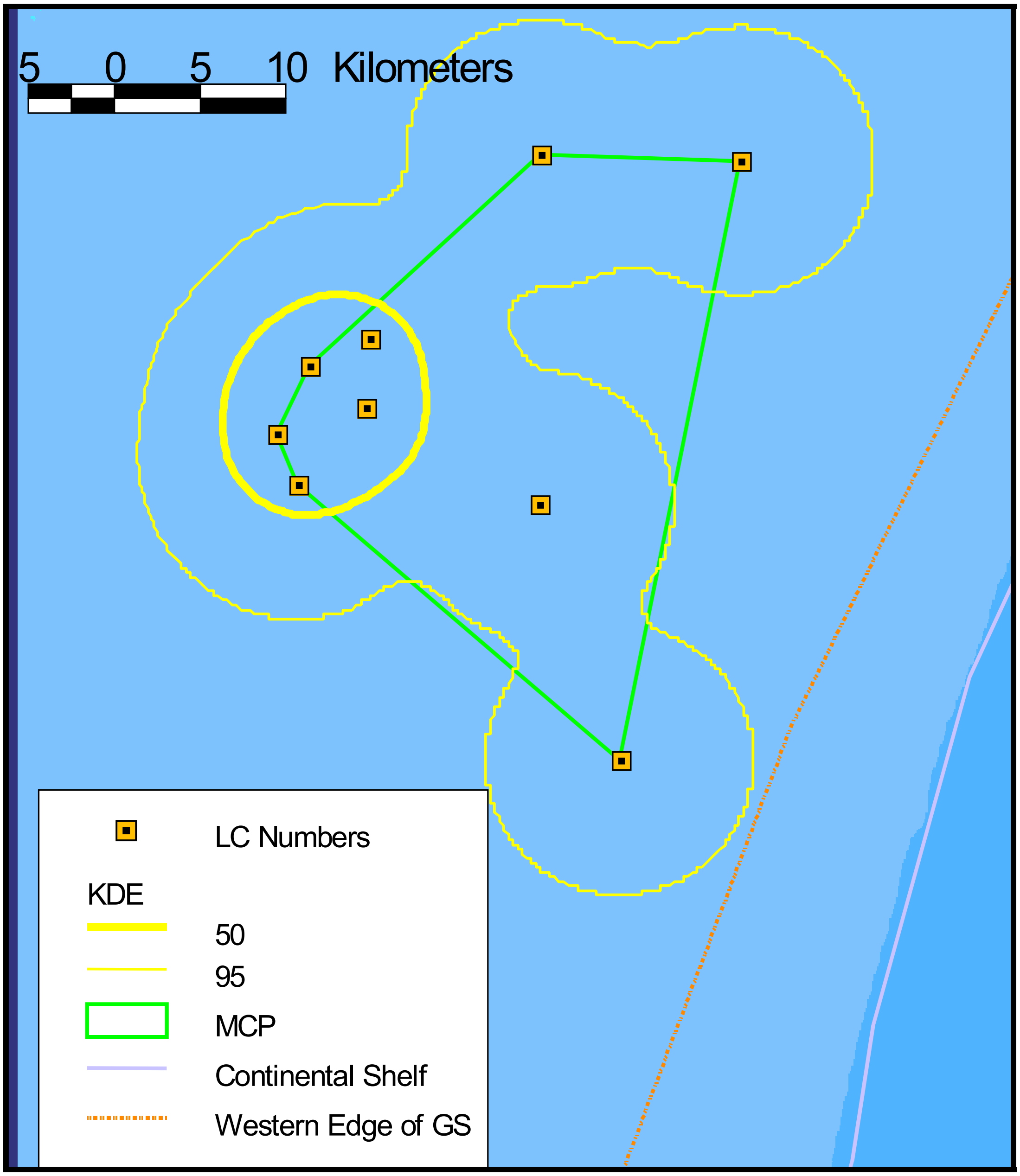

Figure 12. Turtle 08003's resident foraging area.

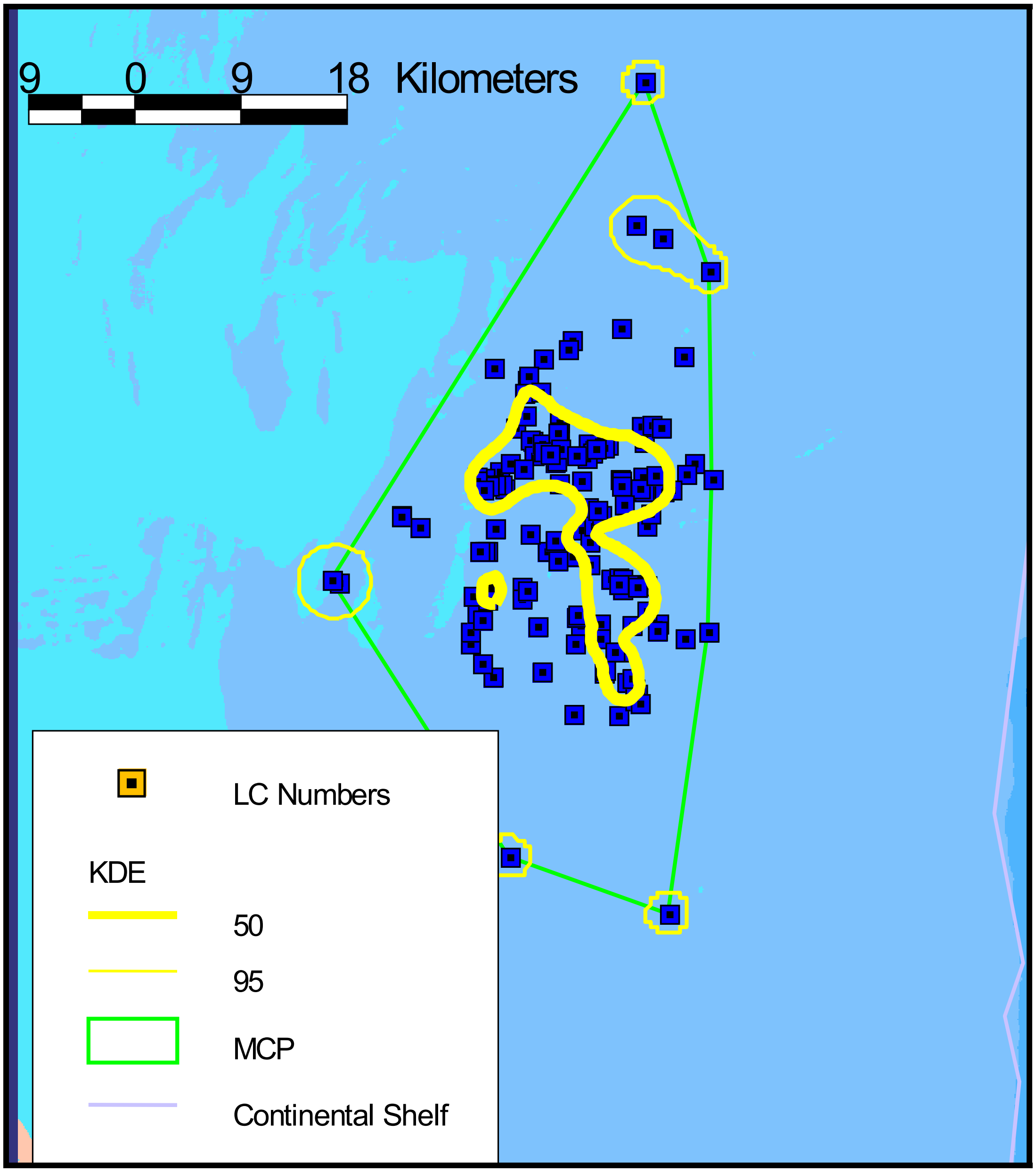

Figure 13. Turtle 08004's northern resident foraging area.

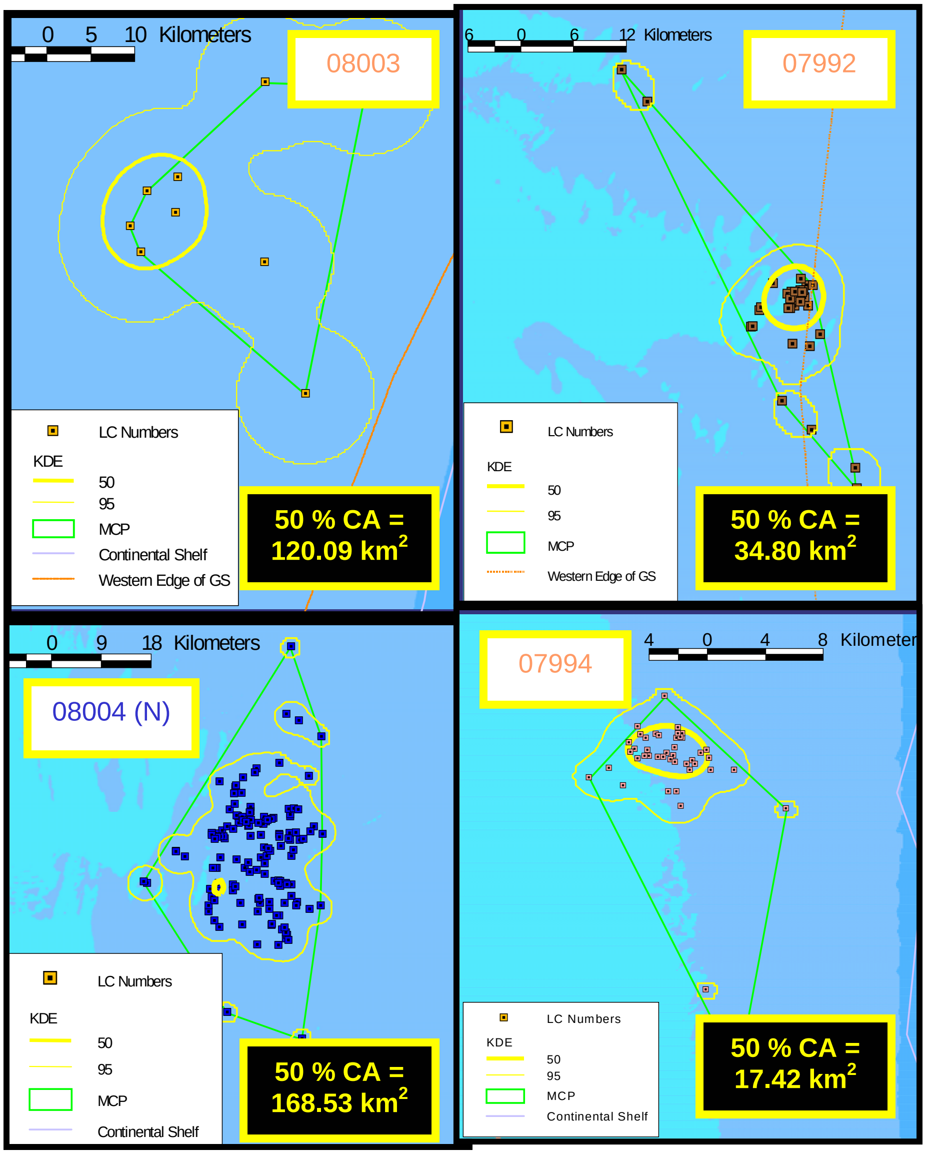


Figure 14. Comparison of 1998 resident foraging areas. Beginning lower right and moving counter-clockwise, size decreases in a north to south gradient.

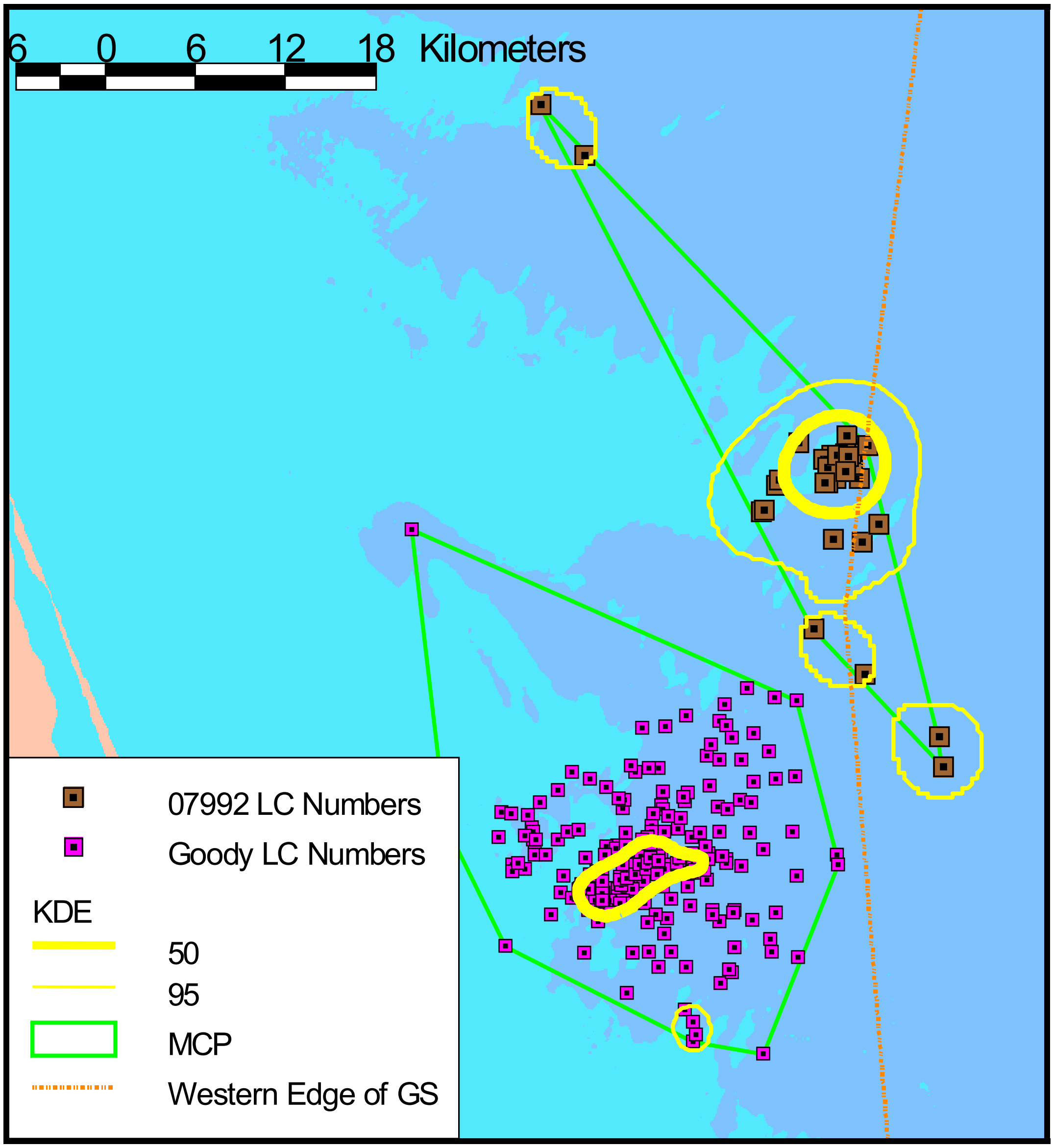

Figure 15. Turtle 07992 and Goody's resident foraging areas.

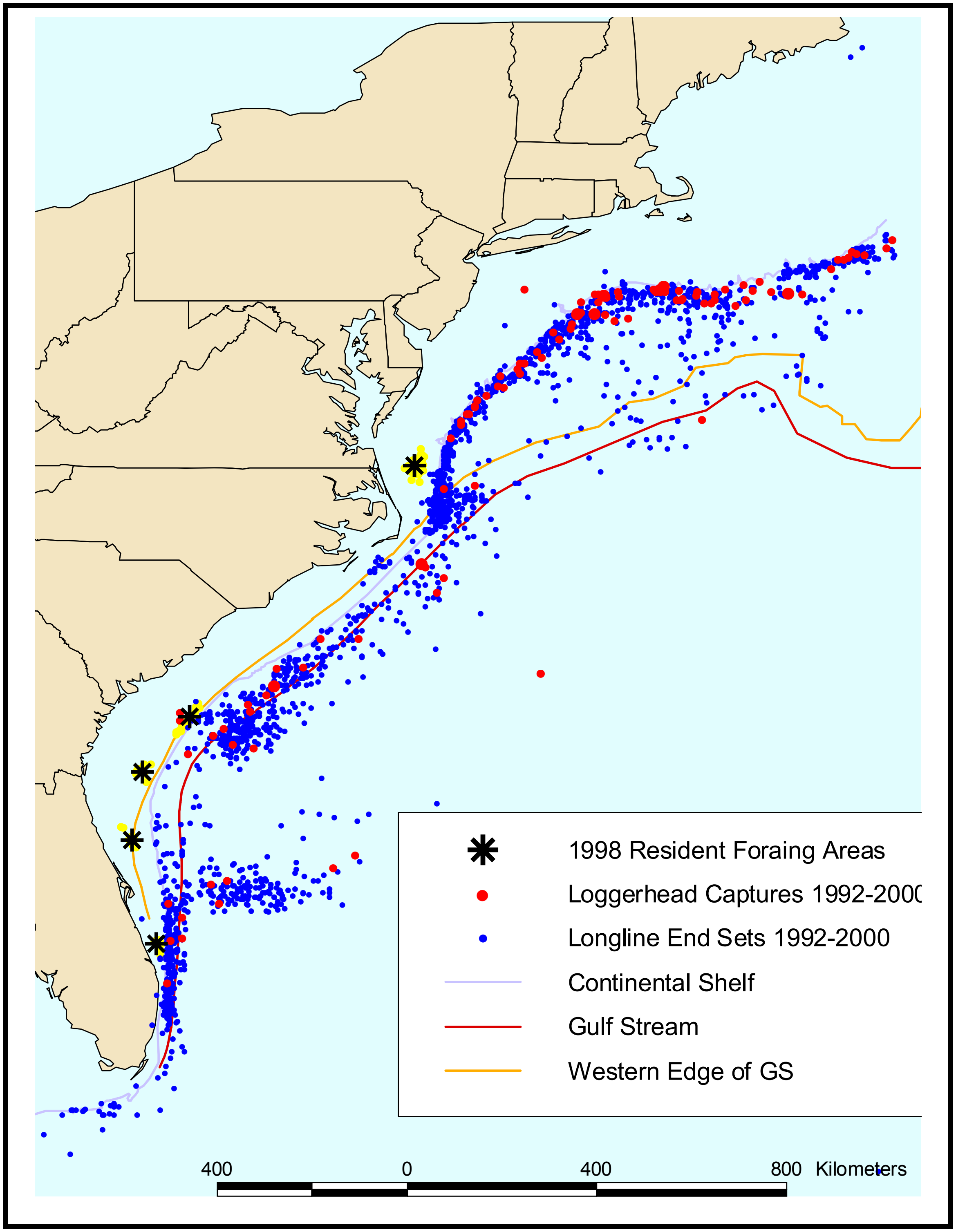


Figure 16. Overlay of 1998 resident foraging areas with observer data on incidental loggerhead captures and fishing effort of the U.S. longline fleet (1992 – 2000).

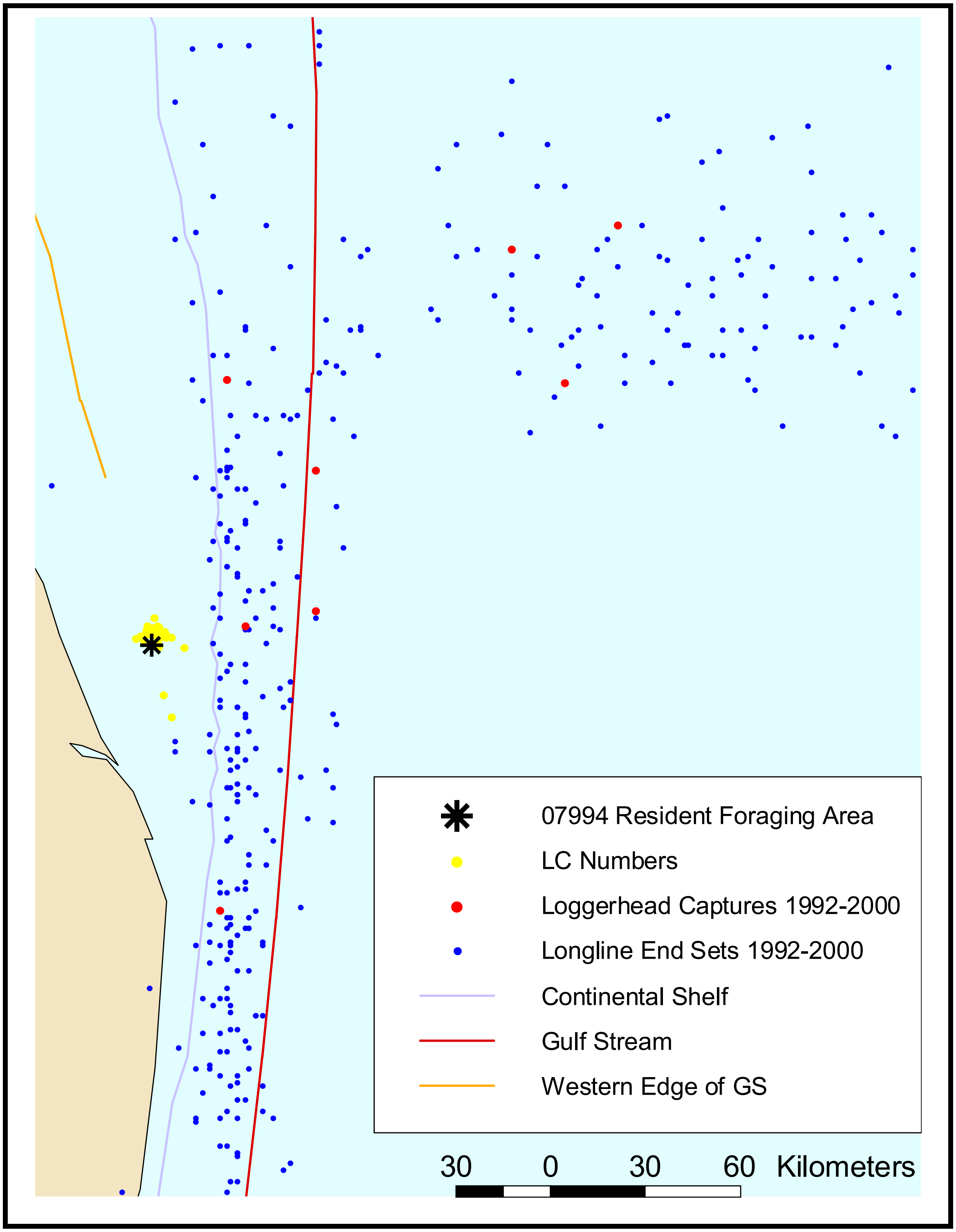


Figure 17. Turtle 07994's resident foraging area relative to fishing sets.

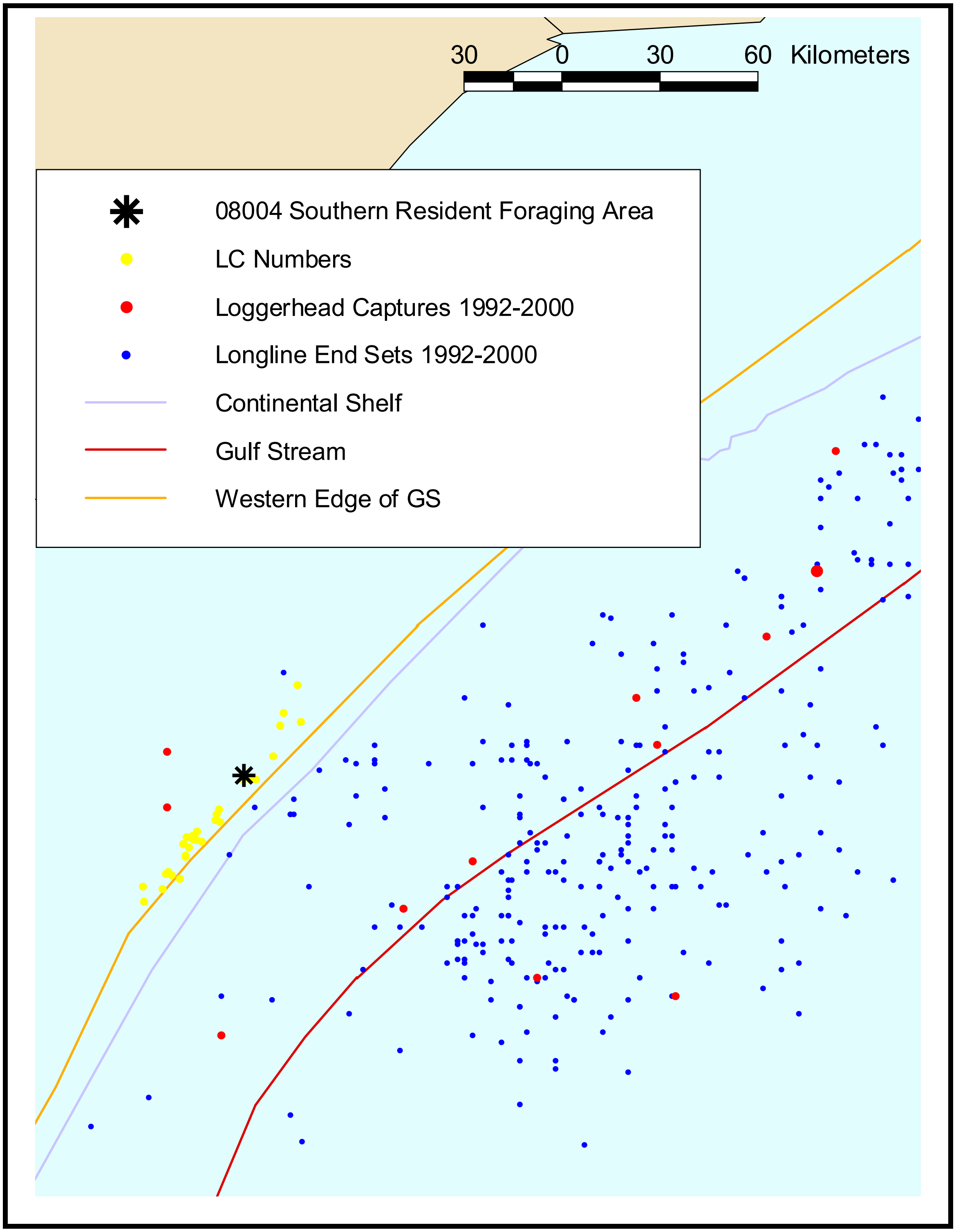


Figure 18. Turtle 08004's resident foraging area relative to fishing sets.