USE OF SATELLITE TELEMETRY TO DETERMINE ECOLOGY AND MANAGEMENT OF LOGGERHEAD TURTLE (CARETTA CARETTA) DURING THE NESTING SEASON IN GEORGIA

by

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(Under the Direction of Steven B. Castleberry)

ABSTRACT

Loggerhead turtle (Caretta caretta) populations are threatened across the distribution, and susceptible to high adult mortality in neritic zone habitats. Commercial fisheries, especially shrimp trawling, are believed to exact heavy losses on the adult loggerhead population within these habitats. Yet, little is known about how commercial shrimp trawler fleets interact with adult loggerhead populations cross temporal and spatial scales. Observations of distribution and movement patterns for adult female loggerhead turtle and the commercial shrimp trawl fishery were made during the 2004 and 2005 nesting seasons in Georgia. Comparisons between the distributions were used to produce potential management scenarios (closures and fleet reductions) designed to reduce the likelihood of interactions. Through application of predictive modeling, spatial closures were identified to have only limited merits as management options, whereas fleet reductions were most likely to produce actual decreases in interactions between turtles and shrimp trawlers during nesting seasons.

INDEX WORDS: accuracy, behavior, Caretta caretta, commercial fisheries, distribution, fixed kernel density, home range, loggerhead turtle, management, movement, predictive models, shrimp trawlers, site fidelity, telemetry
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DEDICATION

There is nothing more important in this world than family. The completion of this thesis was possible only through the graces my family has shown me. They are the light of my heart and the strength I draw from each and every day.
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Chapter 1 – Perspectives on Loggerhead Turtle Status and Management

Introduction

Modern sea turtles (*Cheloniidae* and *Dermochelyidae*) enter the fossil record approximately 110 million years ago (Hirayama 1998) with current species remaining relatively unchanged over the last 40-50 million years (Spotila 2004). During this time sea turtles achieved world wide distribution throughout tropical to temperate waters (Dodd 1988). Generalist strategies of the seven extant species likely led to this long-term persistence amid geologic changes. Despite widespread success tempered across millions of years, recent times have witnessed appreciable and oft times dramatic declines in sea turtle populations (Pritchard 1997). The World Conservation Union currently list leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricate*), and Kemp’s ridley (*Lepidochelys kempii*) turtles as critically endangered, and loggerhead (*Caretta caretta*), green (*Chelonia mydas*), and olive ridley (*Lepidochelys olivacea*) turtles as endangered across the respective distributions (International Union for the Conservation of Nature 2004). Inadequate information exists for flatback turtle (*Natator depressus*) populations yielding a Data Deficient status (IUCN 2004). The U.S. Department of Interior lists all sea turtle species as endangered except loggerhead turtle, which is given threatened status, and flatback turtle which is currently not listed (Pritchard 1997). The Convention on International Trade in Endangered Species of flora and fauna (CITES) lists all seven sea turtle species on its Appendix H prohibiting international trade among member countries.

Though numerous factors affect sea turtle populations, it is generally accepted that modern anthropogenic sources of mortality exact heavy influence on population trends
(Magnuson et al. 1990). To facilitate conservation and recovery of these species, a thorough understanding of the dynamic system in which they persist is necessary. Ecological information describing all life stages is needed, and understanding interactions between turtles and humans at each different life stage is a priority (National Marine Fisheries Service 1991). Human induced sources of mortality that are thought to take turtles in substantial numbers include, but are not limited to, boat propeller strikes, channel dredging, gill netting, human consumption, ingestion of marine debris, longline fisheries, pound net fisheries, power plant entrapment, and shrimp trawl fisheries (Magnuson et al. 1990, National Marine Fisheries Service 1991). In most cases, little quantifiable information exists regarding interactions between turtle species and known sources of mortality.

This investigation was directed towards studying sexually mature female loggerhead turtles among the northern subpopulation of the southeastern United States nesting aggregation. The purpose of this investigation was three-fold: 1) quantify spatial distribution patterns during nesting season movements of loggerhead turtles utilizing the Georgia coastline; 2) compare turtle distributions with the distribution of the shrimp trawl fishery operating concurrently in the same region; 3) produce informed management recommendations for state and federal agencies to aid conservation efforts for loggerhead turtle during the nesting season portion of the adult female life stage.
Background

Population Definitions

Loggerhead nesting rookeries of the southeastern U.S. represent 35-40% of nesting for the species worldwide (Ross 1982) and 75-80% within the Atlantic Ocean basin (Spotila 2004), which makes their conservation important for recovery of the species. The large aggregate of nesting beaches across the southeastern U.S. have been divided into three distinctive subpopulations (Figure 1.1), as defined by the IUCN, based largely on past mtDNA analysis (Bowen et al. 1993, Encalada et al. 1998, Pearce 2001). Each subpopulation – Florida Panhandle, Southern Florida, and northern – is considered an isolated management unit with area-specific management goals (National Marine Fisheries Service 1991). The Turtle Expert Working Group (TEWG) recommends that these genetically distinctive subpopulations be managed and conserved separately because of low dispersal mediated gene flow along the maternal line (Turtle Expert Working Group 2000). However, recent work using nuclear DNA indicates little distinction between subpopulations (Bowen et al. 2005). High distinction between subpopulations using mtDNA and no significant distinction using nuclear DNA implies that females show high philopatry to natal beaches, but males are less restrictive causing sex-biased gene flow across the entire southeastern U.S. loggerhead turtle population. Avise (1994), Moritz (1994), and Waits et al. (2000) all came to similar conclusions when faced with low mtDNA variability and high nuclear DNA variability. However, the loggerhead population studies using nuclear DNA are based only on four or five loci (Pearce 2001, Bowen et al. 2005) offering conservative estimates of population relatedness; more thorough investigation using 15-20 is preferable (e.g. Waits et al. 2000). Nonetheless, despite potentially high male mediated gene flow across subpopulations, Bowen et al. (2005) recommend that the recognized management
units still be maintained as separate conservation entities. The TEWG (2000) state loss of females within a given subpopulation will lend to local extirpation because slow colonization rate of new females from other subpopulations is insufficient to repopulate any such area in modern times (Turtle Expert Working Group 2000).

Life history

Loggerheads are long-lived, slow growing reptiles with complex life history patterns (Figure 1.2). To fully distinguish best management actions, intricacies of the loggerhead life history for the northern subpopulation must also be fully understood. Using standardized terminology outlined by Bolten (2003a) each of the four major life stages is summarized below relative to the northern subpopulation of eastern U.S. loggerhead turtles. Transitional life stages were not included in this summary, not because of any disagreement in their use or validity, but rather because this summary is only meant to be a general overview of the basic life history pattern. More extensive review of the adult female loggerhead life stage is presented below because it is the primary focus of this research.

Hatchling Stage – Hatchling loggerheads of the northern subpopulation emerge from nests buried in primary sand dunes of barrier islands between the months of July and October, 50-70 days post-oviposition (Richardson 1980). After emerging and crawling to the ocean they enter an active swimming period termed “swim frenzy” (Wyneken and Salmon 1992). This frenzy is fueled by yolk sac energy reserves, which carries them to the Gulf Stream and the North Atlantic Gyre. There, they maintain a pelagic feeding strategy, using rafts of sargassum weed as escape cover and foraging habitats (Carr and Meylan 1980).
Oceanic Juvenile Stage – Hatchlings that reach the Gulf Stream enter the oceanic juvenile life stage. Once termed ‘The Lost Years’ by Archie Carr (1967), this stage was a constant enigma for sea turtle researchers. Many holes in the knowledge base still exist, though more recent discoveries using satellite telemetry, and genetic analysis has elucidated many aspects. For instance, based on genetic analysis of loggerhead tissue collected in the Azorean, Mediterranean, and Caribbean waters, Bolten (2003b) concluded that loggerheads circumnavigate the North Atlantic likely through passive drift on the North Atlantic Gyre. Other genetic analyses indicate significant permeation of western North Atlantic oceanic juvenile loggerheads into the Mediterranean waters (Laurent et al. 1998, Bolten 2003b). There is still uncertainty whether oceanic juveniles rotate around the North Atlantic constantly for the entire 8-12 years of this stage, or whether they periodically leave the Gyre for extended periods of time. Recent evidence using satellite telemetry suggest the latter, that at least some turtles of the oceanic juvenile stage spend time in established home ranges near the Azorean waters (Bolten 2003a). Previous research has suggested that turtles of this life stage make short trips into the neritic zone of continental shelves, but then reenter the gyre system (Bolten 2003a, Eckert and Martins 1989).

Neritic Juvenile Stage – As oceanic juveniles gain size and deep diving capability, they leave the Gyre and return to the North American continental shelf. At this point turtles enter the neritic juvenile life stage adopting a predominately benthic foraging strategy preying largely on mollusks and crustaceans (Dodd 1988). Turtles from the northern subpopulation use neritic habitats stretching from the western Gulf of Mexico around Florida up the east coast to possibly as far north as Nova Scotia, Canada (Shoop et al. 1981). Turtles of the neritic juvenile stage exhibit low but measurable population structure; turtles are more likely to establish home ranges
close to other members of the same subpopulation rather than members of different subpopulations (Bowen et al. 2005). Mixing between subpopulations does occur, but at a lesser degree than if it occurred in purely random fashion (Bowen et al. 2005).

In northern latitudes juvenile loggerheads exhibit seasonal migrations, seemingly to avoid adverse water temperatures (Epperly et al. 1995a, Epperly et al. 1995b, Keinath et al. 1996, Coles and Musick 2000). Mark-recapture evidence over multiple years as well as tracking data of relocated individuals suggest these turtles return to the same foraging grounds in sequential years (Avens et al. 2003), although the consistency of this pattern over the entire neritic juvenile stage is unclear. Whether migratory behavior is only expressed in turtles of northern latitudes where temperature changes provoke such behavior, or if repeated predictable seasonal movements also occur in more thermally stable latitudes is unknown (Hopkins-Murphy 2003).

Adult Stage – Loggerheads of the southeastern U.S. reach sexual maturity after approximately 28-33 years (Spotila 2004), whereupon they begin the adult life stage. Female loggerheads exhibit iteroparous behavior within and among years (Plotkin 1995) with the adult female life stage generally described as an oscillation between active nesting seasons and extended foraging periods (Schroeder et al. 2003).

Females migrate from foraging habitats to breeding grounds (NMFS 1991). It is unknown but assumed that males migrate with the females to breeding grounds. Courtship and mating occur between late March and early June (Caldwell et al. 1959, Fritts et al. 1983). Though much of courtship and mating behavior in loggerheads is not understood (NMFS 1991), genetic analysis of hatchlings within individual nests suggested that polyandry (multiple sires) occurred in 31% of nests laid in Florida (Moore and Ball 2002). Sperm storage, which facilitates fertilization of egg clutches as they develop throughout the nesting season, allows competition
between male gametes (Bernasconi et al. 2004). After breeding occurs females continue to the
nesting grounds (Caldwell et al. 1959), which may be close to the breeding location (Frick et al.
2000). Bowen et al. (1993), and Encalada et al. (1998) offer strong support for philopatry
through genetic analysis of mtDNA with each subpopulation, but the degree of philopatry
expressed by the population has not been adequately tested.

Nesting in Georgia begins slowly in early May and continues through mid August
(Appendix A) (Richardson 1980, NMFS 1991). During a nesting season females are thought to
rely solely on stored energy reserves as foraging behavior during this time period has not been
documented (Hopkins-Murphy et al. 2003). Loggerheads are nocturnal nesters though
exceptions to this tendency do occur (Richardson 1980). During an active nesting season
females can lay up to seven clutches (Lenarz et al. 1981; Talbert et al. 1980) with an estimated
mean of 4.1 nests per female per season (Murphy and Hopkins 1984). Between each nest there
is an internesting interval – the number of days between consecutively laid nests by a single
individual – of approximately 14 days (NMFS 1991). Considerable variation exists in the
internesting interval (Richardson 1980). Average clutch size on Georgia beaches is estimated as
120 eggs (Richardson 1980), but is geographically variable ranging from 100-126 across the
whole southeastern United States (NMFS 1991). Within a nesting season, female loggerheads
exhibit varying degrees of nesting site fidelity or tendency to nest near areas used earlier that
season (Schroeder et al. 2003). Richardson (1980) remarked on this variable degree of fidelity
by arbitrarily labeling turtles either as alpha (low nesting site fidelity) or beta (high nesting site
fidelity) turtles relative to their nesting activity on Little Cumberland Island (LCI). Some turtles
laid 3-6 nests on the small 4 km beach of LCI, while others would nest only once or twice
presumably nesting on other beaches further away.
Movements of adult females between nesting events is poorly understood. Attempts have been made to document movements during this phase of loggerhead life history (e.g., Hopkins and Murphy 1981, Stoneburner 1982, Bartol and Musick 1998, Mansfield et al. 2001, Addison et al. 2002), but adequate observation to offer sound description of habits have proved difficult. Habitat preferences are unknown, although anecdotal evidence suggests they tend to locate within 10 km of shore and sometimes enter estuarine habitats behind barrier islands (Hopkins and Murphy 1981, Stoneburner 1982) and may associate with areas of high relief like shipping channels or shoals (Hopkins-Murphy et al. 2003).

After turtles lay their final nest of the season they migrate to foraging grounds to begin replenishing lost energy reserves (Miller and Limpus 2003). It has been shown through tag recoveries (Bell and Richardson 1978), and more recently with satellite telemetry that these foraging grounds are located all along the east and gulf coast with a majority of northern subpopulation turtles migrating north to waters between Long Island, New York and Cape Hatteras, North Carolina (Mansfield et al. 2001, Plotkin and Spotila 2002, South Carolina Department of Natural Resources, unpublished data). Adult female turtles continue foraging for as many years as required to replenish body energy stores that will allow them to physically endure another nesting season (Wilbur and Morin 1988). This period, termed the remigration interval, can last from one to nine years (Dodd 1988), with most intervals lasting for two to three years. For males, it is unclear whether they engage in mating behavior every season once reaching sexual maturity. Because energy expenditure is likely considerably less for male turtles than females, males may not require multiple years between active mating seasons to replenish reserves.
In northern latitudes, primarily above Cape Hatteras, seasonal migrations occur for neritic juvenile and adult loggerheads (Shoop and Kenney 1992, Mansfield et al. 2001, Avens et al. 2003). Temperature appears correlated with migration timing and shifts in turtle distributions, making it a likely cue (Epperly et al. 1995b, Coles and Musick 2000). Studies monitoring turtles in more southerly latitudes where water temperatures are more stable could aide in understanding migration patterns in neritic loggerheads. Further investigation into forage availability, photoperiodism, and other potential cues is also necessary.

**Population Monitoring**

Counting total annual nests within a given management unit is commonly accepted as an adequate means of monitoring long-term loggerhead population trends (NMFS 1991, TEWG 2000). Counts of this nature are an indirect index to population abundance and yield weaker inferences about true population abundance than formal estimation methods (Williams et al. 2002). Conroy (1996), Pollock et al. (2002), and Rotella and Ratti (1986) all warn heavily against using indirect indices unless index values are validated against a known population size or independently derived population estimates. In the case of the northern subpopulation of loggerhead turtles, mark-recapture data and independent aerial surveys were used to evaluate the relationship and found a consistent linear association of 4.1 nests per female per active nesting season (Murphy and Hopkins 1984).

Trend analysis of indices requires the critical assumption that detectability remains constant both spatially and temporally (Williams et al. 2002). Constant detectability in turtles requires that the average number of nests per female does not change over space and time. Changes in resource quality and/or quantity on foraging grounds could positively or negatively
alter the mean number of nests laid per female per season across the population from year to year. Based on Wilbur and Morin (1988), it is similarly possible that changes in resource availability could alter the population mean remigration interval. If either situation is realized, index values to turtle population abundance would fluctuate inconsistently with the true population abundance and the assumption of consistent temporal detection would be violated making index values less reliable as a means to monitoring true population trends. Due to these potentially confounding factors and others unknown at this time, periodic reevaluation of index parameters should be conducted to ensure the data maintain a constant proportion to population size (Rotella and Ratti 1986).

If the assumption of a constant linear relationship between the nest number index and true population is accepted as robust, then annual nest totals over time are functional for population trend analysis under standardized survey effort conditions. Hawkes et al. (2005) found nest numbers on Baldhead Island, North Carolina, to be stable over a 24-year time series of standardized survey conditions (1980-2003). Over a 33-year time series (1973-2005) three Georgia beaches maintained relatively standardized survey effort. The 33-year time series data suggest a 1.5% annual decline in loggerhead nesting within the state of Georgia (Dodd and MacKinnon 2006).

Monitoring nesting activity to index population trends does not provide complete information regarding the population as a whole. Nesting trends offer no means to include male or smaller size class turtles, which make up a considerable and important proportion of the population. Also, with such a long time span to age of first reproduction, there is a substantial lag between when a problem in the hatchling or juvenile stages (oceanic or neritic) occurs to when it is detected by lack of recruitment to the adult nesting population. Long-term
standardized random in-water catch-per-unit-effort (CPUE) surveys of coastal waters would be a useful tool for early monitoring of population trends (Maier et al. 2004). Formal estimation procedures based on mark-recapture data could be possible, as well as estimation of recruitment rates into nesting populations by maturing large juvenile turtles.

**Threats and Management**

Since the late 1960’s and early 1970’s, a considerable proportion of sea turtle management effort has been, and still is, directed towards ensuring high levels of nest protection and hatchling production (NMFS 1991). Public awareness generated from beach patrol efforts produces intrinsic investment by society, which aids tremendously in promoting legislation and regulation designed for species conservation. Nevertheless, sensitivity analysis of population model parameters by Crouse et al. (1987) and Crowder et al. (1994) indicate fluctuations in the hatchling life stage are least responsive for promoting recovery in loggerhead populations. Population recovery is positively responsive to increases in survival rates for the pelagic and neritic juvenile stage, and adult stage loggerheads (Crouse et al. 1987, Crowder et al. 1994).

Oceanic juvenile stage turtles from the southeastern U.S. populations incur high anthropogenic mortality prior to recruitment back to the continental shelf habitats (TEWG 2000). Mortality between subpopulation management units cannot be separated during this stage due to thorough mixing of the subpopulations yielding no detectable population structure (Bowen et al. 2005). Pelagic longline fisheries targeting mostly swordfish and tuna are considered significant sources of mortality for pelagic juvenile stage loggerhead turtles from the southeastern population assemblages (Bolten et al. 1994, Aguilar et al. 1995). Pelagic juveniles potentially encounter several longline fisheries from the Azorean waters, Mediterranean, and Caribbean
during their multi-year circumnavigation of the North Atlantic (TEWG 2000). Recent use of circle hooks show potential for increasing survival rates of turtles post release. The shape allows for less frequent snagging of delicate internal tissue of the alimentary canal.

Most neritic zone in-water management for loggerhead turtle has focused on reducing mortality associated with the commercial shrimp trawl fishery (Henwood and Stuntz 1987, Epperly and Teas 2002, Epperly 2003). Turtle Excluder Devises (TEDs) that allow an escape route out of trawl nets for captured turtles were made mandatory year-round for all shrimp trawlers in 1991. Royle and Crowder (1998) found a suggestive correlation between timing of mandatory TED use and reduction in turtle strandings in Georgia (1980-1997). Initial analyses indicated a 40% reduction of strandings on South Carolina beaches, and 58% reduction on Georgia beaches. However, more recent analysis of the Georgia data that took into account fluctuations in shrimp landing levels - indicative of shrimp trawling effort - suggest a more modest reduction of 37% in strandings after TEDs were made mandatory (Royle 2000). In contrast, stranding data collected on Georgia beaches from 1989 to 2004 using standardized monitoring effort do not show a general downward trend in loggerhead stranding numbers (Appendix B). Similar findings of no TED effect were reported for strandings observed on Cumberland Island (Shoop et al. 1999) and the Gulf of Mexico (Caillouet et al. 1996) following implementation of mandatory TED regulations.

Number of adult loggerhead turtle strandings ($\geq 87$ cm CCL) on Georgia beaches fluctuates considerably, but average 21.1 ($\pm 4.2$) annually (Appendix C). Accurate assessment of sex ratio for the adult carcasses is unavailable due to frequent advanced stages of decomposition. Evidence suggests that between 22.2% and 30.7% of turtle carcasses wash up on beaches (Ulrich 1978, Murphy et al. unpublished data, as cited in Murphy and Hopkins-Murphy 1989). Using
the more conservative estimate of 30.7% detectability, as many as 68.8 (± 13.8) adult loggerheads (≥ 87 cm CCL) on average could be killed annually off the coast of Georgia.

The take limits posted by TEWG (2000) limit the total number of strandings to 9 adult loggerhead turtles (≥ 98.6 cm CCL) within the northern subpopulation zones. Using the larger curved carapace length classification of 98.6 cm, the average number of adult loggerheads stranded in Georgia is 10.1 (± 2.6), which exploits the total allowable take for the whole northern subpopulation without including additional strandings that inevitably occur in the other portions of the northern subpopulation range. This assessment used Potential Biological Removal (PBR) adapted from Barlow et al. (1995) for marine mammal stocks and has many caveats as stipulated by TEWG (2000) when applied to loggerheads. More direct investigation into recruitment levels and survival rates at the larger size classes of loggerheads is needed.

Management of gill net fisheries specific to sea turtle mortality is in its infancy (Trent et al. 1997). These fisheries are known to take loggerhead turtles, but the extent of take is largely unknown. Limited observer data and anecdotal stranding data indicate potentially high levels of take (TEWG 2000). South Carolina, Georgia, Florida, Louisiana, and Texas state waters are currently closed to gill net fishing. Mid-Atlantic states of New Jersey, Delaware, Maryland, Virginia, and North Carolina as well as federal waters are all still open to this form of fishing. There are several active gillnet fisheries operating off the Atlantic coast including inshore and nearshore fisheries (e.g. monkfish and dogfish fisheries) in state waters of the mid-Atlantic states, as well as the shark drift gill net fishery operating in federal waters adjacent to Georgia and Florida. Large scale observer effort may be necessary to accurately evaluate impacts this fishery poses to turtles.
Research Direction

Modern anthropogenic sources of mortality likely are primary factors pushing survival rates down for large size class loggerhead turtles of the northern subpopulation, fueling the precipitous decline observed in nesting numbers. Successful management strategies for the northern subpopulation that would mediate and reduce interactions with detrimental human activities at critical life stages are possible. Delineation of such management strategies requires two initial directions for research. First, spatial and temporal distribution, movement patterns, and habitat use tendencies of critical life stages must be thoroughly investigated. Second, spatial and temporal distribution of commercial fisheries known to take loggerheads must also be rigorously investigated. Combining results from both research directions can provide precise information about location and timing of potential interactions, which would allow exploration of different management options to reduce those interactions. Predictive models can then be developed to evaluate the likelihood that the different management options would elicit actual reductions in interaction probability between the fisheries and turtles if implemented.

The thesis research that follows provides working examples of investigations into distributions of both adult female loggerhead turtle and the commercial shrimp trawl fishery, as well as evaluation of different conceptual management scenarios through predictive modeling. The first chapter is a general review of loggerhead turtle ecology and management identifying specifically why management effort is needed for the northern subpopulation of loggerhead turtle. The second chapter evaluates satellite telemetry as a method for tracking loggerhead turtles. The third chapter describes adult female loggerhead turtle distribution and movement patterns during the nesting season. Chapter 4 compares the turtle distribution described in the previous chapter with the concurrent shrimp trawler distribution coupled with development and
evaluation of potential management options using predictive models. Discussion and overall conclusions concerning loggerhead management and the effectiveness of predictive models as a management tool for loggerheads are presented in the fifth and final chapter.

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loggerhead turtles *Caretta caretta* at Bald Head Island (North Carolina, USA) after 24 years of intensive monitoring and conservation. Oryx 39(1):65-72.


STONEBURNER, D. L. 1982. Satellite telemetry of loggerhead sea turtle movement in the
Georgia bight. Copeia 1982:400-408.


Figure 1.1. Subpopulation locations and rookery sizes across the southeastern U.S. loggerhead turtle distribution.
Figure 1.2. Generalized life history flow chart of Atlantic loggerhead turtles. Boxes represent life stages and corresponding ecosystems. Solid arrows indicate movements between life stages and ecosystems. Dotted lines and arrows indicate speculative life stages and movements. Recreated from Bolten (2003b).
Introduction

Satellite telemetry has become a common method of remotely tracking movements of marine fauna, such as sea turtles and marine mammals. The remote acquisition of location and behavior data from species that otherwise spend the majority of their time in conditions unobservable through conventional research methods allows insights into many aspects of their life history previously undocumented. Understanding accuracy of telemetry systems used during wildlife movement studies is an important consideration when quantifying movement or habitat association parameters (White and Garrott 1990, Kenward 2001). Knowledge of transmission rates expected from remote telemetric systems is also an important consideration when planning movement studies. Currently, adequate testing of satellite telemetry error has not been conducted particularly in marine systems, and the decrease in transmission rates of high quality locations for satellite transmitters have not been presented for loggerhead turtles.

Service Argos (1996) places each satellite location from active transmitters into 1 of 7 categories of location quality labeled 3, 2, 1, 0, A, B, and Z from best to worst quality. The one standard deviation errors predicted for location classes 3 (<150 m), 2 (<500 m), 1 (<1000 m), and 0 (>1000 m) cited by Service Argos (1996) are based on complex algorithms that require transmitters to make at least 4 uplinks with a satellite during a single pass-over event (Goulet et al. 1999, Kenward 2001). Location classes (LCs) A, B, and Z are produced from 3, 2, and 1 uplinks respectively during a single pass over of a satellite, which precludes them from the accuracy calculation algorithms (Service Argos, Pers. Comm.). Additionally, algorithmic
calculation based on physics of ultra high frequency radio waves and geometry of satellite position relative to transmitter position during uplink events, does not constitute a tested estimation of error associated with the different location classes (Service Argos, Pers. Comm.). The only way to obtain actual error rate estimates for telemetry systems is through on the ground tests using known locations (White and Garrott 1990). In satellite telemetry systems, error rate estimates can only be obtained using fixed position trials (Service Argos, Pers. Comm.).

A few attempts have been made to estimate accuracy levels for satellite transmitters using opportunistic (e.g., Goulet et al. 1999) or planned fixed position trials (e.g., Stewart et al. 1989, McConnell et al. 1992, Hayes et al. 2001, Vincent et al. 2002, Robson et al. 2004). However, sample size limitations both in number of transmitters used and/or number of locations used during previous evaluations limit the reliability of the estimates (Table 2.1). More information is needed on accuracy levels for each Argos location class and transmission rates based on research with large enough sample sizes to make definitive conclusions. The objectives of this investigation were to examine accuracy levels for all location classes (excluding LC Z locations), and evaluate the effect of loggerhead turtle (*Caretta caretta*) behavior on transmission rate for each location class.

**Methods**

In 2005, twelve satellite-based Platform Terminal Transponders (PTTs) (ST-20; Telonics Inc.) were positioned on a house roof 4 m above sea level adjacent to a salt marsh in Meridian, Georgia, USA. All transmitters were activated during the same 5 day period (May 10-15) under a continuous 24-hour duty cycle and a minimum 40-second repetition period between
consecutive uplinks with tracking satellites. Precise coordinates of the testing location was
determined by calculating mean latitude and longitude from 10 Global Positioning System
(Garmin 12; Garmin International Inc.) locations.

Deviation of all recorded satellite locations obtained during the testing period from the
known location, grouped by location class, were estimated three ways relative to the testing site
location: 1) longitudinal deviation; 2) latitudinal deviation; and 3) straight line distance
development. Differences in straight line distance accuracy levels among location quality classes (3,
2, 1, 0, A, and B) were examined using ANOVA blocked by transmitter. Differences in latitude
and longitude deviation were not examined using ANOVA because they are descriptive
measures of the potential error polygon, whereas straight line distance deviation is the actual
accuracy. Location class Z was excluded from this analysis because it lacks location
coordinates. If no blocking effect was observed, analyses were re-analyzed with the blocking
factor removed. If an overall significant difference was detected, Tukey’s Honestly Significant
Difference (HSD) multiple comparisons test was used to determine which location classes
differed from each other in their level of deviation from the known location. All statistical
analyses were conducted with SAS statistical software (SAS 1999) with the level of significance
set at alpha = 0.05.

Comparisons between transmission rates during the fixed position trial and post-
deployment on adult female loggerhead turtles were conducted to evaluate the level of
performance reduction loggerhead turtle behavior imposes on PTT transmission rate.
Differences in PTT transmission rate among location quality classes pre- and post-deployment
were examined using ANOVA under a two factor factorial design blocked by transmitter.
Location quality class factor had 7 levels (3, 2, 1, 0, A, B, and Z) and sampling period factor had
2 levels (pre and post deployment). If no transmitter (blocking factor) effect was observed, analyses were re-analyzed pooled across transmitters. If transmission rate of the different location classes was dependent on the sampling period, ANOVA was conducted separately for each sampling period. In the case of significant differences within factors on transmission rate, Tukey’s Honestly Significant Difference (HSD) multiple comparisons test was conducted to determine which location classes or sampling periods differed.

Results

A total of 1,266 satellite fixes were recorded from 12 transmitters during the 5-day fixed-position trial that preceded transmitter deployment. An examination of straight line distance accuracy level of the 6 location classes indicated that transmitter (blocking factor) had no effect on observed deviation from the estimated center location ($F_{11, 16} = 0.91; P = 0.53$). Therefore, the data were re-analyzed with location observations pooled across transmitters. A difference in straight line deviation from the center location was observed among location classes ($F_{5, 1260} = 21.84; P < 0.0001$). Results from Tukey’s HSD revealed that classes B and 0 had higher deviation tendencies from the true center than that observed from classes A, 1, 2, and 3, which showed no difference in deviation between each other (Table 2.2). With the exception of location classes A and B, accuracy error by satellite transmitters exhibits strong longitudinal bias (Figure 2.1) as reflected by the error statistics (Table 2.2).

Examining of variation in PTT ($n=12$) transmission rate among location classes between both pre- and post-deployment indicated that individual transmitters were not influencing the transmission rate ($F_{11, 11} = 0.98; P = 0.51$). Thus, the data were re-analyzed with the blocking
factor removed. An interaction between period and location class was revealed ($F_{6,154} = 81.83; P < 0.0001$). Tukey’s HSD indicated that location classes 3, 2, and 1 did not differ from each other in their transmission rate, and transmitted more frequently ($F_{6,77} = 155.84; P < 0.0001$) than that observed from location classes 0, A, B, and Z, which also did not differ from each other during the fixed-position trial period (Figure 2.2). This relationship was reversed during the post-deployment period (Figure 2.2). Location class Z had a higher ($F_{6,77} = 28.23; P < 0.0001$) transmission rate than all other location classes, and location class B was ranked second having significantly higher transmission rates than all the remaining classes. Location classes 3, 2, 1, 0, and A did not show detectable differences in transmission rate from each other.

Though there was no detectable overall transmitter effect indicated by the original analysis ($F_{11,11} = 0.98; P = 0.51$), but this was not the case when transmitter effect was isolated by the pre- and post-deployment transmission periods. During the fixed-position trial, where conditions were essentially equal for all transmitters, no transmitter effect on transmission rate across location classes was detected ($F_{11,66} = 0.04; P = 1.000$). During post-deployment transmissions where turtle surfacing behavior was uncontrollable, higher degrees of variation in transmission rate occurred producing a significant transmitter (turtle behavior) effect ($F_{11,66} = 3.52; P = 0.0007$).

**Discussion**

Results from the fixed position trial of this investigation provided the necessary on-the-ground estimate of accuracy for all location classes including class A. My findings support both Hays et al. (2001) and Vincent et al. (2002) insights that satellite tracking studies should use
location classes 3, 2, 1, and A, but exclude 0 and B contingent on biological questions being asked. However, the current investigation provided necessary estimates of error produced from multiple transmitters operating under identical conditions and all from the same location. The sample sizes used to estimate the mean straight line deviation during this investigation were up to 15 times larger than the previous studies depending on location class.

Class A locations reported by Service Argos for satellite transmitters are useable locations for most movement and habitat studies. The statement issued by Argos (1996) that accuracy levels for LC A locations are not guaranteed has been, until recently (e.g., Hays et al. 2001, Vincent et al. 2002, Robson et al. 2004), misinterpreted to mean that the accuracy was to adequately quantified but too erroneous for use. The LC A locations are not guaranteed because they lack the necessary minimum 4 uplinks per satellite pass over, not because they lack a consistent level of accuracy.

Results of the current study suggest that studies that do not incorporate LC A locations into analyses are not maximizing the potential of the satellite transmitters. Deploying satellite transmitters is expensive (Kenward 2001) making it crucial to use as much data as possible from active transmitters without compromising data and analysis quality (De Solla et al. 1999). Adding LC A locations to the useable satellite location database (Table 2.2) more than doubled satellite data acquisition from an average of 0.43 (location class 3, 2, and 1 combined) fixes per transmitter per day to 1.08 fixes. In situations where investigations allow only a short time period for acquiring locations (i.e. a tracking study of loggerhead turtles during the 2-month nesting season), understanding likely data acquisition rates beforehand is an especially important consideration.
A key assumption of a fixed position trial assessing accuracy of satellite transmitters is that errors associated with different location classes during fixed position trials are equivalent to the errors associated with the same location classes post-deployment (Vincent et al. 2002). That assumption is currently untested for loggerhead or other marine turtles, but testable in a captive situation. Future studies should try to evaluate the robustness of that assumption.

**Literature Cited**


Table 2.1. Accuracy estimates (mean deviation from fixed-position PTTs from known locations) and sample sizes (number of satellite fixes) for satellite location classes obtained from 6 previous studies compared with Argos predicted accuracy levels.

<table>
<thead>
<tr>
<th>Source</th>
<th>PTTs</th>
<th>Duration</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n)</td>
<td>(days)</td>
<td>km (n)</td>
<td>km (n)</td>
<td>km (n)</td>
<td>km (n)</td>
<td>km (n)</td>
<td>km (n)</td>
</tr>
<tr>
<td>Stewart et al. 1989</td>
<td>?</td>
<td>?</td>
<td>---- (0)</td>
<td>1.10 (12)</td>
<td>1.70 (17)</td>
<td>15.00 (13)</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>McConnell et al. 1992</td>
<td>?</td>
<td>?</td>
<td>---- (0)</td>
<td>1.02 (15)</td>
<td>2.24 (45)</td>
<td>3.79 (5)</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Goulet et al. 1999</td>
<td>1</td>
<td>26</td>
<td>---- (4)</td>
<td>---- (2)</td>
<td>1.33 (21)</td>
<td>43.80 (39)</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Hays et al. 2001</td>
<td>9</td>
<td>15-16</td>
<td>0.27 (38)</td>
<td>0.54 (28)</td>
<td>1.33 (19)</td>
<td>10.10 (9)</td>
<td>0.99 (18)</td>
<td>7.00 (22)</td>
</tr>
<tr>
<td>Vincent et al. 2002</td>
<td>4</td>
<td>11-22</td>
<td>0.23 (25)</td>
<td>0.37 (51)</td>
<td>0.76 (55)</td>
<td>2.79 (60)</td>
<td>1.00 (103)</td>
<td>5.86 (132)</td>
</tr>
<tr>
<td>Robson et al. 2004</td>
<td>?</td>
<td>1</td>
<td>0.28 (91)</td>
<td>0.90 (78)</td>
<td>1.50 (56)</td>
<td>4.48 (40)</td>
<td>4.13 (9)</td>
<td>9.06 (9)</td>
</tr>
<tr>
<td>Argos Predicted 1996</td>
<td>----</td>
<td>----</td>
<td>0.15</td>
<td>0.35</td>
<td>1.00</td>
<td>&gt;1.00</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>
Table 2.2. Accuracy estimates for individual location classes produced from a fixed position trial of PTTs (n = 12). Accuracy was measured as mean deviation (± 95% confidence interval) in latitude, longitude and straight-line distance from a known location. Samples were pooled across PTTs as no difference in accuracy of locations between transmitters across location classes was detected (F=0.91_{11,16}; p = 0.5272).

<table>
<thead>
<tr>
<th>Location Class</th>
<th>Number of Locations (n)</th>
<th>Latitudinal (km ± C.L.)</th>
<th>Longitudinal (km ± C.L.)</th>
<th>Straight Line Distance (km ± C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>346</td>
<td>0.12 ± 0.02</td>
<td>0.24 ± 0.03</td>
<td>0.29 ± 0.03</td>
</tr>
<tr>
<td>2</td>
<td>308</td>
<td>0.26 ± 0.03</td>
<td>0.58 ± 0.06</td>
<td>0.69 ± 0.06</td>
</tr>
<tr>
<td>1</td>
<td>296</td>
<td>0.78 ± 0.12</td>
<td>1.39 ± 0.12</td>
<td>1.77 ± 0.14</td>
</tr>
<tr>
<td>0</td>
<td>116</td>
<td>1.84 ± 0.34</td>
<td>5.64 ± 1.49</td>
<td>6.18 ± 1.49</td>
</tr>
<tr>
<td>A</td>
<td>111</td>
<td>1.86 ± 0.47</td>
<td>1.56 ± 0.33</td>
<td>2.69 ± 0.53</td>
</tr>
<tr>
<td>B</td>
<td>89</td>
<td>10.38 ± 3.77</td>
<td>10.98 ± 3.77</td>
<td>16.93 ± 5.09</td>
</tr>
</tbody>
</table>
Figure 2.1. Location error distribution for each location class assigned by Service Argos compared to a known center point based on fixed position trials of 12 transmitters. The dashed lines on the LC 0 and LC B distributions represent the extent used to plot the distribution of locations for the other 4 LCs.
Figure 2.2. Mean transmission rate (mean number of locations/PTT/day) among location classes during a 5-day fixed position trial and the same PTTs after deployment on loggerhead turtles during the 2005 nesting season.
Chapter 3 – Nesting Season Movement and Distribution Patterns of Female Loggerhead Turtles

Introduction


The Recovery Plan for the northern subpopulation of loggerhead turtle delineates six major actions necessary for recovery of the species (National Marine Fisheries Service 1991). Included among those critical actions is determining distribution and movements of all life history stages of loggerheads in the marine environment. Few attempts have been made to document small scale movements or habitat use by adult females during active nesting seasons within the northern subpopulation. Among 3 studies, 47 females have been tracked in the
northern subpopulation using various telemetric systems (Hopkins-Murphy et al. 2003). Hopkins and Murphy (1981) used sonic telemetry over three nesting seasons (1977-79) to track 37 adult females that nested on South Carolina beaches. Only 28 turtles were relocated following initial release. During nesting attempts on Cumberland Island, Georgia, 8 females were equipped with the first satellite transmitters used on marine turtles (Stoneburner 1982). Unfortunately, the floating platform terminals that housed the transmitters were too conspicuous resulting in numerous interactions with people prematurely terminating transmission of data (Hopkins-Murphy et al. 2003). Only 2 turtles tracked by Stoneburner (1982) yielded usable data on habitat use during the nesting season (Hopkins-Murphy et al. 2003). Bartol and Musick (1998) outfitted 2 females with satellite transmitters during nesting attempts on Virginia beaches. Only 1 turtle yielded data on internesting habitat use and movements as the other appeared to have completed its nesting season (Hopkins-Murphy et al. 2003).

Small sample sizes (Stoneburner 1982, Bartol and Musick 1998) or difficulties associated with tracking procedures (Hopkins and Murphy 1981, Stoneburner 1982, and Bartol and Musick 1998) severely limit strong inferences from data collected in previous studies. Despite the limitations, these studies provide the most detailed data available on internesting movements of female loggerheads in the subpopulation. In general, results suggest that turtles tend to stay within 10 km of shore and sometimes occupy estuarine habitats during nesting seasons (Hopkins-Murphy et al. 2003). Hopkins and Murphy (1981) observed that turtles frequently occupied areas of high relief, such as shipping channels and shoals, in South Carolina. Movements immediately following nesting events tended to be highly directional and largely parallel to shore until a destination was reached where upon movements became unpatterned within a limited core area. Turtles appear to be more diurnal in their movement patterns.
(Hopkins and Murphy 1981) despite their propensity to find nesting sites at night. Hopkins-Murphy et al. (2003) commented that both Hopkins and Murphy (1981) and Stoneburner (1982) made observations of turtles positioning themselves at or near isolated areas of stable substrates (i.e., shipwrecks, artificial reef sites, or limerock outcrops).

Nesting behavior by northern subpopulation loggerhead turtle has received much attention in the past (e.g. Bell and Richardson 1978, Richardson 1980, Shoop et al. 1985, Hopkins-Murphy et al. 2001, Hawkes et al. 2005), but has not been studied from the unique perspective offered by satellite telemetry. Within a nesting season, female loggerheads exhibit varying degrees of nesting site fidelity or tendency to nest near areas used earlier that season (Schroeder et al. 2003). Different behaviors associated with nest site fidelity for northern subpopulation loggerhead turtle were suggested by Richardson (1980) indicating potentially complex or variable movement strategies during internesting periods. A bimodal distribution of nest attempts per female was observed during constant nighttime tagging patrols on the small 4-km nesting beach of Little Cumberland Island (LCI). Numerous turtles were observed to nest 4-5 times, all on LCI, but a high proportion of turtles were also observed nesting only 1-2 times on LCI over the course of a single nesting season. Presumably, the turtles nesting 4-5 times on the 4-km beach of LCI exhibited a high degree of nest site fidelity, whereas turtles nesting only once or twice on LCI were likely also nesting elsewhere indicating a lower degree of nest site fidelity. Confirmation of turtles nesting elsewhere came from observations made by nighttime tagging efforts on other Georgia barrier islands like Cumberland, Jekyll, Blackbeard and Wassaw (Bell and Richardson 1978). Tagging data indicated similar findings of differing levels of fidelity to nest locations for green turtles on Ascension Island in the South Atlantic (Mortimer and Portier 1989). Reliable estimation of actual nest site fidelity levels within nesting populations is
difficult using tagging studies due to lack of complete nighttime beach coverage across all possible nesting locations (Hawkes et al. 2005). Size of a turtle has been suggested as a predictor of whether or not a turtle will show fidelity to a specific area (i.e. smaller turtles were more likely to place nests larger distances apart) (Richardson 1980, Hawkes et al. 2005). Satellite telemetry of nesting turtles offers resources for directly estimating nest site fidelity levels of known individual turtles regardless of behavior by determining nest locations wherever they are deposited.

The goal of this investigation was to implement portions of the mandated Recovery Plan for the northern subpopulation of loggerhead turtle (National Marine Fisheries Service 1991) by using remote and manual telemetric systems to document distribution patterns and movement behaviors of the adult female life stage during active nesting seasons. To achieve that goal, three basic questions needed to be answered. First, do loggerhead turtles distribute in specific patterns relative to different physical features or locations such as shoreline, deep channels, reef sites, estuaries, or different jurisdictional boundaries during the nesting season? Third, what movement behaviors do loggerhead turtles exhibit during the nesting season? Finally, what degree of nest site fidelity is exhibited by loggerhead turtles to specific nesting beaches and how much variability exists in that fidelity? Answering these three primary questions will help increase understanding of a poorly described portion of the adult loggerhead life stage for the northern subpopulation.
Methods

Capture and Attachment

Nesting loggerhead turtles were captured and tagged at night on four Georgia barrier islands during 2004 (n = 12) and 2005 (n = 12) nesting seasons (Figure 3.1). Turtles were tagged on Cumberland, Jekyll and Sapelo island beaches in 2004, and on Sapelo and Blackbeard island beaches in 2005. Patrols began mid-May to increase probability of encountering females during initial nesting attempts of the season (Appendix A). Survey effort continued until all 12 transmitters per season were deployed. In 2004, a notably slow nesting season, the final two transmitters were fitted on turtles 7 July, 41 days after the first turtle was encountered. The 2005 season was a more typical nesting season and the last transmitter was deployed 31 May, 8 days after the season’s first turtle was marked.

Females encountered on the beach were detained on their return to the water, either post-oviposition or after a failed nest attempt. Plywood corals were placed around encountered turtles providing a safe controlled environment for both the researchers and the turtles during data collection and transmitter attachment (Appendix D). Each study animal was measured and marked with external flipper tags and Passive Internal Transponder (PIT) tags unless tags were already present (Appendix E). Presence or absence of propeller wounds was recorded, and blood samples and skin biopsies were taken for use in separate investigations.

Transmitters secured to the carapace of study animals included satellite based Platform Terminal Transponders (PTTs) (ST-20; Telonics Inc.), sonic (modified CHP-87-S; Sonotronics), and, in 2005, VHF (MOD-305; Telonics Inc). In 2004, tethered floating VHF transmitters were initially attempted and subsequently excluded from the study due to early entanglement problems despite use of a safety break-away system at the base of the tether. Carapaces of turtles were
scrubbed clean of epibiota, and transmitters were attached following Mitchell (1998) using Sonic Weld (Ed Greene and Company, Sparta, TN) and Fastfoil (Power Fasteners Inc., New Rochelle, NY), a quick-drying two-part marine epoxy (Appendix F). Sonic transmitters were couched in an aluminum frame which was anchored to the carapace behind the satellite or VHF transmitter (depending on year) along the vertebral scutes of the carapace using the quick-drying epoxy (Appendix G). Total time of turtle detainment was approximately 1-1.5 hours from initial detainment to release. Turtle handling and tagging procedures were conducted under University of Georgia Institutional Animal Care and Use Committee guidelines (permit number A2004-10128-0).

Tracking

Immediately following release, NOAA GOES satellites monitored transmitters during daily passes (Service Argos 1996). Locations by satellite are largely unhindered by time of day or weather allowing randomly obtained locations of turtles across all portions of the day (Kenward 2001). Duty cycles for satellite transmitters differed between nesting seasons (Table 3.1). Satellite transmitter location fixes were automatically assigned one of seven location quality class codes (ranked best to worst; 3, 2, 1, 0, A, B, and Z) by Service Argos (1996). The quality class determination is based on complex algorithms that account for the number of uplinks received by the satellite during a single pass over event, the change in Doppler shift between those uplinks, and the geometry of the satellite path relative to the global transmitter position (Kenward 2001). In addition to latitude and longitude coordinates and location quality class, PTTs also transmitted time and date of location as well as elevation of location position. Satellite transmitters were equipped with saltwater switches that turn batteries off while units
were submerged increasing transmitter longevity. Location data from the previous day were received automatically each morning with a minimum time lag of approximately 6 to 8 hours from actual location times the night before.

Manual tracking using VHF and sonic telemetry was conducted during daylight hours using 2 small boats (17’ Boston Whaler, and 21’ Privateer) during internesting intervals as recommended by Collazo and Epperly (1995). Most recent satellite locations (preference given to higher quality locations) for each turtle were used as center points for daily search grids in manual tracking efforts (Figure 3.2). Turtle locations were obtained using the homing technique (White and Garrott 1990) though this was only intermittently possible for VHF transmitters as salt water precluded radio wave transmission requiring the turtle to surface before a signal was heard. Range of sonic transmitter signals varied dependant on static from boat motors operating in close proximity, and water turbidity. When static was low, sonic ranges were between 1-2 km, but dropped to 0.5 km when static was high. Once in close proximity of tracked turtles, boats were anchored until turtle location was visual confirmed by sighting the turtle at the surface. Precise location coordinates for the turtle were recorded using a handheld Global Positioning System (GPS) unit (Collazo and Epperly 1995).

Prior to analyzing distribution and movement patterns of marked turtles, the satellite telemetry location database was subjected to manual and automated censoring. First, all satellite fixes classified with location classes Z, B, and 0 were deleted as they either produced no coordinate data (Z) or possessed too poor an error rate (B and 0) to validate inclusion for distribution and movement analyses (Hays et al. 2001). Next, duplicate entries in the satellite telemetry database were identified and eliminated. To ensure high likelihood that no duplicates remained, a subset of satellite data for each turtle was manually scanned. Outliers for each turtle
were identified and eliminated based on liberal swim speed restrictions (10 km/hr). Remaining satellite fixes were then plotted using program ArcView 3.2 (ESRI 1999). Locations appearing on land beyond the range of the error rate, other than potential nest or nest attempt sites, were deleted from the database.

With satellite telemetry it is common to have fixes occur minutes apart because multiple satellites, which can have line of sight with a transmitter at the same time, are used independently to acquire locations. Also, because manual telemetry occurred simultaneously, occasions arose where locations from each technique were recorded in close temporal proximity. This potentially confounding issue of temporal autocorrelation was addressed by imposing a 2-hour minimum time period between points on a combined satellite and manual telemetry location database. The minimum time period between points served to reduce autocorrelation between successive points while maintaining adequate sample sizes of locations (De Solla et al. 1999). In the case where an elimination decision was eminent, the location with the highest quality level was kept over lower quality points. Location quality was ranked from highest to lowest as visual observation, followed by satellite location classes 3, 2, 1, and A, respectively. In cases where quality levels were identical then the earliest location was always kept.

In-water Distribution

Metrics describing in-water distribution of marked loggerhead turtles were calculated using ArcView 3.2 (Environmental Systems Research Institute 1999). Proportion of activity each turtle exhibited in state jurisdictional waters (0-4.83 km from shore) versus federal jurisdictional waters (4.83 – 321.82 km from shore) was estimated by dividing the number of locations for each turtle that occurred within the different jurisdictional waters by the total
number of observations recorded for the respective turtle. Proportion of time each turtle spent in estuarine (behind the Colregs Demarcation Line), near shore (<10 km), and off-shore habitats (>10 km) was estimated by dividing the number of locations for each turtle that occurred within the different habitats by the total number of observations recorded for the respective turtle. Mean distance from initial release site, mean distance from shore, and maximum coastal distance used (north most point to south most point) were calculated for each turtle. Proximity of turtle locations to substrate features like deep channels, as well as sites with bottom structure (reef sites, wrecks, and other structure types) also was calculated (Appendix H).

Movement Strategies

Turtle movement behavior during internesting intervals was initially investigated by evaluating tendency of marked turtles towards either fidelity to specific home ranges or nomadic movement behavior. Site fidelity for each turtle was tested using the Monte Carlo random walk procedure developed by Spencer et al. (1990) and modified by Hooge et al. (2001). For each turtle, distances between successive points of a turtle track were pooled then randomly selected without replacement and assigned a random direction (0 to 360°) beginning at the release location. All random walk tracks were constrained by a shoreline graphic using ArcView 3.2 (Environmental Systems Research Institute 1999) and Animal Movement Extension developed by Hooge and Eichenlaub (1997) to allow meaningful comparisons between actual turtle movements and the simulated random movements. Mean squared distance (MSD) from the release site (akin to Schoener’s $r^2$ value; Schoener 1981) and a linearity index (LI) were calculated for 1000 random walks for each turtle. These two values represent a measure of location data dispersion and directed movement. If actual mean squared distance and linearity
index values for individual turtles were below respective lower 95% confidence intervals generated by the random walks (i.e., exhibited neither significant dispersion nor linearity) then they were considered to exhibit site fidelity to a specific area (i.e., established a consistent home range). On the contrary, behavior was described as nomadic if actual movement values were greater than the lower 95% confidence interval of the mean squared distance or the linearity index. Nomadic turtles were consequently precluded from later home range statistical analyses (Spencer et al. 1990).

Home ranges were calculated for turtles that exhibited site fidelity using fixed kernel utilization distributions (Worton 1989). The 95% home ranges and 50% core use areas were calculated using Animal Movements Extension (Hoogie et al. 2001) in program ArcView 3.2 (Environmental Systems Research Institute 1999) for any turtle that yielded 15 or more locations during the internesting interval. The smoothing parameter for each home range was calculated individually using LSCV. Because for all practical purposes turtles do not use land (except during nesting attempts), portions of home ranges that overlapped land were removed prior to analysis.

For turtles that failed the site fidelity test, cumulative straight line distance between successive points, starting from the release site, was calculated. The cumulative straight line distance was then measured against the number of locations used to acquire the metric to assess the level of correlation in the measurement. If a significant correlation between cumulative distance between locations and total number of locations existed then the metric was considered ineffectual as a descriptor for nomadic turtles during nesting season movements.
Nest Site Fidelity

Nest site locations were determined through direct visual observation during initial captures and nighttime beach patrols or deduced from satellite location data. Criteria used to determine nest locations from satellite data included high location quality (a rare occurrence for in-water locations) near the expected nesting interval time (10-19 days after previous nest) at or near nesting beach shorelines. Above sea level elevation for locations were also useful clues. Because not all emergences onto nesting beaches result in a successful nesting attempt, beach patrols were contacted to compare satellite location coordinates with coordinates obtained by handheld GPS units of all nests laid during the same night to identify matches. The GPS coordinates from confirmed nest locations provided highly accurate coordinates which potentially reduced error associated with satellite locations. Nest location data were used to estimate mean number of nests per female, mean distance between successive nests per female, maximum linear shoreline distance between northern most and southern most nest locations for each female, and number of different barrier islands used per female. Correlation between turtle carapace length and maximum distance between nests for turtles also was assessed.

Results

Tracking

Twenty-two of 24 marked turtles yielded usable data during the nesting season (Table 3.2). The two pressure-sensor PTTs deployed July 7, 2004 from Sapelo Island were too late in the nesting season to produce enough data for inclusion into analyses. Remaining PTTs provided 7,774 satellite uplinks of which 14.42% (n = 1,121) were of usable quality (location
class 3, 2, 1, A). Direct visual observations of marked turtles through beach patrol efforts and manual tracking accounted for an additional 182 locations. Combining satellite and visually observed turtle positions, the study produced 1,303 usable locations (Table 3.2). Censor of the combined location database to decrease autocorrelation and eliminate outliers reduced total usable locations by 26.7% to 955 locations.

In-water Distribution

Most tagged turtles were distributed in state or federal waters that were directly adjacent to Georgia nesting beaches (Figure 3.3). Two turtles during the 2004 field season (both tagged on Cumberland Island) moved to St. Augustine, Florida where they each appear to have deposited nests. One of those turtles also made a long movement north to federal waters that were adjacent to the South Carolina shore. During 2005, only one turtle moved out of Georgia and the adjacent waters swimming north to the Broad River inlet north of Hilton Head Island, South Carolina.

Use of Georgia state waters was high among tracked turtles ranging between 11.2 and 100% (mean = 79.8% ±11.8) of locations positioned within the jurisdictional boundary. With the exception of the few locations observed in Florida and South Carolina state waters, the remaining proportion of locations for each turtle were found within federal waters (mean = 18.2% ±10.5). Turtles used estuarine habitats on average 20.9% (±10.2) of the time (range 0 -- 86.7% (Appendix I). Use of near-shore habitats by turtles was higher on average (mean = 67.3% ±10.0) compared to estuarine habitats, but ranged between 13.3 and 96.2%. Offshore habitats were only used by a few turtles during internesting intervals with turtles being located out beyond 10 km from shore on average 11.8% (±8.4) of the time (range 0 -- 71.2%). By
calculating mean distance (km) from shore for individual turtles, two principal behaviors emerged (Figure 3.4). ‘Near-shore’ turtles (n = 20) were located on average 2.7 (± 0.7) km from shore, whereas ‘off-shore’ turtles (n = 2) were located on average 26.0 (± 12.2) km from shore. Excluding the off-shore turtles, the near-shore turtles were located within estuarine habitats 22.9% (± 10.7) of the time on average.

Most turtles stayed close to initial capture locations with a mean of 19.4 (± 7.5) km across turtles and range of 4.5 to 62.5 km (Appendix J). The mean maximum length of shoreline used by individual turtles during nesting season movements was highly variable with at 71.4 (± 29.3) km and ranged between 15.3 to 286.6 km. The ranked ordering of individual turtle estimates for maximum shoreline used showed three categories of turtles: short (0-75 km: n=15), mid (100-125 km: n=5), and long (>200 km: n=2) ranging turtles (Figure 3.5). Turtles did not appear to locate near known natural or artificial reef sites, but some turtles did frequently locate in or near deep channels (Table 3.3). The level of use of channel areas by individual turtles was highly variable (Appendix K). Interestingly, nearly all manual locations that occurred in estuarine habitats (96.4%; 54 of 56) occurred directly in deep channels whereas only 52% (16 of 31) of manual locations in near-shore habitats beyond the estuarine boundary occurred within deep channels. Excluding the offshore turtles, the near-shore turtles were found in or within 1 km of deep channel areas 36.3% of the time.

Movement Strategies

Not all turtles exhibited home range based movement strategies during the nesting season. The site fidelity test that compared observed turtle movements to random walk simulations (n=1000) showed 18 of 22 (81.8%) turtles to exhibit the home range based
movement strategy during the nesting season. Each of the 4 turtles (2/year) that failed the site fidelity test had higher mean squared distance from their release location than the lower 95% confidence interval of the respective random walk simulations, which makes their movement behavior better described as nomadic (Table 3.4). No turtle failed the linearity index portion of the site fidelity test indicating that no turtles were singular in their overall directionality (i.e., they were not on a migration pathway).

Excluding nomadic turtles, mean 95% fixed kernel density home range size for marked turtles during the nesting season was 63.31 (± 37.15) km², but were highly variable, ranging between 1.54 – 308.46 km² (Table 3.5). The sizes of 50% core use areas for turtles showed a similarly wide range as the 95% home ranges with a mean of 8.44 (± 6.38) km², and ranged from 0.27 – 65.79 km². Half the home range turtles (n = 9) established 2 core areas of activity, one being directly in front of nesting locations where the turtle was presumably preparing to nest during the subsequent nights and the other area of activity was used consistently during the internesting interval while the next clutch of eggs was maturing (Appendix L). Other turtles (n = 8) utilized only one core area that was either directly adjacent to nesting locations or offset away from nesting sites. One turtle had 3 core areas of activity between nesting events.

Nomadic turtles used both near-shore and off-shore habitats, although all locations remained on the continental shelf (Appendix M). Cumulative straight line distance for nomadic turtles averaged 675.76 km but ranged from 252.46 – 1,180.53 km. Mean distance between locations ranged from 11.03 to 15.37 km and averaged 13.29 km. Cumulative distance between locations was correlated (r = 0.97; P = 0.05) with the number of locations recorded for each turtle (Figure 3.6), but low sample size does restrict the inferential power of the data.
Nest Site Fidelity

During the 2005 season, monitored turtles deposited 4.5 nests per female (Table 3.6). The 2004 turtles were excluded from average clutch size analysis due to late capture dates (Appendix E) and low likelihood these turtles were captured during first nesting events of the season (Appendix A). Twelve of 22 turtles used a single barrier island to deposit all observed clutches of eggs while 9 turtles used 2 islands. One turtle deposited a clutch of eggs on 4 different islands. Calculation of maximum distance between nests for each turtle suggests 2 distinct behaviors. Turtles expressed either strict nest site fidelity by consistently nesting in a specific localized area (n=16; 72.7%), or loose nest site fidelity by nesting within a general region (n=6; 27.2%) (Table 3.6). On average, strict nest site fidelity turtles placed all nests within a 2.94 (± 0.87) km stretch of beach (range 0.82 – 6.55 km). Conversely, loose nest site fidelity turtles on average deposited all nests within 41.57 (±15.84) km of beach, but ranged between 17.59 and 64.55 km. Turtle size (curved carapace length) was not correlated (r = -0.032; P = 0.50) with maximum distance between nests exhibiting a random, nonlinear relationship between the two factors (Figure 3.7).

Discussion

In-water Distribution

Near-shore habitats (<10 km from shore) were used heavily by adult female loggerhead turtles during nesting season movements in Georgia. More importantly from a management perspective, state jurisdictional waters (0 - 4.83 km from shore) were most heavily used by turtles. These data indicate that the burden of creating in-water management strategies for adult
female loggerheads nesting on the beaches in the northern subpopulation distribution rests heavily with the respective state agencies. Observations made during this investigation of in-water distribution were in part similar to those reported by 3 previous northern subpopulation investigations of nesting season movements (i.e. Hopkins and Murphy 1981, Stoneburner 1982, Bartol and Musick 1998). For instance, in South Carolina adult females were consistently located within 10 km of shore during the nesting season (Hopkins and Murphy 1981).

Estuaries and deep channels appear to be critical habitat for loggerhead turtle during the nesting season portion of the adult female life stage. Both estuaries and deep channel habitats were used a higher percentage of the time by near-shore turtles (22.9% and 36.3% respectively; n=20) compared to the habitat availability (12.7% and 18.6% respectively) within the near-shore area out to 10 km from shore. Limited use of estuarine habitats was previously reported for nesting loggerheads (i.e., Hopkins and Murphy 1981, Stoneburner 1982, and Bartol and Musick 1998), but this investigation demonstrated through manual tracking efforts that deep channel locations specifically within estuaries are the critical component of the estuaries that are used. Murphy and Hopkins (1981) also frequently observed turtles using areas of high relief, such as channels. The documentation of extensive loggerhead turtle use of deep channels in near-shore habitats hold specific importance for the timing of sediment dredging operations designed to maintain or deepen shipping channels, as sediment dredges are known to cause mortality of sea turtles (Magnuson et al. 1990, National Marine Fisheries Service 1991).

Offshore habitats (>10 km from shore) appear to by used by only a small fraction of the adult female loggerhead population during active nesting season movements (n = 2 in this study). Offshore turtles could potential encounter different risks during the nesting season than near-shore turtles. During the investigation of movements and distribution patterns of loggerhead
turtle nesting in South Carolina, Hopkins and Murphy (1981) were able to record locations from only 75.7% of their marked turtles over the duration of the study using sonic telemetry. It is possible that some of their unobserved turtles (n=9) were using offshore habitats or perhaps moved far to the north or south beyond the extent of the study’s coverage area. Their findings likely represent valid insight into the portion of population that remains near shore, but not the relatively small portion of the population that travels long distances from capture locations.

Natural and artificial reef sites were not observed to be important rest areas for females between nesting events while they prepare the next clutch of eggs (Table 3.3). This observation contradicts observations made by Hopkins and Murphy (1981), and Stoneburner (1982) for females of the northern subpopulation. Similar observations of female loggerheads making directed movements to the general vicinity of rock outcroppings and reef sites were reported in other populations by Yano and Tanaka (1991), and Addison et al. (2002). However, both Yano and Tanaka (1991) and Addison et al. (2002) monitored turtles for short durations that, based on a mean interval period of 14 days, spanned no more than 3% (3-8 hours; Addison et al. 2002) or 15% (22-48 hours; Yano and Tanaka 1991) of a single internesting interval (National Marine Fisheries Service 1991).

Movement Strategies

Observing nomadism among the population of female loggerhead turtles was not surprising. If maintaining a home range offers no particular advantage, or movements are not energetically costly, or if it is beneficial to relocate to new home ranges periodically, then nomadic behavior should occur within a species (Sinclair 1983). For loggerheads, all three conditions exist at different points during the life history (e.g. Keinath et al. 1996, Bolten 2003,
Specifically within the nesting season, loggerheads do not forage (Hopkins-Murphy et al. 2003) alleviating the requirement for them to locate consistently near high quality forage sites as in resident foraging areas (Avens et al. 2003). Sea turtles are also thought to use ocean currents to aid in movements (Luschi et al. 2003b) theoretically reducing energetic costs of those movements. It could be that only a small portion of the monitored population (18.2%) exhibited the nomadic behavior because there is a selective advantage to adult females that maintain consistent home ranges. On the contrary, perhaps there is a lack of heavy selective pressure for any particular movement strategy, which is why multiple behavior types and high variability in home range sizes was observed among monitored turtles.

Previous studies of loggerhead movements have involved documenting migration routes (Sakamoto et al. 1997, Bentivegna 2002, Plotkin and Spotila 2002), homing behavior (Papi et al. 1997, Avens et al. 2003, Luschi et al. 2003a), swim speeds and directionality (Yano and Tanaka 1991, Addison et al. 2002) or movement patterns (Hopkins and Murphy 1981, Stoneburner 1982, Hays et al. 1991, Bartol and Musick 1998). Only a few movement studies of loggerhead turtle have reported home range estimates (e.g. Byles 1988, Renaud and Carpenter 1994, Hawkes et al. 2006) and none tested for site fidelity during any time period of those movements. Godley et al. (2003) claim site fidelity to specific foraging areas by two adult female loggerheads in the Mediterranean, but the data were qualitative and not formally tested. Of all movement studies of sea turtles, only Shaver et al. (2005) was found to have reported a test of site fidelity. Shaver et al. (2005) used the random walk site fidelity test (Spencer et al. 1990, and Hooge et al. 2001) to discern two different behaviors expressed among 11 adult male Kemp’s ridley (Lepidochelys kempii) turtles. The majority (8 of 11) established resident home ranges (presumably foraging areas) through the duration of the study. The remaining 3 turtles were observed to make
unidirectional movements (perhaps migration routes) to other regions until transmission stopped. The failure of the 3 male Kemp’s ridley turtle’s to establish home ranges are not synonymous to the failure of the 4 nesting females observed during this investigation. The female loggerheads exhibited nomadic behavior by failing the Mean Squared Distance test indicating a significant dispersion in location position (i.e. they moved randomly within the general area around the nesting beaches). Male Kemp’s ridley turtles exhibited what appears to be migratory behavior by failing the Linearity Index test indicating a significant directionality among the movements (i.e. they moved in approximately the same direction with little deviation from the course).

The larger portion of the female loggerhead population that establish consistent home ranges during the nesting season offer more predictable pattern, which allows potential management options to be more clearly identified (Murawski et al. 2000, Meyer and Holland 2005). For instance, marine protected areas are becoming a common management tool to hedge against overexploitation of species (Lauck et al. 1998, Sanchirico 2000), but appropriate size and shape of marine protected areas can alter the honest benefits received by a species (Murawski et al. 2000). Knowledge of typical area requirements needed by individuals of a population targeted for conservation by the protected area help guide identification of the appropriate protected area attributes (Meyer and Holland 2005). When devising strategies for conservation, nomadic turtles pose more difficulty to managers than turtles that establish consistent home range areas (Murawski et al. 2000). By definition, there is less predictable pattern to nomadic movements as they mimic random walks (Hooge et al. 2001). Also, the current investigation indicates nomadic behavior makes turtles more apt to cross multiple jurisdictional boundaries than turtles that establish home ranges. However, based on these data, nomadism during the nesting season is only exhibited by a small percentage (18.2%) of northern subpopulation turtles.
Nest Site Fidelity

Results suggest that loose nest site fidelity within the northern subpopulation is much less common than previously reported. Observations made by Richardson (1980) suggested that females exhibit one of at least two different behaviors relative to fidelity to specific nesting islands: alpha turtles nest on multiple islands; and beta turtles nest on a single island. This investigation supported the two behaviors hypothesis set by Richardson (1980) but offer that maximum distance between nests rather than use of specific islands may be a better estimator of nest site fidelity. For instance, 4 strict nest site fidelity turtles observed during 2005 nested on 2 different islands (Sapelo and Blackbeard) that were separated only by a small tidal creek (Figure 3.1). If their behavior was described using the individual island method of determining fidelity each would have been classified as an alpha (Richardson 1980) or loose nest site fidelity turtle. Based on observations of the nesting habits of northern subpopulation loggerheads reported by Richardson (1980), and Hawkes et al. (2005) it was expected that the majority of our tracked turtles would exhibit loose nest site fidelity, but instead the contrary was observed with only 27.3% of observed turtles exhibiting the behavior. An overestimation of the prevalence of loose nest site fidelity behavior in the population would be expected with nighttime tagging projects given the incomplete coverage of other nearby beaches. However, satellite telemetry could underestimate the prevalence of the behavior in a population by missing nests by tracked turtles that occurred prior to instrumentation. The probability of such an error is low given that the turtle would still provide observations on its remaining nests, which would still show the presence or absence of the behavior. If we assume satellite telemetry provides a robust estimate of the prevalence of loose nest site fidelity behavior in the nesting population, then the thinking behind how nesting females use and move between beaches has been misguided.
Familiarity to specific nesting sites are thought to provide advantages for reproductive success to individuals, creating a possible mechanism that could explain the evolution of philopatry (Lack 1954, Hinde 1956). To test whether advantages exist for the evolution of philopatry in loggerhead turtle a comparison of reproductive performance for site faithful and dispersive individuals over time would be required (Lindberg and Sedinger 1997). Specific factors that dictate the expression of different philopatric behaviors by turtles are unexplored. Environmental cues perceived by turtles regarding nest beach conditions could influence turtle decisions to continue nesting in the area or move to a new location for the following clutches. If true then turtles would be expected to change behaviors over multiple nesting seasons such as has been observed in avian site fidelity studies over multiple years (e.g., Greenwood and Harvey 1982, Lindberg and Sedinger 1997). Long term nighttime tagging projects may be able to test that theory with analysis of nest placement data from remigrant turtles. If the behavior is hard-wired by genetics then turtles would not be expected to alter their degree of philopatry across multiple nesting seasons.

Results suggest satellite telemetry may provide a plausible means to estimate nest frequency, circumventing ‘edge effect’ problems described by Murphy and Hopkins (1984) associated with observations made on single islands. Measure of nesting frequency by individual turtles in the past were determined from nighttime tagging patrols where individual turtles were observed and identified during multiple nesting events separated by an average internesting interval of 14 days (Talbert et al. 1980, Mager 1985, Lund 1986, Webster and Cook 2001, Broderick et al. 2002, Hawkes et al. 2005). Observations made on one (or multiple) nesting beach do not offer a complete window into nesting patterns for all females observed on that beach (Richardson 1980, Murphy and Hopkins 1984, LeBuff 1990, Broderick et al. 2002,
Hawkes et al. 2005). Coupling satellite location data with extensive beach monitoring (day or night) in the current study allowed for confirmation of nest sites. Visual observations by nighttime beach patrols help verify that satellite locations could be used to determine nest locations. Formal testing of the accuracy associated with using satellite location data as a means of identifying nest placement would benefit from genetic analysis.

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Table 3.1. Satellite transmitter (PTT) specifications used to track adult female loggerhead turtle (n = 24) movements during 2004 and 2005 nesting seasons off the coast of Georgia, USA.

<table>
<thead>
<tr>
<th>Season (year)</th>
<th>PTT Model</th>
<th>Repetition Period (seconds)</th>
<th>Duty Cycle (hours)</th>
<th>Duration of Duty Cycle</th>
<th>Number of Turtles</th>
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<td>2004</td>
<td>Telonics ST-20</td>
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<td>3 on, 3 off</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>24 on, 24 off</td>
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<td></td>
</tr>
<tr>
<td>2004</td>
<td>Telonics ST-20 (with pressure censors)</td>
<td>40</td>
<td>3 on, 3 off</td>
<td>nesting season (May - Aug 18) post nesting (&gt; Aug. 18)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>24 on, 24 off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Telonics ST-20</td>
<td>40</td>
<td>continuously on</td>
<td>nesting season (May - Aug 18) post nesting (&gt; Aug. 18)</td>
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<td></td>
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Table 3.2. Data acquisition from satellite transmitters by Location Classes (LCs) for each turtle monitored during 2004 and 2005 nesting seasons off the coast of Georgia, USA.

<table>
<thead>
<tr>
<th>Year</th>
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<th>1</th>
<th>0</th>
<th>A</th>
<th>B</th>
<th>Z</th>
<th>Total Satellite Locations</th>
<th>Total Usable Satellite Locations</th>
<th>Time On per Day (hours)</th>
<th>PTT Duration (days)</th>
<th>Total Functional Locations (hours)</th>
<th>Usable Locations per Hour</th>
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Table 3.3. Mean distance of locations from nearest reefs (artificial or natural) and deep channels (dredged or natural) accompanied with the percentage of locations for each turtle within 1 km of the sites by turtles tracked during the 2004 and 2005 nesting seasons off the coast of Georgia, USA.

<table>
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<tr>
<th>Year</th>
<th>Turtle ID</th>
<th>Sample Size (n)</th>
<th>Reefs Locations ≤ 1 km</th>
<th>Reefs Mean dist. (km)</th>
<th>Channels Locations ≤ 1 km</th>
<th>Channels Mean dist. (km)</th>
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<td>10.29</td>
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<td>11.21</td>
<td>8 (38.1%)</td>
<td>4.13</td>
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<td>43</td>
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<td>9.97</td>
<td>10 (23.3%)</td>
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<td>11 (42.3%)</td>
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<td>4 (25%)</td>
<td>3.72</td>
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Mean 43 (± 10) 14.25 (± 1.91) 6.23 (± 3.67)
Table 3.4. Results from the site fidelity test for adult female loggerhead turtles monitored during the 2004 and 2005 nesting seasons off the coast of Georgia, USA. Mean Squared Distance (MSD) values observed for turtles compared to the mean predicted values produced from Monte Carlo correlated random walk simulations (n = 1000) determined behavior classification for turtles during the adult female nesting season life stage. Linearity Index values not presented because no monitored turtle failed the linearity test.

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<th>Mean Random Walk MSD</th>
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<th>Lower 95% Confidence Limit</th>
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Table 3.5. The 95% Fixed Kernel Density (FKD) home range area and 50% FKD core use area (km²) estimated for adult female loggerhead turtles (n = 18) during the nesting season life stage off the coast of Georgia, USA. Home range and core use area estimates produced using least squares cross validation (LSCV) to create the specific smoothing factor appropriate for each turtle. Calculations only performed on turtles that exhibited site fidelity during the correlated random walk test.

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<th>50% FKD (km²)</th>
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Mean 41 (± 8) 3.09 (± 0.91) 63.31 (± 37.15) 8.44 (± 6.38)
Table 3.6. Nest placement parameters and nest site fidelity behavior description recorded for loggerhead turtles monitored during the 2004 and 2005 nesting seasons off the coast of Georgia, USA.

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Mean 4.5*** 1.5 8.74 (± 6.52) 13.48 (± 8.42)

* Mean distance between successive nest attempts for each turtle.
** Maximum distance of shoreline used to deposit all nests by each turtle.
***Mean includes only 2005 turtles.
Figure 3.1. Capture locations of study turtles (n = 24) on four Georgia barrier islands during 2004 and 2005 nesting seasons.
Figure 3.2. Search pattern used during manual telemetry efforts to locate marked female loggerhead turtles during the 2004-2005 nesting seasons off the coast of Georgia USA. The most recent high quality satellite transmitter location for each turtle from the previous day was used as the center point for search grids. The dashed arrow describes the typical search pattern traveled by boat.
Figure 3.3. Amount of time turtles spent within state and federal jurisdictional boundaries based on proportion of locations found within those boundaries averaged across turtles monitored during the 2004 (n = 10) and 2005 (n = 12) nesting seasons.
Figure 3.4. The ranked order of shortest to longest mean distance from shore for individual loggerhead turtles tracked during the nesting season in Georgia 2004 and 2005.
Figure 3.5. The ranked order of shortest to longest maximum shoreline distance used by individual turtles tracked during the 2004 and 2005 nesting seasons.
Figure 3.6. Relationship between cumulative distances (km) traveled and location sample sizes for nomadic turtles monitored during the 2004 and 2005 nesting seasons in Georgia indicate a positive correlation. Cumulative distance traveled by a turtle exhibiting nonlinear nomadic behavior (high dispersion) does not provide a meaningful description of movements by turtles expressing that behavior.
Figure 3.7. No relationship was detected between turtle size (notch to tip curved carapace length) and maximum length of shoreline between nests for turtles monitored during the 2004 and 2005 nesting seasons in Georgia.
Chapter 4 – Using Predictive Models as a Tool for Managing Loggerhead Turtle and Commercial Fishery Interactions

Introduction

Absolute certainty of proper management for biological systems is beyond reach when assessed from finite samples of data (Burnham and Anderson 2002). Random variation within biological systems over space and time as well as inaccuracy and imprecision of system state estimates complicate our understanding (Williams et al. 2002). Furthermore, in systems where the managed resource is directly or indirectly exploited, reaction of the system to imposed management controls adds yet another source of uncertainty (Williams et al. 2002). These factors impose acute challenges on resource managers when attempting development of optimal long-term management strategies (Nichols et al. 1995, Williams 1997, Williams et al. 2002).

Predictive models have been offered as a potential tool that managers can use to address system uncertainties in their management decisions (Walters 1986, Burnham and Anderson 2002, Williams et al. 2002, Dorazio and Johnson 2003). For example, each year new waterfowl harvest regulations are set based on projections made from a set of predictive models that reflect uncertainties about system states that influence waterfowl population dynamics (Williams et al. 2002, Conn and Kendall 2004). Evaluating the expected utility a potential management decision might have on the resource in the face of uncertainty prior to implementation is a key component of predictive modeling (Williams et al. 2002). This process of using predictive models to guide management is especially important for situations involving threatened or endangered species where erroneous management decisions may have deleterious impacts on species persistence (Brook et al. 2000).

The goal of this investigation was to use predictive models to evaluate different management scenarios for loggerhead turtle. This predictive modeling approach was applied to management of a commercial shrimp trawl fishery operating off the Georgia coast to reduce the level of interaction between trawlers and female loggerheads during the nesting season portion of the life stage. Development of predictive models that evaluate possible management options to reduce interaction between turtles and trawlers required completion of specific objectives. First, the in-water distribution patterns for loggerhead turtle and shrimp trawlers needed to be identified during the nesting season. Second, a baseline measure of interaction between trawlers and turtles needed to be calculated. Third, distribution patterns of both trawlers and turtles had to be compared to identify potential management scenarios that could potentially reduce likelihood of interactions between them. Fourth, predicted effects the management scenarios would have on interactions between turtles and shrimp trawlers had to be modeled allowing the change in level of interaction under each scenario to be compared to baseline values.
Background

The Southeastern United States nesting aggregation of the loggerhead turtle is divided into 3 major subpopulations (Florida Panhandle, Southern Florida, and Northern) based on mitochondrial DNA analyses of rookeries (Bowen et al. 1993, Encalada et al. 1998). Turtles nesting in Georgia are part of the northern subpopulation that includes nesting beaches stretching continuously from northeast Florida through North Carolina and southern Virginia (National Marine Fisheries Service 1991). Subpopulations are considered evolutionary significant management units (Moritz 1994, Bowen et al. 2005), which require different management objectives based on regional variation in population trends and threats (National Marine Fisheries Service 1991, Turtle Expert Working Group 2000).

Population growth trends for sea turtles are determined from indexing changes in nest totals laid on beaches within the distribution (National Marine Fisheries Service 1991). The National Marine Fisheries Service (1991) concluded that the northern loggerhead subpopulation was either stable or declining, a conclusion that was also supported by Turtle Expert Working Group (2000). To illustrate, analysis of long-term data (1973-2005) for loggerhead turtle nest totals obtained through consistent monitoring effort on 3 beaches in Georgia indicate a 1.5% annual decline (Dodd and Mackinnon 2005). In contrast, Hawkes et al. (2005) failed to detect a significant trend in nest numbers on one beach in North Carolina over a 24-year time series (1980-2003).

For long lived species like loggerhead turtles that have a protracted age until first reproduction followed by a prolonged period of sexual maturity, high survival of the large size classes is critical (Crouse et al. 1987, Whitehead 2004). Population models indicate that increasing survival rates for neritic zone juveniles or sexually mature females by themselves can

Finding ways to reduce interactions between shrimp trawl fisheries and northern subpopulation loggerhead turtle is considered a priority action necessary to recover the species (National Marine Fisheries Service 1991). Possible management options could encompass overall reduction in fishing effort and temporal and spatial closures (South Atlantic Fisheries Management Council 2002). However, effectiveness of strategies for reducing interactions is difficult to assess due to lack of information on sea turtle abundance and distribution. Thus, detailed information on sea turtle movements and habitat use was considered critical for formulation of effective management strategies to reduce shrimp trawler-related mortality on the northern subpopulation.

Current information indicates female loggerhead turtles of the northern subpopulation reach sexual maturity at approximately 28-33 years (Spotila 2004), whereupon they begin the adult life stage. Loggerhead turtle exhibits iteroparous behavior within and among years (Plotkin 1995) with the adult female life stage generally described as an oscillation between short active nesting seasons and extended foraging periods (Schroeder et al. 2003). The active nesting season for loggerhead turtle begins in early May and continues through mid August (Appendix A) (Richardson 1980, National Marine Fisheries Service 1991). During a nesting season females can lay up to seven clutches (Lenarz et al. 1981, Talbert et al. 1980) with an estimated mean of 4.1 nests per female per season (Murphy and Hopkins 1984). The internesting interval, the
number of days between consecutively laid nests by a single individual, is approximately 14 days (National Marine Fisheries Service 1991). Distribution and behavior of loggerhead turtle between nesting events is poorly understood, although anecdotal evidence suggests they tend to locate within 10 km of shore and sometimes enter estuarine habitats behind barrier islands (Hopkins and Murphy 1981, Stoneburner 1982). Some may associate with areas of high relief like shipping channels or shoals (Hopkins-Murphy et al. 2003).

Methods

Distribution Patterns

Nesting loggerhead turtles (n = 24) were captured and tagged during night patrols on four Georgia barrier islands during 2004 and 2005 nesting seasons (n = 12 per year). Turtles were tagged on Cumberland, Jekyll and Sapelo island beaches in 2004 and on Sapelo and Blackbeard island beaches in 2005 (Figure 4.1). Patrols began mid-May each season and continued until all 12 transmitters per season were deployed (July 7, 2004, and May 31, 2005). Females encountered on the beach were detained on their return to the water, either post-oviposition or after a failed nest attempt. Each study animal was measured and marked with external flipper tags and Passive Internal Transponder (PIT) tags unless tags were already present. Tracking of turtles was facilitated by securing satellite based Platform Terminal Transponders (PTTs) (ST-20; Telonics Inc.), sonic (modified CHP-87-S; Sonotronics), and, in 2005, VHF radio (MOD-305; Telonics Inc) telemetry transmitters to the carapace of study animals following Mitchell (1998; Appendix F).
Upon release, NOAA GOES satellites monitored PTT transmitter signals (Service Argos 1996). Only fixes from satellite transmitters of Location Classes (LCs) 3, 2, 1, and A were used in this investigation (Hays et al. 2001, Vincent et al. 2002). Location data for each transmitter from the previous day were received automatically in the morning with a minimum time lag of approximately 6 to 8 hours from actual location times the night before. Manual tracking using VHF and sonic telemetry took place during daylight hours by using most recent satellite locations (preference given to higher quality locations) of each turtle as center points for daily search grids. Turtle locations from manual tracking efforts were visually confirmed by sighting the turtle at the surface. Precise location coordinates for the turtle were recorded using a handheld Global Positioning System (GPS) unit (Collazo and Epperly 1995).

Prior to analyzing distribution and movement patterns of marked turtles, the satellite telemetry location database was combined with the manual tracking database and subjected to censoring processes to eliminate duplicate entries, outliers based on liberal swim speed restrictions (10 km/hr), and locations appearing on land beyond the range of the error rate. Also, a 2-hour minimum time period between points was imposed on the combined database to reduce serial autocorrelation between successive points while also maintaining adequate sample sizes of locations (De Solla et al. 1999). In the case where an elimination decision was eminent, the location with the highest quality level was kept over lower quality points. Location quality was ranked from highest to lowest in the current investigation as visual observation, followed by satellite location classes 3, 2, 1, and A, respectively. In cases where quality levels were identical then the earliest location was always kept.

Turtle movement behavior during internesting intervals was investigated by evaluating tendency of marked turtles towards either fidelity to specific home ranges or nomadic movement
behavior. Site fidelity for each turtle was tested using the Monte Carlo random walk procedure constrained by shoreline developed by Spencer et al. (1990) and modified by Hooge et al. (2001) using ArcView 3.2 (ESRI 1999) and Animal Movement Extension developed by Hooge and Eichenlaub (1997). Home ranges were calculated for turtles using fixed kernel utilization distributions (Worton 1989) with least squares cross validation (LSCV) as the smoothing factor (Blundell et al. 2001). The 95% home range and 50% core use area was calculated for each turtle using Animal Movements Extension (Hoogie et al. 2001) in program ArcView 3.2 (Environmental Systems Research Institute 1999) for any turtle that yielded 15 or more locations during the internesting interval (Blundell et al. 2001). Because loggerhead turtles do not use land (except during nesting attempts), portions of home ranges that overlapped land were removed.

Trawler location data was acquired from the Georgia Department of Natural Resources who conducted complete count aerial surveys over state and federal jurisdictional waters off the Georgia coast for 7 consecutive years (1999-2005). Methods of observation for surveys were standardized across all flights. Precise location coordinates for every shrimp vessel observed during the surveys were recorded using handheld GPS units. The trawler location database was filtered to include only locations of actively trawling vessels, eliminating locations of trawlers that were hauling in nets, anchored, or traveling to different locations. Furthermore, only flights that occurred between May and August were included for these analyses to coincide with turtle observations during the nesting season portion of the adult female life stage.
Baseline Trawler Activity

To evaluate merits of different management scenarios, a baseline estimate of current trawler activity around turtles was first established. The method of defining turtle use areas that would best reflect the actual likelihood of interaction between shrimp trawls and turtles was uncertain. Thus, 3 different definitions of turtle use area were created and used to evaluate management scenarios separately: 1) 95% FKD home range contour; 2) 50% FKD core use area contour; and 3) placement of a 1-km radius buffer around each location. Under each definition of turtle use area the baseline of trawling activity was determined by first counting the number of trawler locations that occurred within the area boundary. The total number of observed trawlers was then divided by the total number of flights used to acquire the trawler data. The resulting average number of trawlers observed per flight around each turtle was then divided by the total area (km²) used by the respective turtle under the corresponding turtle use area definition. The resulting density of trawlers per flight became the observed baseline Trawler Activity Index (TAI) value. In essence, the observed baseline TAI described the 7-year average trawler density that occurred within turtle use area boundaries of each turtle during the nesting season.

A null trawler distribution model was also created and was used to calculate an alternative set of baseline values for trawler activity around turtles under each turtle use area definition. To produce the null trawler distribution a random point generator extension in ArcView 3.2 (Environmental Systems Research Institute 1999) assigned new latitude and longitude coordinates to each trawler location. The only constraint set on the random trawler locations was that they had to occur in equal proportion to how they were originally distributed relative to state and federal water boundaries. Ten iterations of the random redistribution of trawlers for the null model were conducted with a new TAI calculated each time for each turtle.
The ten new TAI values for each turtle were then averaged to provide an estimated null baseline TAI value.

The null baseline trawler distribution model also was used to identify patterns in the observed baseline trawler distribution relative to turtle use areas. A comparison between baseline TAI values for each turtle under the observed and null trawler distribution models was conducted by dividing the null baseline TAI by the observed baseline TAI. If the observed trawler distribution occurred in a random pattern then the ratio between the two baseline values would equal one. If the ratio between baseline values is >1.0, then the observed trawler distribution was clumped, but in areas that turtles did not use heavily. If the ratio between baseline values is <1.0, then the observed trawler distribution was clumped in areas that turtles also used heavily. Comparison between the null and observed baseline trawler distributions were averaged across the 3 defined turtle use areas.

Management Scenarios

Different management scenarios were created following general conceptual formats outlined by the South Atlantic Fishery Management Council (2002). Options considered in this investigation included spatial closures (synonymous to marine protected areas), which could be either a single large or configurations of several small closures, and total fleet reductions at different levels. Potential utility of the different management scenarios was evaluated by simulating possible reactions of the commercial shrimp trawler fishery, which created new trawler distributions. The new predicted distributions of trawlers were then used to calculate new TAI values for each turtle allowing direct comparison to the different baseline values under each turtle use area definition.
**Spatial Closures** – Preliminary analyses of loggerhead 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. Three closure scenarios with a single large closed area and two closure scenarios with several small closures were designated.

A single large closure in front of Cumberland Island (hereafter called the Cumberland closure) extending out to the state water boundary (4.83 km off shore) was selected as one management scenario (Figure 4.5). Cumberland Island was considered a major nesting beach in Georgia and was already designated as a national seashore so extending the protective boundary into the ocean seemed a reasonable option. The Cumberland Island closure was considered a low trawler impact model, which is why the southern tip of Cumberland Island was not closed. That area was used extensively by shrimp trawlers but not by turtles.

A single large closure placed in front of the Sapelo/Blackbeard Island complex (hereafter called the Sapelo closure) was selected as a single large closure option (Figure 4.5). Like the Cumberland closure, the Sapelo closure boundary was extended out to the state water jurisdiction line 4.83 km off shore. Also like Cumberland, Sapelo and Blackbeard Islands were considered major nesting beaches. Both turtles and trawlers used the area heavily making the Sapelo closure a high trawler impact option.

The last single large closure scenario considered was a state wide closure out 1 mile (1.6 km) from shore (hereafter called the 1-mile closure), leaving 2 miles (3.2 km) of state waters open to commercial shrimp trawling (Figure 4.5). This option placed a no trawling zone in front of all nesting beaches in Georgia. A state wide 1-mile closure was developed because both
trawlers and turtles tended to locate close to the shoreline, and was considered a high trawler impact model.

The first closure scenario that established several smaller protected areas focused around deep channel locations (hereafter called the Channels closure) identified across coastal Georgia (Figure 4.6). Some of the monitored turtles as well as the trawlers appeared to have an association with the channel areas. The closure boundary around each channel was delineated by placing a 1-km buffer around the channel area. This process was not necessary in estuaries as that habitat is already closed to shrimp trawling. The channel closure option was considered a high trawler impact option for the several small closure models.

The low trawler impact option under the several small closures scenarios was designed to focus on the entrances to estuaries between the different barrier islands. Essentially the current estuary boundaries were extended out to the ColRegs Demarcation Line (hereafter called the ColRegs closure) (Figure 4.6). This closure scenario offers some protection of channel habitats, but also adds more closure area to the estuarine habitat.

Calculating new TAI values for each turtle under spatial closure scenarios was a multi-step process (Figure 4.2). After the boundary for a spatial closure management scenario was defined, the trawler locations positioned within the closure boundary were eliminated from the database. It was assumed that displaced trawlers would continue to actively fish, relocating elsewhere within the extent of the trawler distribution that was determined from the aerial surveys. Uncertainty existed as to how the displaced trawlers would redistribute when faced with a closure around an area they previously operated. Thus, 3 competing hypotheses that described potential trawler redistribution patterns were evaluated. First, it was predicted that trawlers would relocate (randomly) within a 2-km buffer along the outside edge of the new
closure boundary (Sweeting and Polunin 2005). The premise behind this prediction was two-fold: 1) shrimp boat captains would want to stay near areas they previously fished; or 2) the captains would view the sanctuary as a source population of shrimp and so would concentrate operation around closure edges gleaning shrimp outflow from the unexploited sanctuary area. The second hypothesis was that trawlers would relocate randomly across the study area, but would do so in equal proportion to pre-closure distribution within state and federal jurisdictional waters (Hiddink et al. 2006). This hypothesis assumes that trawlers would operate under the same general trends as before but do so in largely unpredictable ways. The third hypothesis was that trawlers would redistribute randomly across the study area, but remain in equal proportion to pre-closure distribution relative to low (0.001-2.5 trawlers/km²), medium (2.501-5.0 trawlers/km²), and high (>5.0 trawlers/km²) density areas (Hiddink et al. 2006, Hunter et al. 2006). The premise driving the third hypothesis was that captains would likely concentrate on areas that already receive high level of trawling activity presumably because they produce a more consistent or profitable catch.

Homogeneity in response by displaced trawlers to a closure was considered unlikely, meaning a single 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 turtles under each of the 3 hypotheses were averaged together to produce a new mean TAI value for each turtle. Because the mean TAI values for each turtle was created from a random process, 10 iterations of the 3-hypothesis trawler redistribution model were run producing a mean estimated TAI value for each turtle under each spatial closure management scenario for each turtle use area.
definition. Preliminary analyses indicated that 10 iterations of each management scenario simulation were enough to stabilize the mean TAI for all turtles.

*Fleet Reductions* – Potential fleet reduction management scenarios were simulated at 5 different levels (10%, 30%, 50%, 70% and 90%). Similar to spatial closure scenarios, calculating new TAI values for each turtle under different commercial shrimp trawl fishery fleet reduction scenarios also was a multi-step process (Figure 4.3). To simulate the fleet reduction management scenarios at the different percent reduction levels, the corresponding proportion of trawler locations were randomly eliminated from the trawler distribution database. Remaining trawler locations were used to recalculate the new TAI for each turtle under the reduction scenario. Because the new TAI value for each turtle was created from a random process, 10 iterations of the trawler reduction model were performed producing a mean estimated TAI value for each turtle under each fleet reduction management scenario for each turtle use area definition. Preliminary analyses of the fleet reduction model outputs indicated that 10 iterations of each reduction scenario simulation were enough to stabilize the mean TAI for each turtle.

**Model Evaluations**

Two-tailed t-tests were performed to compare baseline TAI values (observed and null baseline trawler distributions compared separately) among turtles to TAI values produced from each management scenario. Potential impacts of the 10 different management scenarios on mean trawler activity within each of the three different measures of turtle use area (95% contour, 50% contour, and 1-km location buffer) were tested separately. All tests were performed using SAS 8.2 (Statistical Analysis System 1999). The level of significance for all tests was set at $\alpha = 0.05$. 
Results

Distribution Patterns

Detailed distribution of turtles is described in the previous chapter. In general, turtles expressed wide variability in area of the FKD 95% home range and 50% core use area contours (Table 4.1). Site fidelity was expressed by 18 of 22 turtles with the other 4 turtles better described as having nomadic movement patterns. Tracked turtles on average were observed within state jurisdictional waters approximately 82% of the time (Figure 4.4), with the majority of the turtles (n=20) considered near-shore turtles located on average 2.70 (± 0.73) km from shore. The other two females were classified as offshore turtles, located on average 26.0 (± 12.2) km from shore. Some turtles showed propensity to locate in or near deep channels between barrier islands, while none showed association with reef locations (Table 4.2).

During seven years of monitoring trawler activity, 43 flights occurred between May and August producing 3,221 locations of actively trawling shrimp vessels (Appendix N). Of those locations, 87.5% occurred in Georgia state jurisdictional waters and the rest in the first 5 kilometers of federal water jurisdiction (Table 4.3). Similarly, shrimp trawlers also tended to locate close to shore (Appendix O), with just over 40% of the observations made occurring within the first 2 km from the shoreline. Average distance of trawlers from channels was 2.91 km; however, 27.6% of the observed trawler locations were positioned within 1 km of the channels. Channels buffered by 1-km make up 13.8% of the seascape within 6 miles of shore (estuaries not included in estimates as they are closed to trawlers). The general distribution pattern observed in actual trawler locations within the first 10 km from shore is best described as mostly random. The ratio between null and observed TAI values showed 84.5% of the trawler activity around turtles was attributed to random pattern of trawler locations throughout the
seascape. Conversely, 15.5% of the trawler activity around turtles was explained by the clustering of trawler locations around specific areas that turtles also used.

**Model Evaluations**

*Spatial Closure* – Single large spatial closure management scenarios generally reduced mean TAI values more than scenarios composed of several small closure areas. This trend held true regardless of which turtle use area was used to calculate TAI values (Figure 4.7). The mean TAI values produced by the several small closure options appear nearly unchanged from the baseline trawler activity levels predicting little change to trawler activity around turtles if implemented. Only the Sapelo closure consistently predicted significant reductions (P < 0.05) in the TAI around turtles when compared to the baseline TAI calculated from observed trawler locations (Table 4.4). However, decreases in trawler activity predicted by the Sapelo closure were dependent on which baseline TAI was used for the comparison. When the null baseline TAI model was used for the comparison no significant decreases were identifiable (Table 4.4). A significant reduction in trawler activity was observed for the 1-mile closure scenario, but only for the 1-km location buffer turtle use area definition (Table 4.4). The Cumberland closure never produced a significant reduction in trawler activity regardless of turtle use area or baseline trawler distribution.

*Fleet Reductions* – The TAI values within turtle use areas tended to decrease as increasingly higher trawler fleet reduction levels increased (Figure 4.8). For both the 95% FKD home range and the 1-km point buffer turtle use area, a 30% trawler fleet reduction produced a decrease (P < 0.05) in the TAI (Table 4.4). A 50% reduction was required before a decrease was observed within the 50% core use area of turtles (Table 4.4). Only fleet reductions of 50% or
more consistently produced decreases in TAI values when compared to the null model (Table 4.4).

Discussion

Fleet reductions as a management strategy offered the most consistent results for reducing trawler activity around loggerhead females during nesting season movements. Fleet reductions of 50% or greater were the only management scenarios that significantly reduced trawler activity around turtles regardless of which trawler distribution was used as the baseline or which measure of turtle area definition was used. Uncertainty exists over which measure of turtle use area would be most adequate to reflect actual changes in trawler activity around turtles. It is also unknown if the best measure for tracking changes in trawler activity around turtles is consistent for turtles that exhibit different movement behaviors such as establishing home ranges and nomadic movement patterns. The consistency in reducing interactions as a result of fleet reductions in the face of all the uncertainty increases their merit as the most conservative strategy.

Comparison between both turtle and trawler distributions was necessary to identify potential areas of high overlap and consequently potentially high probability for trawler/turtle interactions. The evaluation of concurrent distribution data to identify potential management options is a relatively new concept for sea turtle conservation management (e.g., Kobayashi and Polovina 2005), but the concept has been applied more frequently in management systems for various fish species (Sweeting and Polunin 2005). For example, it was used to find ways to minimize billfish bycatch in longline sets (Goodyear 1999), and identify the best location and
timing for spatial closures to limit the take of thornback rays (Hunter et al. 2006). In either case, the distribution of both the species and the fishery vessels were used to identify areas of high overlap, which then aided the development of management options with which to proceed.

Estimates of population distribution and movement parameters are used for evaluating size and shape requirements of marine protected areas (Murawski et al. 2000, Meyer and Holland 2005). Distribution data observed during this investigation suggest a potential marine protected area designed to protect turtles from shrimp trawl mortality in coastal Georgia should be centered in front of a major nesting beach that spans the estuarine inlets and extends out to at least the state water jurisdictional boundary line. For instance, consider that loggerheads tended to stay within state jurisdictional waters, 50% of the population used less than 40 km of shoreline, and that most turtles (68%) tended to locate within 15 km of initial capture sites on nesting beaches. The approximate size of such a protected area would be 193 km² (40 km long x 4.83 km wide) which is larger than 73% of the home ranges estimated for the adult female turtles of this investigation and approximately the same size as the Cumberland and Sapelo closures (Table 4.5).

It was not surprising that the several small closure options did not perform well in reducing trawler activity around loggerheads. When considering closure management options, resource managers need to consider movement of the target species across closure boundaries, and account for the distribution and quantity of displaced fishing effort (Apostolaki et al. 2002, Murawski et al. 2000). When managing for over-fished species that have wide ranging movement patterns, only large closures will benefit the species (Apostolaki et al. 2002, Murawski et al. 2000, Sweeting and Polunin 2005). This point was exemplified especially well by the channel closure scenario where the total collective area contained within the closure
boundaries was the second largest of the 5 different scenarios considered, and displaced the second largest set of trawler locations. Yet, the channel closure did not incur any perceived benefits for the population.

It was surprising that only the Sapelo single large closure scenario showed potential as a management option. The Sapelo closure was not dissimilar in shape and size from the Cumberland closure. The only major differences were the number of trawlers displaced and the number of turtles using the closure area, which may indicate an important dynamic managers should consider when evaluating different closure areas. On the contrary the 1-mile closure was nearly double in size compared to the Sapelo closure, and displaced more trawlers, but the results showed little decrease in the trawler activity around turtles. The key difference between the Sapelo and 1-mile closure was likely the narrow parallel-to-shore shape of the 1-mile closure, which bisected many turtle home ranges. The resulting partial containment of turtle home ranges allowed redistributed trawlers to relocate back into turtle home ranges negating the initial reduction. Furthermore, most of the baseline trawler activity that occurred around turtles (84.5%) was attributed to random distribution of trawlers across the seascape, meaning that little variability would be expected in TAI values from different closure scenarios of similar shape and size. However, the Cumberland and Sapelo closure scenarios, though similar in shape and size, yielded different results in reducing turtle/trawler interactions. The primary difference between the two closure scenarios is the level of trawler activity that was displaced. Based on these results, single large spatial closures that maximize the amount of overlap between high trawler and turtle activity areas would be most likely to elicit a significant decline in trawler activity around turtles.
The added ecological benefits of establishing marine protected areas that were not modeled here should not be ignored. This investigation only considered benefits to a single species. Hiddink et al. (2006) warn heavily against such an approach based on their evaluation of impacts marine protected areas had on increases and stability species richness and overall biomass of the benthic invertebrate community after a beam trawl fishery was excluded from the closure areas. In light of the risks of managing the shrimp trawl fishery for a single species, the best ecosystem-based approach may actually be a combination of the Sapelo closure which could have high community level benefits and a fleet reduction which would help ensure trawling density did not increase in other areas after the closure was implemented.

**Management Implications**

Based on distribution data, in-water management of loggerhead turtles nesting in Georgia falls heavily on state resource managers. Given the data, the best management option to decrease the likelihood of interactions between shrimp trawlers and loggerhead turtles under the least amount of uncertainty is a 50% reduction in the fleet. Heavier reductions of trawler activity yielded better results for turtles, but would also exact heavier economic impacts on the state commercial shrimp trawl fishery. Fleet reductions offered consistent benefits to all monitored turtles (Figure 4.10) and, by themselves, offer the best option to reduce interactions between trawlers and loggerhead turtles during the nesting season off the coast of Georgia. A single large closure in front of Sapelo Island showed promise as a potential marine reserve designed to provide a sanctuary for nesting loggerheads during the internesting interval. However, single large spatial closures did not offer consistent reductions to all monitored turtles due to
displacement of trawlers out of the closure area into areas used by other turtles negating some of the overall population benefit (Figure 4.9). The best approach under the ecosystem management paradigm may actually be a combination of a single large closure, like the Sapelo closure, and a 30-50% fleet reduction to maintain or reduce the trawler density across the remaining open trawling waters.

Reducing adult loggerhead mortality in Georgia incurred by shrimp trawls is important, but results from this investigation offer little value outside the scope of Georgia waters during the nesting season. What is more important is elucidating the potential of predictive modeling as a management tool. Similar efforts should be expanded to other regions and life history stages for loggerheads of the northern subpopulation. For example, adult females spend approximately 2 months on the nesting grounds after laying the first nest (previous chapter), but spend 2-3 years on the foraging grounds building up body reserves prior to entering another active nesting season (Dodd 1988, Wilbur and Morin 1988, Miller and Limpus 2003). Efforts to combine turtle distribution data during this prolonged foraging stage of the adult female life history with distribution data of commercial fisheries have high potential for producing management options through predictive modeling that could strongly influence overall survival rates of adult female turtles for the whole northern subpopulation. Also, neritic juvenile life stage turtles spend perhaps as much as 15-20 years within the neritic zone habitats of the continental shelf before reaching sexual maturity. Increasing the survival rate of neritic juvenile loggerheads was shown to be more effective in stabilizing a declining population than any other life stage (Crouse et al. 1987). Understanding distribution patterns of neritic juveniles and the distribution of the various commercial fisheries during this crucial and prolonged life stage should be the highest priority for conservation efforts. I contend that use of predictive models offer the best tool to go forward
with for pinpointing best management actions to streamline future management efforts for those important life history stages.

**Literature Cited**


SOUTH ATLANTIC FISHERY MANAGEMENT COUNCIL. 2002. Final Amendment 5 to the Fishery Management Plan of the South Atlantic Region (Rock Shrimp), including a final supplemental EIS, initial regulatory flexibility analysis, regulatory impact review, and social impact assessment/fishery impact statement. Charleston, South Carolina, USA.


U.S. FISH AND WILDLIFE SERVICE. 1978. Listing and protecting loggerhead sea turtles as


Table 4.1. Measurements of area (km$^2$) associated with the 3 definitions of turtle use area (95% FKD home range, 50% FKD core, and 1-km location buffer) for each monitored turtle tracked during the 2004 and 2005 nesting seasons off the coast of Georgia, along with the location sample size used to acquire the measurements.

<table>
<thead>
<tr>
<th>Turtle ID</th>
<th>Sample size (n)</th>
<th>50% Core (km$^2$)</th>
<th>95% Home Range (km$^2$)</th>
<th>1-km Point Buffer (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49422</td>
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<td>1.06</td>
<td>11.35</td>
<td>207.35</td>
</tr>
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<td>21</td>
<td>3.29</td>
<td>20.55</td>
<td>65.97</td>
</tr>
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<td>49424</td>
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<td>5.38</td>
<td>43.17</td>
<td>135.09</td>
</tr>
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<td>3.80</td>
<td>24.66</td>
<td>81.68</td>
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<td>0.87</td>
<td>6.35</td>
<td>50.27</td>
</tr>
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<td>97.84</td>
<td>1058.65</td>
<td>339.29</td>
</tr>
<tr>
<td>49428</td>
<td>17</td>
<td>7.51</td>
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<td>53.41</td>
</tr>
<tr>
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<td>0.95</td>
<td>7.00</td>
<td>135.09</td>
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<td>20.48</td>
<td>255.39</td>
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<td>69.12</td>
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<td>38.88</td>
<td>341.37</td>
<td>56.55</td>
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<td>15.80</td>
<td>175.35</td>
<td>138.23</td>
</tr>
<tr>
<td>57655</td>
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<td>21.59</td>
<td>253.17</td>
<td>116.24</td>
</tr>
<tr>
<td>57656</td>
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<td>1.48</td>
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<td>131.95</td>
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<td>1.50</td>
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<td>4.77</td>
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</tr>
</tbody>
</table>

Mean 43.36 (± 9.75) 25.22 (± 22.85) 206.48 (± 173.77) 136.66 (± 30.72)
Table 4.2. Mean distance of locations from nearest reefs (artificial or natural) and deep channels (dredged or natural) accompanied with the percentage of locations for each turtle within 1 km of the sites by turtles tracked during the 2004 and 2005 nesting seasons off the coast of Georgia, USA.

<table>
<thead>
<tr>
<th>Year</th>
<th>Turtle ID</th>
<th>Sample</th>
<th>Reefs</th>
<th>Reefs</th>
<th>Channels</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Size (n)</td>
<td>Locations ≤ 1 km</td>
<td>Mean dist. (km)</td>
<td>Locations ≤ 1 km</td>
<td>Mean dist. (km)</td>
</tr>
<tr>
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<td>49422</td>
<td>66</td>
<td>1 (1.5%)</td>
<td>10.29</td>
<td>2 (3.0%)</td>
<td>8.57</td>
</tr>
<tr>
<td></td>
<td>49423</td>
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<td>0 (0%)</td>
<td>11.21</td>
<td>8 (38.1%)</td>
<td>4.13</td>
</tr>
<tr>
<td></td>
<td>49424</td>
<td>43</td>
<td>0 (0%)</td>
<td>9.97</td>
<td>10 (23.3%)</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>49425</td>
<td>26</td>
<td>0 (0%)</td>
<td>12.87</td>
<td>11 (42.3%)</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td>49426</td>
<td>16</td>
<td>0 (0%)</td>
<td>14.20</td>
<td>4 (25%)</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td>49427</td>
<td>107</td>
<td>12 (11.2%)</td>
<td>21.35</td>
<td>2 (1.9%)</td>
<td>23.44</td>
</tr>
<tr>
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<td>12.23</td>
<td>7 (41.2%)</td>
<td>3.48</td>
</tr>
<tr>
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<td>0 (0%)</td>
<td>18.85</td>
<td>28 (65.1%)</td>
<td>1.17</td>
</tr>
<tr>
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<td>34</td>
<td>0 (0%)</td>
<td>10.10</td>
<td>10 (29.4%)</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
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<td>0 (0%)</td>
<td>29.10</td>
<td>0 (0%)</td>
<td>39.61</td>
</tr>
<tr>
<td>2005</td>
<td>57651</td>
<td>84</td>
<td>0 (0%)</td>
<td>15.41</td>
<td>45 (53.6%)</td>
<td>2.18</td>
</tr>
<tr>
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<td>57652</td>
<td>22</td>
<td>1 (4.5%)</td>
<td>9.51</td>
<td>0 (0%)</td>
<td>6.98</td>
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<td>15.37</td>
<td>11 (28.2%)</td>
<td>4.34</td>
</tr>
<tr>
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<td>0 (0%)</td>
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<td>29 (47.5%)</td>
<td>2.17</td>
</tr>
<tr>
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<td>65</td>
<td>1 (1.5%)</td>
<td>10.73</td>
<td>17 (26.2%)</td>
<td>4.45</td>
</tr>
<tr>
<td></td>
<td>57660</td>
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<td>17.57</td>
<td>26 (86.7%)</td>
<td>0.54</td>
</tr>
<tr>
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<td>0 (0%)</td>
<td>11.56</td>
<td>3 (12.0%)</td>
<td>6.56</td>
</tr>
<tr>
<td></td>
<td>57662</td>
<td>62</td>
<td>1 (1.6%)</td>
<td>12.57</td>
<td>23 (37.1%)</td>
<td>3.01</td>
</tr>
</tbody>
</table>

Mean 43 (± 10) 14.25 (± 1.91) 6.23 (± 3.67)
Table 4.3. Shrimp trawler location distribution data obtained through complete count aerial surveys from May through August (1999-2005) off the coast of Georgia, USA.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number Flights</th>
<th>State (0-3 ml)</th>
<th>Federal (3-6 ml)</th>
<th>Federal (&gt; 6 ml)</th>
<th>Total Trawlers</th>
<th>Mean per Flight</th>
<th>Mean State* (0-3 ml)</th>
<th>Mean Federal* (3-6 ml)</th>
<th>Mean Federal* (&gt; 6 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>9</td>
<td>584</td>
<td>152</td>
<td>1</td>
<td>737</td>
<td>81.9</td>
<td>0.792</td>
<td>0.206</td>
<td>0.001</td>
</tr>
<tr>
<td>2000</td>
<td>6</td>
<td>440</td>
<td>44</td>
<td>0</td>
<td>484</td>
<td>80.7</td>
<td>0.909</td>
<td>0.091</td>
<td>0</td>
</tr>
<tr>
<td>2001</td>
<td>4</td>
<td>304</td>
<td>31</td>
<td>0</td>
<td>335</td>
<td>83.8</td>
<td>0.907</td>
<td>0.093</td>
<td>0</td>
</tr>
<tr>
<td>2002</td>
<td>3</td>
<td>258</td>
<td>55</td>
<td>0</td>
<td>313</td>
<td>104.3</td>
<td>0.824</td>
<td>0.176</td>
<td>0</td>
</tr>
<tr>
<td>2003</td>
<td>3</td>
<td>302</td>
<td>15</td>
<td>1</td>
<td>318</td>
<td>106.0</td>
<td>0.950</td>
<td>0.047</td>
<td>0.003</td>
</tr>
<tr>
<td>2004</td>
<td>9</td>
<td>495</td>
<td>68</td>
<td>0</td>
<td>563</td>
<td>62.6</td>
<td>0.879</td>
<td>0.121</td>
<td>0</td>
</tr>
<tr>
<td>2005</td>
<td>9</td>
<td>408</td>
<td>63</td>
<td>0</td>
<td>471</td>
<td>52.3</td>
<td>0.866</td>
<td>0.134</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>43</td>
<td>2791</td>
<td>428</td>
<td>2</td>
<td>3221</td>
<td>81.6</td>
<td>0.875</td>
<td>0.124</td>
<td>0.001</td>
</tr>
</tbody>
</table>

* Mean proportion of observed trawlers that occurred within the labeled jurisdictional boundary.
Table 4.4. List of 10 management scenarios evaluated with the models and their p-values. Scenarios that produced significant reductions in trawler activity around turtles under the different methods of calculating the trawler activity index are bolded.

<table>
<thead>
<tr>
<th>Management Scenario</th>
<th>Observed Baseline Comparisons</th>
<th>Null Baseline Comparisons</th>
<th>Point Buffer***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% FKD*</td>
<td>50% Core**</td>
<td>95% FKD*</td>
</tr>
<tr>
<td>1-mile closure</td>
<td>0.120</td>
<td>0.166</td>
<td>0.003</td>
</tr>
<tr>
<td>Cumberland Closure</td>
<td>0.437</td>
<td>0.582</td>
<td>0.225</td>
</tr>
<tr>
<td>Sapelo Closure</td>
<td><strong>0.022</strong></td>
<td><strong>0.016</strong></td>
<td><strong>0.041</strong></td>
</tr>
<tr>
<td>Channels Closure</td>
<td>0.924</td>
<td>0.582</td>
<td>0.275</td>
</tr>
<tr>
<td>ColRegs Closure</td>
<td>0.839</td>
<td>0.859</td>
<td>0.783</td>
</tr>
<tr>
<td>10% reduction</td>
<td>0.462</td>
<td>0.612</td>
<td>0.492</td>
</tr>
<tr>
<td>30% reduction</td>
<td><strong>0.017</strong></td>
<td>0.101</td>
<td><strong>0.034</strong></td>
</tr>
<tr>
<td>50% reduction</td>
<td>&lt;0.0001</td>
<td>&lt;0.004</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>70% reduction</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>90% reduction</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

* 95% fixed kernel density area contour for each turtle used to calculate TAI values.
** 50% fixed kernel density core use area contour for each turtle used to calculate TAI values.
***1-km buffer around each turtle’s locations used to calculate TAI values.
Table 4.5. Characteristics of closure management scenarios and their potential influence on the shrimp trawler fleet and adult female loggerhead turtles during nesting season life history stage off the coast of Georgia, USA.

<table>
<thead>
<tr>
<th>Closure Scenario</th>
<th>Closure Type</th>
<th>Closure Size (km²)</th>
<th>*Percent Area</th>
<th>Trawlers Displaced</th>
<th>Trawler Density within Closure</th>
<th>Trawler Impact</th>
<th>**Home Ranges Within Closure</th>
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*Percentage based on area of closure compared to total area (2006.6 km²) of waters used by shrimp trawls (0-6 miles from shore).

** Turtle home ranges (95% FKD) were included if they were completely or partially overlapping closure boundaries.
Figure 4.1. Study area showing the Georgia state jurisdiction water boundary 3 miles (4.83 km) out from shore, and the first 3 miles (4.83 – 9.66 km from shore) of federal water jurisdiction.
Figure 4.2. Flow Chart for evaluating spatial closure management scenarios showing calculation of baseline trawler activity index values for all turtles (n=22) and calculation of new trawler activity index values, which were an average across the 10 iterations of the trawler redistribution model. The flow chart represents the process used to obtain a comparison (t-test) between 1 of 3 different turtle use areas with 1 of 5 different spatial closure management scenarios. The process was repeated for each combination of turtle use area and spatial closure scenario.
Figure 4.3. Flow Chart for fleet reduction management scenarios showing calculation of baseline trawler activity index values for all turtles (n=22) and calculation of new trawler activity index values, which were an average across the 10 iterations of the random trawler reductions. The flow chart represents the process used to obtain a comparison (t-test) between 1 of 3 different turtle use areas with 1 of 5 different fleet reduction management scenarios. The process was repeated for each combination of turtle use area and fleet reduction scenario.
Figure 4.4. Mean proportion of locations across turtles during both (2004 and 2005) seasons and across years for aerial trawler surveys (1999-2005) that occurred in state (0-3 miles) and federal (3-6 miles) jurisdictional waters.
Figure 4.5. Shape and location of the 3 ‘single large’ closure scenarios: A) Cumberland closure scenario, which represents a low trawler impact option; B) Sapelo closure scenario, which represents a high trawler impact option; C) 1-mile closure scenario, which represents another high trawler impact option.
Figure 4.6. Shape and location of the 2 'several small' closure scenarios. Channel buffer closures, divided into 3 sections from across the state: A) northern; B) middle; and C) southern and represent a high trawler impact option. Extension of the estuarine boundary out to the ColRegs Demarcation Line, divided into 3 sections from across the state: D) northern; E) middle; and F) southern and represent a low trawler impact option.
A) 95% FKD home range

B) 50% FKD core area

C) 1-km location buffer

Figure 4.7. Comparison among baseline TAI (trawlers/km²/flight) estimates (observed and null) and estimates of TAI values predicted by the 5 spatial closure scenarios. Each set of estimates was conducted for the 3 different measures of turtle use area: A) 95% FKD home range; B) 50% FKD core area; and C) 1-km location buffer. All estimates are bounded by 95% confidence limits.
Figure 4.8. Comparison among baseline TAI (trawlers/km²/flight) estimates (observed and null) and estimates of TAI values predicted by the 5 fleet reduction scenarios. Each set of estimates was conducted for the 3 different measures of turtle use area: A) 95% FKD home range; B) 50% FKD core area; and C) 1-km location buffer. All estimates are bounded by 95% confidence limits.
A) Cumulative frequency distribution for 1-mile closure under 95% FKD turtle use area.

B) Cumulative frequency distribution for 1-mile closure under 50% FKD turtle use area.

C) Cumulative frequency distribution for 1-mile closure under 1-km point buffer turtle use area.
D) Cumulative frequency distribution for Cumberland closure under 95% FKD turtle use area.

E) Cumulative frequency distribution for Cumberland closure under 50% FKD turtle use area.

F) Cumulative frequency distribution for Cumberland closure under 1-km point buffer use area.
G) Cumulative frequency distribution for Sapelo closure under 95% FKD turtle use area.

H) Cumulative frequency distribution for Sapelo closure under 50% FKD turtle use area.

I) Cumulative frequency distribution for Sapelo closure under 1-km point buffer turtle use area.
J) Cumulative frequency distribution for Channels closure under 95% FKD turtle use area.

K) Cumulative frequency distribution for Channels closure under 50% FKD turtle use area.

L) Cumulative frequency distribution for Channels closure under 1-km point buffer use area.
Figure 4.9. (A-O). Cumulative frequency distributions showing the number of turtles that fit into different ranges of percent change in TAI values under the different spatial closure management scenarios compared to observed baseline TAI values under the 3 turtle use area definitions (95% FKD home range, 50% FKD core area, and 1-km location buffer).
A) Cumulative frequency distribution under 95% FKD turtle use area.

B) Cumulative frequency distribution under 50% FKD turtle use area.

C) Cumulative frequency distribution under 1-km point buffers turtle use area.

Figure 4.10. Cumulative frequency distributions showing the number of turtles that fit into the different ranges of percent change in TAI values under the 5 levels of shrimp trawler fleet reduction management scenarios compared to observed baseline TAI values under each turtle use area definition: A) 95% FKD home range; B) 50% FKD core area; C) 1-km Location Buffer.
Chapter 5 – Conclusions and Recommendations for Managing Loggerhead Turtles

Conclusions

Recovery of the northern subpopulation of the southeastern U.S. nesting aggregation of loggerhead turtle (*Caretta caretta*) requires management efforts to reduce mortality of large size class turtles caused by commercial fisheries within the neritic zone of the continental shelf (National Marine Fisheries Service 1991, Turtle Expert Working Group 2000). This study demonstrated the plausibility of using predictive modeling to evaluate management strategies for reducing interactions between turtles and shrimp trawlers prior to their implementation thereby reducing source mortality. Using predictive modeling to evaluate management strategies is especially critical when developing management plans for threatened or endangered species like loggerhead turtle because erroneous management decisions may have long lasting or permanent deleterious impacts on species persistence (Brook et al. 2000).

Model results suggest that, during the nesting season portion of the adult female life history stage, fleet reductions of the shrimp trawl fishery operating in and around Georgia waters are the most reliable management strategy to reduce the interactions between turtles and trawlers. Fleet reductions would benefit adult females and also may benefit other neritic zone life history stages, like juveniles and adult males, not accounted for in the model. Spatial closures also may benefit loggerheads, but analyses indicate that careful consideration of size, shape, and placement must be taken prior to implementation. Single large marine protected areas placed in Georgia state waters of 200 km² (approximately 40 x 5 km dimensions) placed in front of major nesting beaches had mixed results dependent on trawler activity previously observed within (and consequently displaced) the closure and the number of turtles utilizing the closure area.
Successful closure scenarios benefited a portion of the population strongly, but negatively impacted another portion of the population, which negated some of the overall population benefit.

Incorporating distribution data for both the nesting loggerhead turtle and commercial shrimp trawl fishery was critical in facilitating the predictive modeling process. Through tracking efforts, nesting loggerheads generally stayed close to shore, remaining within state jurisdictional waters approximately 82% of the time. Additionally, for a large portion of the population, use of estuaries and deep channels was high compared to its availability. Analysis of trawler locations identified state waters and channel locations as significant areas of overlap between the distributions, which allowed streamlined management options to be developed and evaluated.

Finally, merits of satellite telemetry as a tracking tool to estimate turtle distribution and movement parameters were previously inadequately tested. This investigation demonstrated that accuracy levels of satellite telemetry are acceptable depending on the biological questions being asked, but that transmission rate of useable location data is low for loggerhead turtles during nesting season movements. Inclusion of LC A locations in the useable locations is warranted based on fixed position trials, which more than doubled the data acquisition during monitored turtle movements.

Management Recommendations

1. Reducing the shrimp trawler fleet operating in Georgia waters is the best and most conservative approach for ensuring a reduction in interactions between shrimp trawlers
and adult female loggerhead turtles during nesting season movements off the coast of Georgia. The timing of the reduction should occur between early April through at least August.

2. If spatial closures are pursued as a management option, then only single large closures that extend from the shoreline out to at least the state water jurisdictional boundary should be considered. The size of the closure should be a minimum of 200 km$^2$, and be positioned in front of a major nesting beach, preferably Sapelo Island.

3. Aerial surveys of the shrimp trawl fleet should continue in order to examine reactions of the fleet to management scenarios after implementation.

4. Efforts should be made to account for juvenile and adult male loggerhead turtle distributions in and around Georgia waters to allow for a more comprehensive assessment of population benefits received from implementation of different management strategies.

5. Investigation into community level benefits to marine protected areas for closures within Georgia state jurisdictional waters would aid the decision making process of choosing the management strategy works best under the ecosystem management paradigm.

6. Expand predictive modeling efforts to regional foraging areas used by adult females during periods between active nesting seasons, which constitutes a large portion of their life history at the adult stage.

7. A region wide predictive modeling approach to evaluating management strategies for the northern subpopulation as a whole has potential to aid recovery efforts tremendously by streamlining large-scale management strategies. Such an effort must account for distributions of different turtle life history stages and different commercial fisheries over spatial and temporal scales.
8. Research efforts to increase precision of estimates for nest site fidelity and mean number of nests deposited per female should continue, which will help provide better estimates of population trends and size.

**Literature Cited**


Appendix A. Seven-year average and 95% confidence intervals of loggerhead nesting activity by week throughout the nesting season on Georgia beaches, 1999-2005 (Georgia Department of Natural Resources, unpublished data).
Appendix B. Annual carcass counts of loggerhead turtles (all size classes) washed up on Georgia beaches over a 16-year time series (1989-2004) with consistent standardized monitoring procedures. Data courtesy of the Georgia Department of Natural Resources.
Appendix C. Annual carcass counts of adult loggerhead turtles (CCL ≥87 cm) washed up on Georgia beaches over a 17-year time series with consistent standardized monitoring procedures. Data courtesy of the Georgia Department of Natural Resources.
Appendix D. Simple Plywood Corral. Successfully held all 12 of the 2005 turtles. A) Corrals allow safe access to turtles while attaching transmitters to the carapace. The white towel over the eyes helped keep the turtle calm. B) Team members Sam Truesdell (left), and Mandi McElroy (right) prepare carapace surface to accept bonding agents.
Appendix E. Release data and physical observations of turtles captured and equipped with telemetry transmitters during nesting attempts made on beaches during the 2004 and 2005 nesting seasons in Georgia, USA.

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<th>Longitude</th>
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* Turtle carapace measurements are curved lengths.  ** Length measurements not possible because posterior portion of carapace was missing.

1. Cleaning carapace at and around all areas transmitters are placed.
   a. Scrape macro epibiota from carapace with chisels.
   b. Use stiff wire brush on carapace (loosens algae).
   c. Apply water to rinse material.
   d. Scrub carapace with green scrubby (household dish scrubber).
   e. Apply water again.
   f. Dry thoroughly with paper towels.
   g. Sand paper the carapace (100 grit only) scuff the surface.
   h. Apply water.
   i. Pat dry thoroughly with paper towels.
   j. Pour Acetone over washed area.
      i. take extra care to avoid spilling acetone over turtle’s eyes!
      1. cloth towels between carapace and head worked well).
      ii. let acetone evaporate dry.

2. Securing transmitters to carapace (Satellite, Sonic, and VHF).
   a. Satellite transmitter  (placement = just behind 1st vertebral).
      i. Prep the sonic weld  -  Mix by hand until color is even.
         1. Do quickly (<5 minutes) as material cures fast.
      ii. Make coils out of the sonic weld immediately.
         1. Apply coils to outside edge of bottom of transmitter.
         2. leave 2 small gaps in coils to allow spill out of epoxy.
      iii. Fast Foil 2-part epoxy (self mixing nozzle).
         1. fill reservoir on bottom of transmitter between coils.
            a. Don’t overfill, very messy.
      iv. Stick on turtle holding firmly down applying even pressure.
      v. Apply 1 thick bead of epoxy around outer edge of transmitter and over top of transmitter in front of antenna.
         1. smooth out epoxy bead at base of transmitter (putty knife).
      vi. Allow epoxy to cure until hard but still tacky.
      vii. Repeat steps iv, v, and vi 2 more times or until desired level of epoxy is placed around transmitter.
   b. Radio Transmitter  (placement = approximately 3rd vertebral).
      i. Same sonic weld and epoxy procedure though only two applications of epoxy was needed for smaller transmitter size.
   c. Sonic Transmitter    (placement = approximately 4th vertebral).
      i. Same sonic weld and epoxy procedure except no bead over the top of the transmitter in front of the antenna (Step 2.a.v) was necessary.

3. Wait for epoxy to be nearly dry (not tacky) then release the turtle.
Appendix G.  A) Placement of transmitters from front to back was satellite, radio (none in 2004) and sonic.  B) These were attached on second, third, and fourth vertebrae respectively.  Fastfoil epoxy bead in front of satellite antenna helped protect antenna base from abrasion.  In some cases sonic transmitters and metal coach they were placed in were lost prematurely during the nesting season (especially problematic for 2005 season).
Appendix H. Location and distribution of deep channels and natural and artificial reef sites in and adjacent to Georgia state waters.
Appendix I. Ranked order of the proportion of total locations for each turtle in estuarine habitats during the nesting season in Georgia 2004 and 2005. Dashed line shows the proportion (0.127) of the study area (out to 10 km from shore) composed of estuarine habitats.
Appendix J. The ranked order of shortest to longest mean distance from initial capture location for individual loggerhead turtles tracked during the nesting season in Georgia 2004 and 2005.
Appendix K. Ranked order of the proportion of total locations for each turtle in or within 1 km of deep channels that occur between barrier islands. Dashed line shows the proportion (0.186) of the study area (out to 10 km from shore) composed of channels buffered by 1 km.
Appendix L. Movement maps for the 18 home range turtles including 95 and 50% FKD utility distributions along with in-water and nest site locations.

Appendix L-1. Turtle ID 49422. Sample size and frequency of different location classes:
Total (66); Visually confirmed locations (6); LC 3 (6); LC 2 (11); LC 1 (10); LC A (33).
Appendix L-2. Turtle ID 49423. Sample size and frequency of different location classes: Total (21); Visually confirmed locations (6); LC 3 (1); LC 2 (3); LC 1 (1); LC A (10).
Appendix L-3. Turtle ID 49424. Sample size and frequency of different location classes: Total (43); Visually confirmed locations (6); LC 3 (5); LC 2 (4); LC 1 (6); LC A (22).
Appendix L-4. Turtle ID 49425. Sample size and frequency of different location classes:
Total (26); Visually confirmed locations (16); LC 3 (1); LC 2 (2); LC 1 (1); LC A (6).
Appendix L-5. Turtle ID 49426. Sample size and frequency of different location classes: Total (16); Visually confirmed locations (10); LC 3 (0); LC 2 (2); LC 1 (2); LC A (2).
Appendix L-6. Turtle ID 49428. Sample size and frequency of different location classes:
Total (17; Visually confirmed locations (3); LC 3 (2); LC 2 (4); LC 1 (2); LC A (6).

Map Legend

- 95% KHR
- 50% Core
- Channels
- Reefs
- Nest sites
- Visual Obs.
- LC 3
- LC 2
- LC 1
- LC A

15 km
Appendix L-7. Turtle ID 49429. Sample size and frequency of different location classes: Total (43); Visually confirmed locations (10); LC 3 (3); LC 2 (4); LC 1 (7); LC A (19).
Appendix L-8. Turtle ID 49430. Sample size and frequency of different location classes: Total (37); Visually confirmed locations (3); LC 3 (1); LC 2 (4); LC 1 (3); LC A (26).
Appendix L-9. Turtle ID 57651. Sample size and frequency of different location classes: Total (84); Visually confirmed locations (18); LC 3 (12); LC 2 (11); LC 1 (4); LC A (39).
Appendix L-10. Turtle ID 57652. Sample size and frequency of different location classes: Total (22); Visually confirmed locations (6); LC 3 (3); LC 2 (0); LC 1 (2); LC A (11).
Appendix L-11. Turtle ID 57654. Sample size and frequency of different location classes: Total (44); Visually confirmed locations (6); LC 3 (6); LC 2 (8); LC 1 (6); LC A (18).
Appendix L-12. Turtle ID 57656. Sample size and frequency of different location classes: Total (42); Visually confirmed locations (8); LC 3 (2); LC 2 (6); LC 1 (2); LC A (24).
Appendix L-13. Turtle ID 57657. Sample size and frequency of different location classes: Total (39); Visually confirmed locations (5); LC 3 (1); LC 2 (9); LC 1 (2); LC A (22).
Appendix L-14. Turtle ID 57658. Sample size and frequency of different location classes:
Total (61); Visually confirmed locations (15); LC 3 (4); LC 2 (8); LC 1 (5); LC A (29).
Appendix L-15. Turtle ID 57659. Sample size and frequency of different location classes: Total (65); Visually confirmed locations (9); LC 3 (4); LC 2 (8); LC 1 (8); LC A (36).
Appendix L-16. Turtle ID 57660. Sample size and frequency of different location classes: Total (30); Visually confirmed locations (26); LC 3 (0); LC 2 (0); LC 1 (0); LC A (4).
Appendix L-17. Turtle ID 57661. Sample size and frequency of different location classes:
Total (25); Visually confirmed locations (4); LC 3 (2); LC 2 (1); LC 1 (4); LC A (14).
Appendix L-18. Turtle ID 57662. Sample size and frequency of different location classes: Total (62); Visually confirmed locations (7); LC 3 (2); LC 2 (5); LC 1 (6); LC A (42).
Appendix M. Movement path maps for the 4 nomadic turtles including nest site locations.

Appendix M-1. Turtle ID 49427. Sample size and frequency of different location classes: Total (108); Visually confirmed locations (2); LC 3 (14); LC 2 (15); LC 1 (16); LC A (61).
Appendix M-2. Turtle ID 49431. Sample size and frequency of different location classes: Total (52); Visually confirmed locations (2); LC 3 (5); LC 2 (7); LC 1 (8); LC A (30).
Appendix M-3. Turtle ID 57653. Sample size and frequency of different location classes: Total (18); Visually confirmed locations (5); LC 3 (0); LC 2 (2); LC 1 (3); LC A (8).
Appendix M-4. Turtle ID 57655. Sample size and frequency of different location classes: Total (37); Visually confirmed locations (9); LC 3 (2); LC 2 (6); LC 1 (3); LC A (17).
Appendix N. Shrimp trawler locations (n = 3221) recorded during aerial surveys conducted between May and August, 1999-2005.
Appendix O. Proportion of shrimp trawler locations recorded during aerial surveys on the Georgia coast among categories of linear distance to shore. Dashed line indicates the separation between state (left) and federal (right) jurisdictional boundaries.
Appendix P. Results from statistical evaluation of each management scenario compared to the observed and null baseline trawler distributions (1999-2005).

| Turtle Use Area | Baseline       | Management Scenario* | df | t-value | P > |t| |
|-----------------|----------------|----------------------|----|---------|-----|---|
|                 | Observed       | 1-mile closure       | 42 | 1.59    | 0.120 |
| 95% FKD         | Observed       | Cumberland Closure   | 42 | 0.78    | 0.437 |
|                 | Observed       | **Sapelo Closure**   | 42 | 2.38    | **0.022** |
|                 | Observed       | Channels Closure     | 42 | 0.1     | 0.924 |
|                 | Observed       | ColRegs Closure      | 42 | 0.2     | 0.839 |
|                 | Observed       | 10% reduction        | 42 | 0.74    | 0.462 |
|                 | Observed       | **30% reduction**    | 42 | 2.49    | **0.017** |
|                 | Observed       | **50% reduction**    | 42 | 4.52    | <.0001 |
|                 | Observed       | **70% reduction**    | 42 | 6.8     | <.0001 |
|                 | Observed       | **90% reduction**    | 42 | 9.06    | <.0001 |
| 50% Core        | Observed       | 1-mile closure       | 42 | 1.41    | 0.166 |
|                 | Observed       | Cumberland Closure   | 42 | 0.55    | 0.582 |
|                 | Observed       | **Sapelo Closure**   | 42 | 2.5     | **0.016** |
|                 | Observed       | Channels Closure     | 42 | 0.56    | 0.582 |
|                 | Observed       | ColRegs Closure      | 42 | 0.18    | 0.859 |
|                 | Observed       | 10% reduction        | 42 | 0.51    | 0.612 |
|                 | Observed       | 30% reduction        | 42 | 1.67    | 0.101 |
|                 | Observed       | **50% reduction**    | 42 | 3.04    | **0.004** |
|                 | Observed       | **70% reduction**    | 42 | 4.61    | <.0001 |
|                 | Observed       | **90% reduction**    | 42 | 6.1     | <.0001 |
| Point Buffer    | Observed       | 1-mile closure       | 42 | 3.1     | **0.003** |
|                 | Observed       | Cumberland Closure   | 42 | 1.23    | 0.225 |
|                 | Observed       | **Sapelo Closure**   | 42 | 2.11    | **0.041** |
|                 | Observed       | Channels Closure     | 42 | 1.11    | 0.275 |
|                 | Observed       | ColRegs Closure      | 42 | 0.28    | 0.783 |
|                 | Observed       | 10% reduction        | 42 | 0.69    | 0.492 |
|                 | Observed       | **30% reduction**    | 42 | 2.19    | **0.034** |
|                 | Observed       | **50% reduction**    | 42 | 4.04    | **0.000** |
|                 | Observed       | **70% reduction**    | 42 | 6.03    | <.0001 |
|                 | Observed       | **90% reduction**    | 42 | 8       | <.0001 |

*Bold lettering indicates significant reduction from baseline TAI value.

Appendix P-1. Results from statistical evaluation of each management scenario compared to the observed baseline trawler distributions (1999-2005).
| Turtle Use Area | Baseline | Management Scenario* | df  | t-value | $P > |t|$ |
|----------------|----------|----------------------|-----|---------|---------|
| 95% FKD        | Null     | 1-mile closure       | 42  | -0.69   | 0.496   |
|                | Null     | Cumberland Closure   | 42  | -0.04   | 0.965   |
|                | Null     | Sapelo Closure       | 42  | 1.58    | 0.122   |
|                | Null     | Channels Closure     | 42  | 0.78    | 0.441   |
|                | Null     | ColRegs Closure      | 42  | 0.66    | 0.512   |
|                | Null     | 10% reduction        | 42  | -0.15   | 0.884   |
|                | Null     | 30% reduction        | 42  | 1.56    | 0.126   |
|                | **Null** | 50% reduction        | 42  | **3.6** | **<.0001** |
|                | **Null** | 70% reduction        | 42  | **5.93** | **<.0001** |
|                | **Null** | 90% reduction        | 42  | **8.29** | **<.0001** |
| 50% Core       | Null     | 1-mile closure       | 42  | -0.74   | 0.465   |
|                | Null     | Cumberland Closure   | 42  | 0.02    | 0.983   |
|                | Null     | Sapelo Closure       | 42  | 1.83    | 0.074   |
|                | Null     | Channels Closure     | 42  | 0.06    | 0.952   |
|                | Null     | ColRegs Closure      | 42  | 0.45    | 0.655   |
|                | Null     | 10% reduction        | 42  | -0.15   | 0.878   |
|                | Null     | 30% reduction        | 42  | 0.96    | 0.344   |
|                | **Null** | 50% reduction        | 42  | **2.29** | **0.027** |
|                | **Null** | 70% reduction        | 42  | **3.85** | **0.000** |
|                | **Null** | 90% reduction        | 42  | **5.35** | **<.0001** |
| Point Buffer   | Null     | 1-mile closure       | 42  | -1.73   | 0.092   |
|                | Null     | Cumberland Closure   | 42  | 0.18    | 0.858   |
|                | Null     | Sapelo Closure       | 42  | 0.82    | 0.418   |
|                | Null     | Channels Closure     | 42  | 0.51    | 0.615   |
|                | Null     | ColRegs Closure      | 42  | 1.37    | 0.177   |
|                | Null     | 10% reduction        | 42  | -0.97   | 0.337   |
|                | Null     | 30% reduction        | 42  | 0.59    | 0.560   |
|                | **Null** | 50% reduction        | 42  | **2.72** | **0.010** |
|                | **Null** | 70% reduction        | 42  | **5.21** | **<.0001** |
|                | **Null** | 90% reduction        | 42  | **7.85** | **<.0001** |

*Bold lettering indicates significant reduction from baseline TAI value.

Appendix P-2. Results from statistical evaluation of each management scenario compared to the null baseline trawler distributions.