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DETERMINING THE IMPACTS OF BEACH RESTORATION ON LOGGERHEAD (*CARETTA CARETTA*) AND GREEN TURTLE (*CHELONIA MYDAS*) NESTING PATTERNS AND REPRODUCTIVE SUCCESS ALONG FLORIDA'S ATLANTIC COAST

by

ALLISON WHITNEY HAYS
B.S. Principia College, 2004

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Biology
in the College of Sciences
at the University of Central Florida
Orlando, Florida

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ABSTRACT

Artificial beach nourishment, the most common method to mitigate coastal erosion in the United States, is also considered the most ecologically friendly alternative for shoreline stabilization. However, this habitat alteration has the potential to impact nesting marine turtles and developing hatchlings. The first objective of this study was to determine how nourishing beaches with two different design templates affects loggerhead (*Caretta caretta*) and green turtle (*Chelonia mydas*) nesting success, the ratio of nests to the total number of nests and non-nesting emergences, and reproductive success, the ratio of hatched and emerged hatchlings to the total number of eggs deposited. Two types of restoration designs exist along the southern Brevard County, FL coastline, which supports some of the highest density loggerhead and green turtle nesting worldwide. Since 2005, approximately 35 kilometers of beach have undergone 1) full-scale restoration (typically called nourishment), where sand was added above and below the mean high tide line (2005, 2010) or 2) dune restoration, where sand was placed on the dune (2005, 2006, 2008, 2009).

To quantify the effects of these restoration types, we used a Before-After-Control-Impact-Paired Series (BACIPS) model, which tests for significance between the difference in nesting success rates at the impact (engineered) and control sites (natural beach) before and after restoration (Δ). For loggerheads, there was a significant difference in Δ after dune restoration during the years of construction (2005, 2006, 2008, and 2009; $p<0.001$) and one year post-construction (2007; $p<0.05$ and 2010; $p<0.001$). After full-scale restoration, there was a significant difference in Δ during the years of construction (2005 and 2010; $p < 0.001$) and one year post-construction (2006; $p<0.001$). For green turtles, there was a significant difference in Δ after dune restoration during two of the four years of construction (2006; $p<0.05$ and 2008; $p<0.01$) and one of the two one-year post-construction years (2010; $p<0.05$). After full-scale restoration, the significant difference in Δ lasted every season (2005-2010; $p<0.001$). There were no significant differences in Δ for loggerhead or green turtle reproductive success rates after either type of restoration.

The second objective was to use the different restoration designs to study what beach characteristics function as loggerhead nesting cues to explain why altering the beach decreases nesting success rates. We examined beach elevation and slope, sand moisture content, sand grain size, beach width, and distance traveled. Logistic regression model selection found all variables were important ($R^2=0.75$). Further examination of trends, with each crawl divided into quarters, found beach slope served as a nesting cue. In all study sites except one, when turtles false crawled, the beach flattened out in the final quarter of the crawl. Conversely, in nesting emergences, the final quarter rose at a steeper slope than the previous quarter. Additionally, model selection found variables important in nest site selection were also important in hatching ($R^2=0.44$) and emergence ($R^2=0.45$) success. These results offer new insight into how and why marine turtle nesting patterns change after artificial nourishment, providing information necessary to nourish beaches in a more “turtle-friendly” manner.

I dedicate this thesis to anybody who has ever spent a night on the beach searching for turtles while being eaten by mosquitoes and no-see-ums, run survey in the pouring rain, gone netting in 100 degree weather while being swarmed by love bugs, followed a green turtle track into the dune then couldn't find the turtle even though you could hear her, jumped in the ocean on survey, thrown good money after bad, almost been decapitated by fishing line, waited on a green turtle only to have her cover without laying, dug the ATV out of a green turtle pit, biopsied yourself instead of the turtle, biopsied somebody else instead of the turtle, found an emerging leatherback on your last run of the night, spent days pulling cold-stunned turtles out of the Indian River Lagoon, run survey for eight months of the year, watched a turtle bounce off the net on a windy day, done an inventory in December, waited way too long for an emerging turtle that turned out to be a log, gotten excited about a false crawl, been hit by a rogue wave, gone reef netting during an upwelling, had your feet knocked out from under you by a leatherback or green turtle, been outsmarted by the equipment you work with, "laughed" at the penguin joke, laughed at the penguin joke, had the net catch on your clothes and almost pull you off the boat while setting, wondered how you made it from Orlando to Melbourne, been chased by a dog on survey, been chased by the same dog on survey every day of the season, been thrown into the water by something that swam into the net, or screamed when a ghost crab jumped out of an egg chamber at you.

ACKNOWLEDGMENTS

To my committee, Dr. Llew Ehrhart, Dr. John Weishampel, Dr. Ross Hinkle, and Dr. Mario Mota, thank you for your guidance and support throughout this process. Meredith Hickman, Robyn Lee, Greg Norris, and Sarah Krieg, thank you for being an outstanding field crew – I could not have done this project without each of you. Rick Herren and Mike McGarry, thank you for answering all of my questions and taking time to discuss beach nourishment and turtles with me. Thanks to Kristen Kneifl and Ecological Associates, Inc., for working with me to help me collect data in the areas I needed. To the Turtle Lab and UCFMTRG, thanks for being a support system and providing countless entertaining memories over the past several years. Doc, you have been an amazing teacher; I have learned so much from you and am honored to be one of your students. To my family and friends, thank you for your constant love, support, and encouragement.

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CHAPTER 1: GENERAL INTRODUCTION

The world's coastal population is expanding at an unprecedented rate. Current predictions suggest that by 2020, over five billion people will live within 60 kilometers of the coast (Roberts and Hawkins 1999, Brown and McLachlan 2002). Disturbances associated with population growth, such as construction, recreational activities, pollution, and exploitation of resources, are putting beaches under increasing pressures, such as erosion. Erosion can often be attributed to permanent structures on the shoreline that prevent naturally dynamic beaches from migrating landward in response to storms and changes in currents and tides. This coastal squeeze, where beaches are trapped between an immovable shoreline and a changing ocean, will only be exacerbated as sea level rise and storm severity increase with global climate change (Brown and McLachlan 2002, Schlacher *et al*. 2007; 2008). In addition to coastal squeeze, beaches are also facing erosion because of activities that disrupt the natural sand-flow system, such as inlet dredging and jetty construction (Montague 2008). As a result of these multiple anthropogenic factors, many of today's beaches are eroding at an accelerated rate. This can be seen in Florida, where there was an 83% increase in critically eroded beaches between 1989 and 2011 (Florida Department of Environmental Protection 2011a).

One method to provide shoreline protection is hard armoring, or the construction of impermeable structures that reflect wave energy, such as seawalls and groins, on the beach or in nearshore waters (US Army Corps of Engineers 2002). However, hard armoring can interrupt the longshore sediment transport system and prevent the beach from naturally rebuilding, causing increased erosion downdrift of the structure (reviewed in Kraus and McDougal 1996, Brown and McLachlan 2002). In the 1970s, there was a shift towards building beaches or structures to absorb energy in what is known as soft armoring (Valverde *et al*. 1999, US Army Corps of Engineers 2002). In the most common form of soft armoring, which I will be calling full-scale restoration (typically called nourishment), the berm, or flat section of beach formed through wave-induced sediment deposition (US Army Corps of Engineers 2002), is raised and widened when sand is added above and below the mean high water line. An alternate form of soft armoring, called dune restoration, places sand landward of the mean high water line, widening the dune while narrowing the berm (M. McGarry 2011, Brevard County, Melbourne, FL, personal communication).

Habitat alteration, whether natural or anthropogenic, has the potential to alter species' life history characteristics (Bawa and Dayanandan 1998, Johnson *et al*. 1998, Donohue 2002). Placing imported sand on the shoreline, which can differ from native sand in characteristics such as moisture content, grain size, grain shape, mineral content, shear resistance and sand color (Nelson 1991), impacts species that live on the beach, ranging from benthic micro-algae, vascular plants and marine bivalve clams (*Donax* spp) to mole crabs (*Emerita talpoida*) and sanderlings (*Calidris alba*) (Bishop *et al*. 2006; Peterson *et al*. 2000, 2006). In addition, shoreline restoration affects nesting adult marine turtles and their eggs (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009).

Studies of the impacts of full-scale beach restoration projects on nesting patterns of the federally threatened loggerhead (*Caretta caretta*) and the federally endangered green sea turtle (*Chelonia mydas*) show a post-restoration decrease in nesting success, or an increase in aborted nesting attempts relative to successful nest deposition (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009). In loggerheads, this decline usually lasts two to three seasons post-restoration; as the beach returns to its profile equilibrium, an idealized condition based on sediment characteristics and steady wave conditions (Dean 1983), nesting success returns to its pre-restoration state (Steinitz *et al*. 1998, Rumbold *et al*. 2001, Brock *et al*. 2009). Fewer studies have recorded the impacts of restoration on green turtle nesting success; however, nesting success rates have been reported lower than the historical average up to a minimum of four seasons post-restoration (Brock 2005, Ehrhart *et al*. 2010).

As part of this post-restoration decrease in nesting success, an increase in both loggerhead and green turtle non-digging emergences has been recorded (Herren 1999, Brock *et al*. 2009). A non-digging emergence is the first stage at which a turtle can abort nesting; she returns to the water without digging a body pit or an egg chamber (FWC Marine Turtle Conservation Guidelines 2007). This increase in non-digging emergences can often be attributed to the formation of an escarpment, a fairly uninterrupted steep slope caused by erosion that runs parallel to the shore (US Army Corps of Engineers 2002). Escarpments are often intensified on restored beaches and can physically impede turtles from ascending the beach (Davis *et al*. 1993, personal observations). However, even in cases where escarpments did not form, an increase in non-digging emergences post-restoration has still been documented (Raymond 1984, Ernest 2001, Brock *et al*. 2009). Studies of the impacts of full-scale restoration projects have not provided answers as to why this drop in nesting success occurs when there is not a physical barrier blocking access to the upper beach, although Brock (2005) suggested that this could indicate the absence of abiotic cues that initiate nesting.

However, minimal and at times conflicting data about nesting cues make it difficult to assess how beach restoration alters nesting behavior (Crain *et al*. 1995). Beach width, beach length, beach height, beach profile, sand temperature, sand type, sand softness, sand moisture content, distance from human settlement, and presence of a lagoon have all significantly affected loggerhead nest site selection (Stoneburner and Richardson 1981, Provancha and Ehrhart 1987, Cardinal *et al*. 1998, Garmestani *et al*. 1998, Kikukawa *et al*. 1999, Wood and Bjorndal 2000, Karavas *et al*. 2004, Mazaris *et al*. 2006). It has been hypothesized that a combination of changes in beach slope and sand characteristics interact with the distance the turtle crawls to provide the appropriate signal(s) for nest deposition. This can occur through the integration of multiple cues at the appropriate nesting spot or by a stepwise series of signals; after a specific threshold from one environmental characteristic is crossed, the turtle then cues into the next characteristic (Wood and Bjorndal 2000, Mazaris *et al*. 2006).

Nest placement impacts the nesting female's reproductive success and fitness as well as the survival of her offspring, which are affected by factors such as sediment composition, distance from the water line, and distance from the dune (Martin 1988, Bjorndal and Bolten 1992, Hays and Speakman 1993, Mota 2009). Changes in sand type and quality have the potential to impact both the developing and emerging hatchlings by affecting gas and water exchange between the clutch and the sand and the sand and the atmosphere (Crain *et al*. 1995, Mota 2009). Beach restoration has varying effects on reproductive success, defined as hatching success (number of hatchlings hatched from the nest) and emergence success (number of hatchlings emerged from the nest) (reviewed in Brock *et al*. 2009).

I addressed two main objectives for this study. The first was to determine the effects of full-scale and dune restoration on loggerhead and green turtle nesting and reproductive success. Although other published and unpublished studies have determined the impacts of full-scale restoration on loggerhead nesting (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009), only one has examined the impacts of full-scale restoration on green turtles (Brock *et al*. 2009), and none have quantified the impacts of dune restoration on either species. The second objective was to elucidate what beach characteristics function as loggerhead nesting cues by comparing nests and false crawls on natural beaches and beaches with soft armoring (full-scale and dune restoration). The decreased nesting success rates after full-scale restoration could be explained if characteristics that act as proximate cues to initiate nesting on natural beaches are changed too much on nourished beaches. Understanding loggerhead nesting cues will supply data needed to build beaches in a manner more conducive to loggerhead nesting.

CHAPTER 2: EXAMINING THE EFFECTS OF TWO BEACH NOURISHMENT DESIGNS ON MARINE TURTLE NESTING AND REPRODUCTIVE SUCCESS IN BREVARD COUNTY, FL

Introduction

A combination of natural and anthropogenic factors has caused an accelerated rate of erosion on sandy beaches worldwide. Developed coastlines prevent naturally dynamic beaches from migrating landward in response to storms and changes in currents and tides, leaving beaches trapped in a coastal squeeze between the ocean and an immovable shoreline (Brown and McLachlan 2002, Schlacher *et al*. 2007; 2008). This problem will be exacerbated as sea levels rise with global climate change, causing beaches to erode at a rate two orders of magnitude greater than that of the sea level rise (Zhang *et al*. 2004). In addition, activities such as inlet dredging and jetty construction have been removing sediment for centuries, disrupting the natural sand-flow system (Montague 2008).

The principal method to combat coastal erosion in the United States is artificial nourishment (Valverde *et al*. 1999), which is the addition of sand to the beach (US Army Corps of Engineers 2002). Nourishment is more ecologically friendly than other anthropogenic methods for shoreline stabilization, such as the construction of seawalls and jetties (reviewed in Speybroeck *et al*. 2006). However, a newly constructed beach provides a modified habitat that can have different sand characteristics (Nelson 1991) and an altered profile (Speybroeck *et al.* 2006). Habitat alteration, whether natural or anthropogenic, has the potential to affect species' behaviors associated with their life history (Bawa and Dayanandan 1998, Johnson *et al*. 1998, Donohue 2002); studies of beach nourishment have found impacts on species ranging from benthic micro-algae, vascular plants, and marine bivalve clams (*Donax* spp) to mole crabs (*Emerita talpoida*) and sanderlings (*Calidris alba*) (Peterson *et al*. 2000, 2006; Bishop *et al*. 2006).

Habitat changes associated with artificial nourishment can affect migratory marine turtles using the sandy beach for nesting. Studies have found impacts on both gravid marine turtles searching for a nest site and on hatchlings developing in the new substrate (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009). The effects of altering the nesting habitat are made more complex because marine turtles do not choose a nesting beach randomly. They display an evolutionarily stable strategy of philopatry, migrating from foraging grounds to nest in the region of their natal beach every two to more than five years after reaching maturity (Carr 1986, Switzer 1993, Bowen 1995). The individual and population-level consequences of a philopatric turtle returning to nest in an area that no longer provides suitable nesting habitat are unknown.

Florida serves as an important rookery for both the loggerhead (*Caretta caretta*) and green turtle (*Chelonia mydas*), which are listed as threatened and endangered, respectively, under the U.S. Endangered Species Act (1973). Eighty to ninety percent of loggerhead nesting worldwide occurs in Florida and Oman (Witherington *et al.* 2009), and Florida is a regionally important nesting area for green turtles (Meylan *et al*. 1995). Florida's sandy beaches are also facing severe erosion, as evidenced by an 83% increase in critically eroded beach between 1989 and 2011 (Florida Department of Environmental Protection 2011a). Since 1998, approximately 55% of critically eroded beaches have been nourished, which comes at a cost to local, state, and federal governments. Funding requests to the Florida Department of Environmental Protection for the 2011-12 fiscal year totaled more than $82 million for 68 projects (Florida Department of Environmental Protection 2011b). The prevalence of artificial beach nourishment on this important rookery makes understanding its impact on these two species of marine turtles crucial.

In 2010, 23% of loggerhead nesting and 35% of green turtle nesting in Florida occurred in Brevard County (Ehrhart *et al*. 2011), where 59 of 116 kilometers of shoreline are listed as critically eroded (Florida Department of Environmental Protection 2011a). Since 2005, approximately 35 kilometers have been replenished following two different methods. In full-scale restoration (typically referred to as nourishment or renourishment), the berm, or flat section of beach that is formed through wave-induced sediment deposition (US Army Corps of Engineers 2002), is raised and widened when sand is added above and below the mean high water line. Conversely, dune restoration places sand landward of the mean high water line, widening the dune while narrowing the berm (M. McGarry 2011, Brevard County, Melbourne, FL, personal communication).

Despite research since the 1980s on the impacts of beach nourishment on marine turtle nesting, there is still a paucity of information in many critical areas. While several studies have examined how full-scale restoration affects marine turtle nesting (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al.* 2009), none have determined the impacts of dune restoration. In addition, all published studies, except Brock *et al*. (2009), only examined the effect of full-scale restoration on loggerheads. The purpose of this study was to examine the impacts of full-scale and dune restoration on both loggerhead and green turtle nesting and reproductive success, providing new information on the effects of different template designs on both species. The results of this study provide a more thorough explanation of how altering a beach affects loggerhead and green turtle nesting patterns.

Methods

Data collection

We followed standard nesting survey protocol by traversing the beach at sunrise to count tracks left by turtles that came ashore to nest the previous night. When turtles emerge, they either successfully nest or abort nesting prior to egg deposition in what is known as a non-nesting emergence. Nesting success is calculated as the ratio of nests to all emergences. During daily surveys from May 5 -August 31, researchers tallied nests and non-nesting emergences, as characterized by crawl characteristics, for each species by location (to 0.5 km accuracy). The surveyor each morning marked tracks from the previous night so that the following night's crawls could be clearly identified as new on the next survey.

Researchers marked a subsample of nests the morning after deposition to determine reproductive success, or the number of hatchlings that hatched and emerged from the nest. Three days after a hatchling emergence, researchers excavated the nest to enumerate the contents. Eggs were categorized as hatched, unhatched, pipped (a hatchling began hatching but was still in the egg), or damaged by a predator; live and dead hatchlings remaining in the nest were also counted.

Study sites

We analyzed nesting and reproductive success on three treatments: beaches with dune restoration, beaches that have undergone full-scale restoration, and natural beaches. All sites were located on a barrier island on the east central coast of Florida in Brevard County (Figure 2.1). Table 1 shows the minimum and maximum number of loggerhead and green turtle nests deposited and marked from 2005-2010 in each study site.

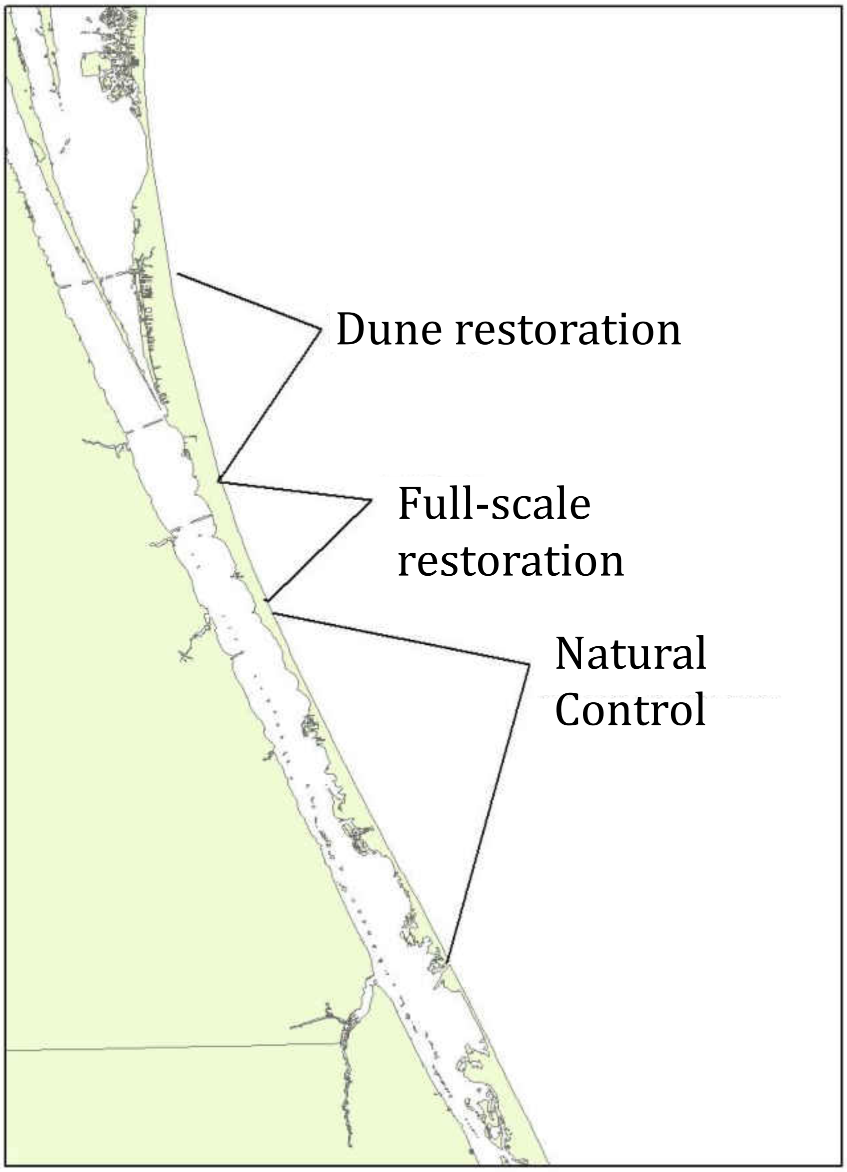


Figure 2.1. Study sites in Brevard County, Florida

Table 2.1. Minimum and maximum number of loggerhead and green turtle nests deposited and marked on each study site from 2005-2010.

	Loggerhead		Green turtle	
Study site	Min nests laid (# marked)	Max nests laid (# marked)	Min nests laid (# marked)	Max nests laid (# marked)
Dune restoration	1690 (37)	2800 (144)	58 (33)	224 (99)
Full-scale restoration	752 (32)	1345 (124)	32 (31)	124 (88)
Natural	1773 (33)	3450 (81)	353 (13)	1242 (50)

Dune restoration (DR)

In response to hurricanes and winter storms, in 2005, 2006, 2008, and 2009, beach quality sand (similar in character to native sand and meeting standards set by Florida's Department of Environmental Protection) was trucked from upland mines to rebuild dunes along a 12 kilometer stretch of shoreline. In 2005, the profile design template called for the addition of sand to shape only the eroded dune (Figure 2.2a). In the following years of dune restoration, the dunes were restored with an alternate design that included a dual slope: a longer, gentler slope preceded the newly shaped dune face (M. McGarry 2011, Brevard County, Melbourne, FL, personal communication) (Figure 2.2b) Each year, the amount of sand added in a given area depended on how much erosion had occurred there, so a constant volume of sediment was not added to the whole restored area (M. McGarry, 2011, Brevard County, Melbourne, FL personal communication).

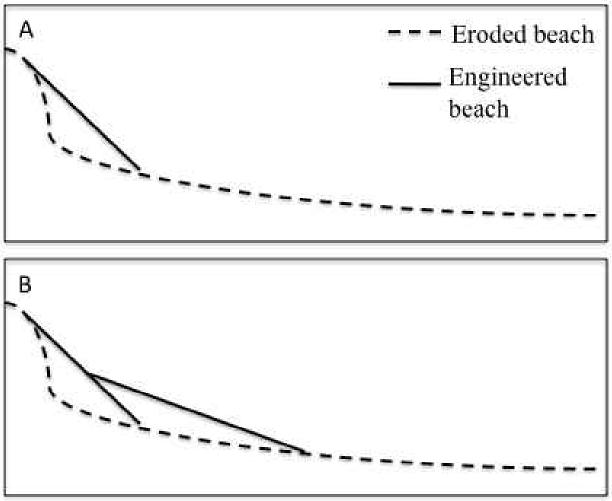


Figure 2.2. The single slope engineered in 2005 compared to B) the dual slope engineered in 2006, 2008, and 2009

Full-scale restoration (FSR)

Full-scale restoration occurred immediately south of the DR site on a 6.5 kilometer stretch of coastline. A pipeline pumped beach quality sand dredged from offshore borrow sites onshore in 2002-2003, 2005, and 2010. The beach fill design called for the beach width to taper at the ends of the engineered area, so I used only the middle five kilometers for this analysis.

Natural beach

Natural areas were located in a 21 kilometer stretch of the Archie Carr National Wildlife Refuge (ACNWR). Following the 2004 hurricane season, Brevard County constructed dunes on the ACNWR in front of permanent structures and county parks. For statistical analyses prior to 2005, I calculated nesting and reproductive success rates from the entire 21 kilometers. Beginning in 2005, I calculated these rates from the remaining natural areas, which constitute approximately 25% of the total area of the ACNWR.

Statistical analyses

I used a Before-After-Control-Impact Paired Series (BACIPS) model to examine the impact of beach restoration on nesting and reproductive success. The BACIPS is a relatively robust design that examines changes in the difference between the Control and Impact sites Before and After restoration (delta, or Δ). The closer Δ is to zero, the more similar the sites. This design accounts for natural variation between the Control and Impact sites, avoiding problems of spatial and temporal variability that occur in other post-hoc impact assessments (Rumbold *et al*. 2001). In addition, the BACIPS demands simultaneous sampling, with each sampling time considered as a replicate.

I used a historical average (1997-2001) for the Before (pre-restoration) data. To see the effect of time since restoration, I separated the After (post-restoration) data into each year of the

After period (2005-2010). I compared each of the two Impact sites (DR and FSR sites) separately to the Control. The Control during the Before period was the entire ACNWR; during the After period, the Control consisted of the natural, unmanipulated areas of the ACNWR.

Nesting success

I calculated the nesting success rate (NSR) for each day of the nesting season for loggerheads from May 5-August 31. Since green turtles begin nesting later in the summer (Weishampel *et al*. 2006), I calculated their NSR from June 1-August 31. I used equation 2.1 to calculate the daily Δ.

$$Control\ NSR\ for\ day\ x\ - Impact\ NSR\ for\ day\ x \tag{2.1}$$

I used log or log10 transformations for non-normal data, tested for significance with a paired *t*-test, then used Holm's test to account for multiple comparisons. Holm's test is more powerful and less conservative than Bonferroni's one-step correction. This test uses a step-down sequential approach, where the *p*-value for each test in the set is corrected in decreasing order of significance (Holm 1979, Garcia 2004).

I tested for temporal autocorrelation in the historical dataset using GS+ (Gammadesign software, version 9). Temporal autocorrelation occurs when measured variables are more similar when closer in time and less similar when further apart in time (Legendre 1993). For both species, autocorrelation was only present in the Control site; since it was not present in all sites, the results will not be considered here. However, this analysis provided new information that is presented in Appendix A.

Finally, I calculated the mean difference in Δs, which is the estimated average effect size. To determine which type of engineering had a larger impact, I used a *t*-test to compare the effect sizes during the years of construction and again one year post-construction at the DR and FSR sites.

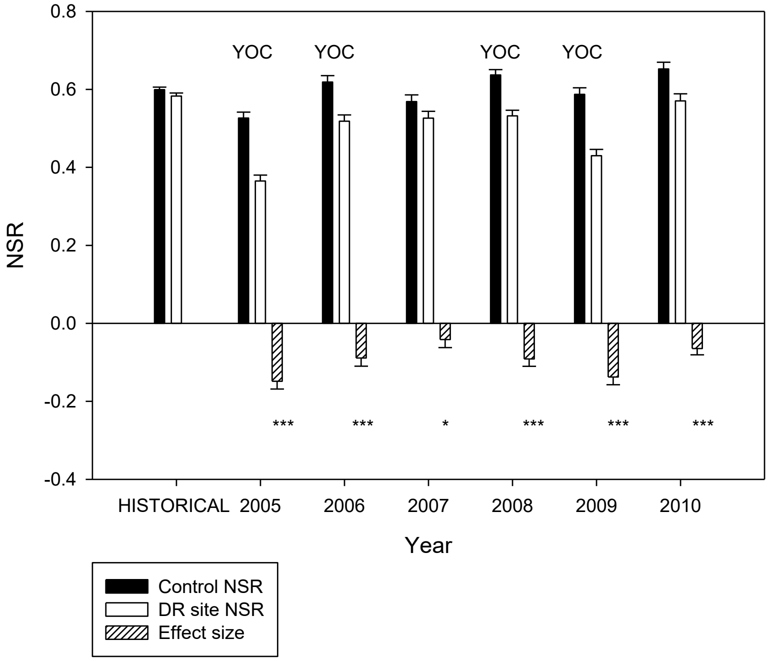
Reproductive success

I calculated reproductive success rates from the subset of nests marked at deposition and followed through incubation. I used two measures of reproductive success: (1) hatching success, the number of hatched eggs divided by the total number of eggs deposited, and (2) emergence success, the number of hatchlings that emerged from the nest divided by the total number of eggs deposited. Since the BACIPS requires simultaneous sampling, I combined data into distinct sampling periods according to the month the nest was deposited: May-August for loggerheads and June-August for green turtles. The distribution of deltas was not normal, so I used the Wilcoxon matched-pairs signed rank test and adjusted the alpha with Holm's test. Since I already averaged the data for each month, I did not test for temporal autocorrelation.

Results

Loggerhead nesting success

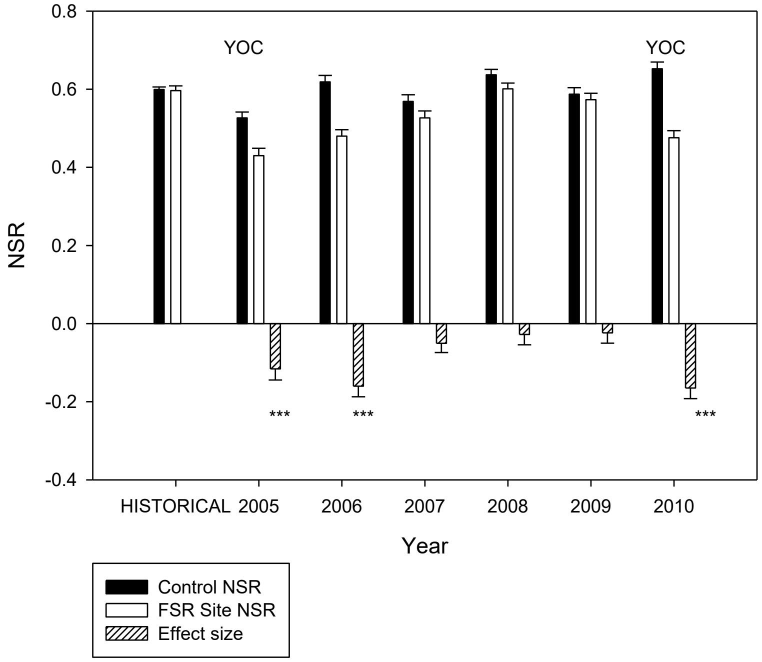
After dune restoration, there was a significant difference in loggerhead nesting success rate Δs during the years construction occurred (2005, $p<0.001$; 2006, $p<0.001$; 2008, $p<0.001$; 2009, $p<0.001$) and during the two seasons that were one year post-construction (2007, $p<0.05$ and 2010, $p<0.001$). Historically, nesting success rates were marginally higher in the Control relative to the DR site, which remained true during each post-restoration season (Figure 2.3).



YOC= year of construction. * indicates significant difference in Δ (estimated average effect size) at < 0.05 (*), <0.01 (**), and <0.001 (***)

Figure 2.3. Loggerhead nesting success rates and effect sizes on the DR site compared to the Control.

Following full-scale restoration, there was a significant difference in loggerhead nesting success rate Δs during the years of construction (2005, $p<0.001$ and 2010, $p<0.001$) and one year post-construction (2006, $p<0.001$) after correcting for multiple comparisons. During 2007-2009, nesting success rates were lower at the FSR site relative to the Control and the historical dataset, but there was not a significant difference in Δs. Historically, nesting success was marginally higher in the Control site, which remained consistent after construction (Figure 2.4).



YOC= year of construction. * indicates significant difference in Δ (estimated average effect size) at < 0.05 (*), <0.01 (**), and <0.001 (***)

Figure 2.4. Loggerhead nesting success rates and effect sizes on the FSR site compared to the Control.

There was not a significant difference in effect sizes between the two Impact areas during the years of construction (Table 2.2). At the FSR site, the effect size one year post-construction increased from the effect size during the years of construction, while the reverse occurred at the DR site. This resulted in a significantly larger effect size at the FSR site compared to the DR site one year post-construction.

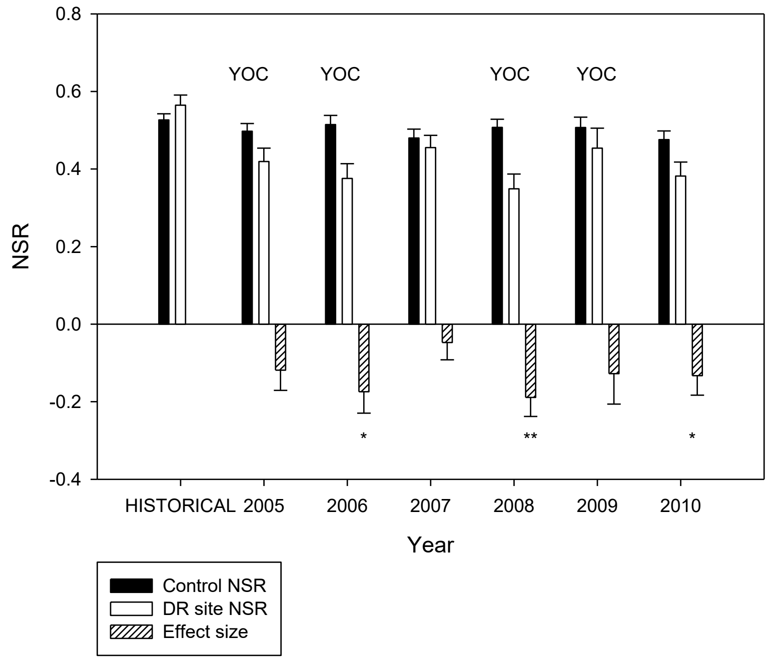
Table 2.2. Loggerhead nesting success rate estimated average effect sizes.

Year	DR effect size	FSR effect size	*p*-value
YOC	-0.1124	-0.1271	0.563
1 year post-construction	-0.0525	-0.1603	<0.001*

YOC = year of construction. The further the effect size is from zero (positively or negatively), the greater the impact.

Green turtle nesting success

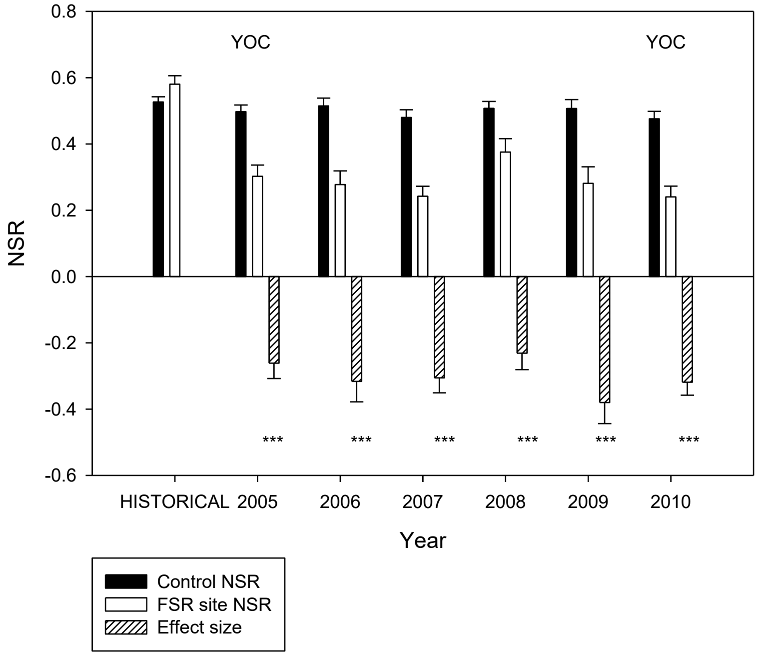
After dune restoration, green turtle nesting success rate Δs differed significantly during two of the four years of construction (2006, $p<0.05$ and 2008, $p<0.01$) and during one of the two one year post-construction years (2010, $p<0.05$). Historically, nesting success rates were higher in the DR site relative to the Control, but during all post-restoration years, nesting success rates were lower at the Impact site compared to the Control (Figure 2.5).



YOC= year of construction. * indicates significant difference in Δ (estimated average effect size) at < 0.05 (*), <0.01 (**), and <0.001 (***)

Figure 2.5. Green turtle nesting success rates and effect sizes on the DR site compared to the Control

The analysis after full-scale restoration showed a significant difference in Δs every season post-construction (2005-2010, $p<0.001$). Historically, nesting success rates were higher in the FSR site relative to the Control; however, after construction, nesting success rates were higher in the Control (Figure 2.6).



YOC= year of construction. * indicates significant difference in Δ (estimated average effect size) at < 0.05 (*), <0.01 (**), and <0.001 (***)

Figure 2.6. Green turtle nesting success rates and effect sizes on the FSR site compared to the Control

There was a significantly larger effect size in the FSR site compared to the DR site during the years of construction ($p<0.01$) as well as one year post-construction ($p<0.001$) (Table 2.3). After dune restoration, the effect size decreased one year post-construction while the opposite trend occurred after full-scale restoration.

Table 2.3. Green turtle nesting success rate estimated average effect sizes

	DR effect size	FSR effect size	p-value
YOC	-0.1474	-0.2920	0.002*
1 year post-construction	-0.0787	-0.3166	<0.001*

YOC = year of construction. The further the effect size is from zero (positively or negatively), the greater the impact.

Loggerhead reproductive success

There were no significant differences in Δ for hatching or emergence success rates after dune restoration. Historically, hatching and emergence success rates in the DR site were higher than in the Control; this remained true post-restoration except in 2008. After full-scale restoration, there were also no significant differences in Δ for hatching or emergence success. Historically, hatching and emergence success rates were higher in the Control than in the FSR site. Post restoration, the hatching and emergence success rates were higher in the FSR site except in 2010, when hatching success was marginally higher in the Control.

Green turtle reproductive success

Following both dune and full-scale restoration, there were no significant differences in Δ for hatching or emergence success rates. Historically, hatching and emergence success in both Impact sites were slightly higher than in the Control, but this was not consistent post-restoration.

Discussion

Dune restoration

The significant difference in loggerhead nesting success rate Δ in the DR site indicates an increased rate of non-nesting emergences relative to successful nest deposition each year that dune restoration occurred. This restoration impact was still significant the year following construction, even though no additional sand was added to the shoreline. The smaller effect size observed during the years without construction (2007 and 2010) indicates that nesting success rates started to return to their pre-restoration state. However, due to the frequency of dune restoration events, it was not possible to examine the long-term effects of a single project to see if or when nesting success rates returned to the historical average.

These results corroborate those of Long *et al*. (2011), who found a consistent decrease in loggerhead nesting success after morphological changes to the beach, specifically the profile. Wood and Bjorndal (2000) concluded that profile is an important element of nest site selection on a natural beach, where loggerheads nest on a slope with their head higher than their tail. If loggerheads are sensitive to topographic changes (Long *et al.* 2011), significantly altering the beach profile, a key factor in nest site selection (Wood and Bjorndal 2000), could affect whether a turtle nests or not. The lower nesting success rates seen in my study could be the result of this sensitivity to the altered beach profile. Even in years where construction did not occur, the beach morphology remained sufficiently altered to negatively impact nesting success rates.

The largest impact for loggerheads occurred in 2005, which was the only year that the template design added sand to shape only the dune. In the following years of construction, when the dunes were restored with a dual slope (Figure 2.2), there was less of an impact on loggerhead nesting success. The decreased difference in nesting success rate Δ during the following years of construction indicates that the dual slope design was more conducive for loggerhead nesting, although this same pattern was not evident for green turtles.

Long *et al*. (2011) concluded that green turtles are also sensitive to changes in the beach shape. However, since green turtles tend to nest closer to the dune than loggerheads (Witherington 1986), both Long (2010) and Brock *et al*. (2009) suggested that green turtles are more influenced when choosing a nest site by specific dune features than by overall topography. The inconsistencies in post-restoration nesting success rates found in my study could be explained if green turtles are responding to more acute changes, such as the presence of a dune feature (Brock *et al*. 2009, Long 2010). It is possible that green turtles were not as affected by the overall altered beach shape as much as by changes in key characteristics that may not have been consistent along the restored shoreline or among years (e.g., dune vegetation may have changed within and among seasons).

There were no significant results in comparisons of both hatching and emergence success rates. Other studies have found that beach restoration has varying effects on reproductive success (reviewed in Brock *et al*. 2009), with sand quality, which can impact both the developing and emerging hatchlings, as the determinant factor (Mortimer 1990). However, the results from this study should be interpreted cautiously because the nests were grouped by month laid, resulting in a small sample size (four for loggerheads and three for green turtles).

Full-scale restoration

Loggerhead results after full-scale restoration showed a similar pattern to those found in other studies (Steinitz *et al*. 1998, Brock *et al.* 2009). A decreased nesting success rate in the FSR site led to significantly larger nesting success rate Δs during the years of construction and one year post-construction. In the following years, the decreasing effect size shows nesting success returning to near normal rates. These results also support the idea that significantly altering the profile can affect whether a loggerhead nests or not (Long *et al*. 2011). Immediately after construction, the beach morphology was severely altered, but as the beach started to return to its profile equilibrium, which can take months to years (Greene 2002), nesting success rates began to return to normal.

Prior to applying Holm's test, the significant difference in deltas continued through the second year post-construction ($p < 0.05$). While it is common practice to adjust the alpha to avoid a Type 1 error, a compelling argument can be made for using an unadjusted alpha of 0.05 when making multiple comparisons. Constantly adjusting the alpha destroys the standard that is used throughout scientific literature and essentially penalizes researchers for performing more than one test (Gotelli and Ellison 2004). When I used Holm's test to adjust the *p*-value rather than using a test that adjusts the alpha, the same argument can be made. The purpose of this research was to determine the length of time that each species was impacted by restoration projects, making multiple tests an integral component of this study. Adjusting *p*-values each post-construction year downplays the restoration impact by making it harder to have a significant result the longer the time since construction. When applying the results of this study, especially for management decisions, one should strongly consider using the unadjusted *p*-values, which show a significant difference in loggerhead nesting success rate deltas during the year of construction and the following two seasons. The only other place in my study where a discrepancy occurs between the original and the adjusted *p*-value is for green turtle nesting in 2005 in the DR site. Whether that value is significant or not, it does not impart any pattern to the impact of dune restoration on green turtle nesting success.

During the five seasons of post-construction monitoring, green turtle nesting success rates never recovered statistically. Post-restoration, the FSR site was substantially wider than before restoration; the 2010 project extended the berm 19.5m seaward (Olsen Associates 2010), which forced turtles to crawl further inland to reach the dune. If the presence of a dune feature is important to initiate green turtle nesting (Brock *et al*. 2009, Long 2010), the wide berm made reaching the dune much more difficult and could have caused the increased number of non-nesting emergences and ensuing lower nesting success rates.

Beaches that have undergone full-scale restoration must be maintained and are re-engineered every three to ten years on average (Weggel 1995). Nesting green turtles' inability to adapt quickly to a beach with full-scale restoration, combined with the frequency of full-scale restoration projects, could permanently alter the nesting patterns of green turtles by not allowing nesting success rates to recover between projects. Serious reproductive consequences will result if gravid females return to natal beaches that no longer provide a suitable nesting environment (Meylan et al. 1995). However, since each treatment was not replicated, the results of this study need to be interpreted cautiously if extrapolated to other beaches (Hurlbert 1984).

As with the DR site, there were no significant results when examining reproductive success, but these results should be viewed cautiously due to a small sample size.

Comparing effect size between engineered sites

Both projects significantly impacted loggerhead and green turtle nesting success rates during the years of construction and one year post-construction. However, the significant differences in effect size for loggerheads (one year post-construction) and green turtles (year of - and one year post-construction) indicate a longer-lasting impact after full-scale restoration. Additionally, the impact on both species was slightly stronger during one year post-construction compared to the year of construction, which was not true after dune restoration. It is clear that both species were not impacted to the same degree by the different types of engineering.

Caveats

Since this study was a post-hoc impact assessment and not a controlled experiment, there were certain factors over which I had no control. The most important of these is the lack of a true Control with physical boundaries that did not change during the entire study period. While it is possible that the altered Control could have impacted the results, there was not a significant difference in nesting success rates at the Before Control compared to the After Control, indicating that the decreased size of the Control site after restoration did not significantly affect the results.

Implications for practice

- Beach nourishment projects can have varied design templates that affect loggerhead and green turtle nesting success rates differently.
- Loggerheads and green turtles respond differently to an altered beach, so the species of turtle nesting on a specific beach needs to be considered when restoring beaches or dunes.
- After dune restoration, loggerhead nesting success rates were less impacted by a dual slope dune than by a single slope dune.

CHAPTER 3: USING NATURAL AND NOURISHED BEACHES TO UNDERSTAND LOGGERHEAD NESTING CUES

Introduction

Migratory marine turtles select a variety of habitats depending on their life stage (reviewed in Musick and Limpus 1997). Adults migrate between foraging and nesting grounds, with philopatry serving as the driving force behind rookery selection (Carreras *et al*. 2007, Shamblin *et al*. 2011). Unlike most avian nesting species, marine turtles leave their nest site after egg deposition, providing no parental care and only remaining on land long enough to deposit the clutch. Bjorndal and Bolten (1992) suggested that an individual turtle may choose a nesting site based on her own survival rather than that of her clutch because of her inability to judge changes in the nest environment over the course of the incubation period (e.g., through hurricane-induced storms and tidal surges). Therefore, the variable(s) that serve as the most important cue(s) for nest site selection may differ from those characteristics that result in the success of the clutch.

Previous research provide minimal and often conflicting results concerning beach characteristics that serve as proximate nesting cues for the federally threatened loggerhead (*Caretta caretta*). Wood and Bjorndal (2000) concluded that significant increases in beach slope indicate beach profile plays a role in loggerhead nest site selection; however, beach width, beach length, beach height, sand temperature, sand type, sand softness, sand moisture content, distance from human settlement and presence of a lagoon have also been shown to significantly affect loggerhead nest site selection (Stoneburner and Richardson 1981, Provancha and Ehrhart 1987, Cardinal *et al*. 1998, Garmestani *et al*. 2000, Kikukawa *et al*. 1999, Wood and Bjorndal 2000, Karavas *et al*. 2004, Mazaris *et al*. 2006). It has been hypothesized that a combination of beach slope and sand characteristics interact with distance traveled to provide the appropriate signal(s) for nest deposition. This could occur in one of two ways: a turtle could nest where the appropriate patterns of associations of all characteristics exist, or she could cue into individual characteristics in a stepwise manner; i.e., after passing the appropriate sand temperature threshold, the turtle then cues into sand moisture content (Wood and Bjorndal 2000, Mazaris *et al*. 2006).

Miller *et al*. (2003) suggested that studying both successful and unsuccessful nesting attempts by manipulating beach characteristics when a turtle chooses a nesting site could better elucidate factors important in nest site selection. Examining unsuccessful nesting attempts (commonly called non-nesting emergences or false crawls) is logistically difficult. Turtles can false crawl for reasons not related to the beach (e.g, interactions with beachgoers, obstructions, etc.), so researchers would have to observe a turtle as she false crawled to make sure her return to the water was not due to alternate reasons. Additionally, manipulating the beach for purposes of a nest site selection study is not a viable option due to logistic difficulties.

However, Brevard County, Florida, contains beaches that have been artificially nourished, which is the principal method to combat mitigate erosion in the United States (Valverde *et al*. 1999). Beach nourishment is the addition of sand to the shoreline, which can alter the beach profile (Speybroeck *et al*. 2006) and introduce sand with different characteristics

(Nelson 1991). In Brevard County, beaches were engineered following two different templates. In the full-scale restoration design, typically referred to as nourishment or renourishment, the berm was raised and widened when sand was added above and below the mean high water line. Alternately, dune restoration placed sand landward of the mean high water line, widening the dune while narrowing the berm (M. McGarry 2011, Brevard County, Melbourne, FL, personal communication). These engineering projects used sand from different areas; the full-scale project piped sand dredged from offshore while the dune restoration project trucked sand from upland mines. Essentially, these projects provided what Miller *et al*. (2003) suggested; they manipulated beach features, giving me the opportunity to study the driving forces behind nest site selection on beaches with different shapes and sand characteristics.

The purpose of this study was to determine what characteristics function as loggerhead nesting cues by examining nests and false crawls on natural and nourished beaches. Previous studies have documented a temporary decrease in loggerhead nesting success, which is defined as an increase in aborted nesting attempts relative to successful nest deposition, after full-scale restoration (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009, Hays 2012: Chapter 2). Examining the role of beach elevation and slope, sand moisture content, and sand grain size on natural and recently nourished beaches will help elucidate characteristics important in nest site selection and provide the mechanism behind this decline. I chose these characteristics based on previous nest site selection studies and because they can be changed after artificial nourishment. Additionally, I determined if those characteristics that played a role in selecting a nesting site were also important in determining the reproductive success of the clutch. I examined two measures of reproductive success: hatching success, which is the percent of hatchlings that hatched from the nest and emergence success, which is the percent of hatchlings that emerged from the nest.

Methods

Study sites

I collected environmental data from turtles' emergence tracks in six study sites in Brevard and Indian River Counties (Figure 3.1). There were three treatments with two replicates of each treatment: full-scale restoration (FSR), dune restoration (DR), and natural beach. Both FSR sites were engineered in the winter-spring of 2010 prior to the nesting season, while the DR sites were engineered in winter-spring of 2009. Ideally, to have the most variation among treatments, all engineering would have occurred during the same season; however, we had no control over the construction schedule.

I designed this project to have two replicates each of FSR, DR, and natural beach. However, the two FSR sites were engineered differently from one another and could not be considered replicates. The site referred to as FSR:flat was engineered with a slightly sloped (1%) berm, while in the site referred to as FSR:sloped, the berm was widened, and a steep dune was constructed on the landward edge of the beach. For this reason, I have two replicates each of natural beach and DR, which I pooled for analyses, but I present results from each FSR site separately.

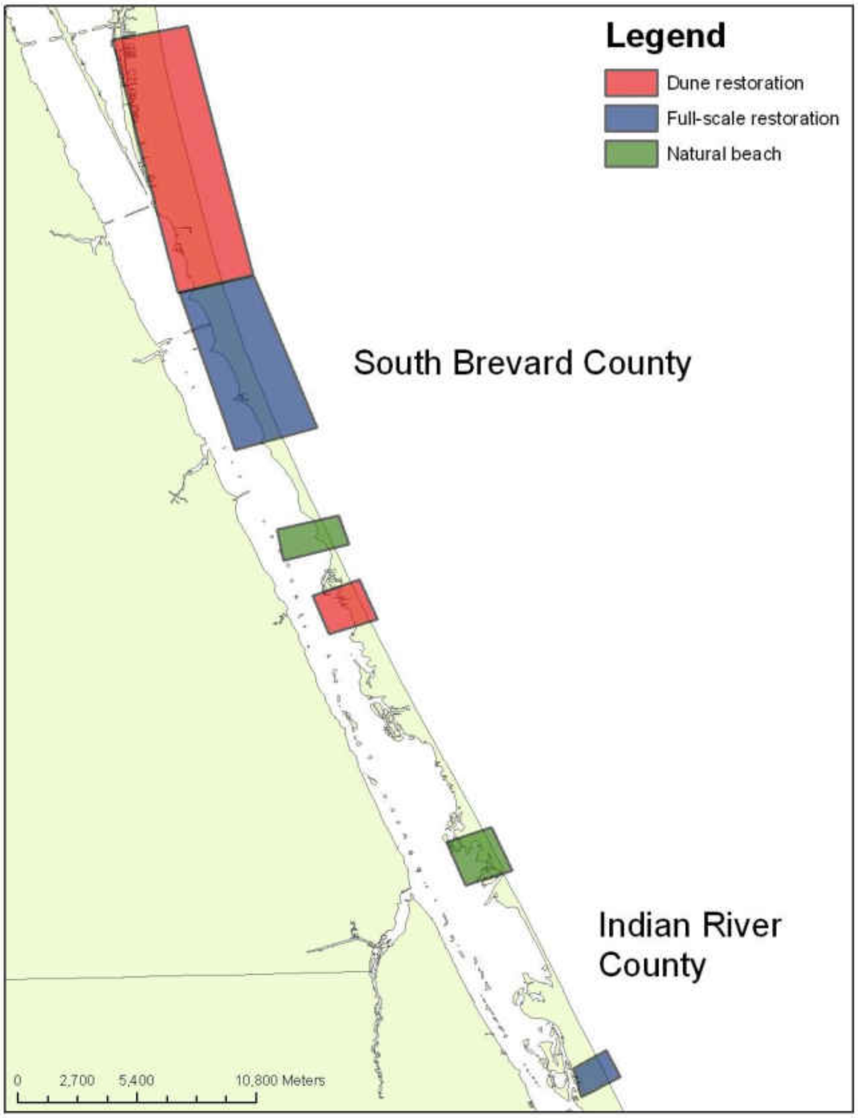


Figure 3.1 Study sites in Brevard and Indian River Counties

Data collection

I collected environmental data along selected turtles' tracks nightly from May – August 2010. After observing an emerging turtle in one of the study sites, I stayed far enough away so as not to disturb her. Once she began egg deposition, I collected sand samples from the water line to the nest site using the incoming crawl as a transect (Wood and Bjorndal 2000). I took surface sand every 1.5 m from where the turtle emerged to just before the point at which she started to body pit, which is the start of egg deposition (the turtle pushes aside loose sand at the surface to create a depression for herself before digging an egg chamber). Additionally, I collected sand samples from the top of the nest chamber and from just in front of the head of the turtle. I took a straight line measurement from the water line to the base of the dune and used a clinometer to profile the beach. I took profile readings every 1.5 m until just landward of the point at which the turtle nested, then I took readings in 10 m increments to the base of the dune.

If I observed an emerging turtle and then saw her turn back to the water before depositing eggs, as long as there was no obvious reason for her return (e.g., she encountered an obstacle, people approached her, etc.), I collected data from her crawl in the same manner as with nesting turtles. However, I only collected data from turtles that false crawled without beginning the nesting process (i.e., they returned to the water without digging a body pit or an egg chamber). Once the turtle begins digging, a new suite of potential cues may be introduced. Examining only turtles that did not start to dig allowed me to focus on the cues that initiate the start of the nesting process.

After each turtle finished nesting or was clearly returning to the water after an aborted nesting attempt, I inserted unique Inconel flipper tags into both front flippers in conjunction with a single passive integrated transponder (PIT) tag in the right front flipper. This allowed me to maintain independence in my sampling.

I marked each nest to monitor its incubation. Three days after a hatchling emergence, I dug up the contents and enumerated the number of hatched and unhatched eggs, eggs damaged by a predator, live and dead hatchlings, and live and dead pipped (the hatchling started to hatch but was still in the egg). From these, I calculated both measures of reproductive success. The calculation for hatching success is displayed in equation 3.1 and emergence success in 3.2:

$$\frac{number\ hatched}{total\ number\ of\ eggs\ deposited} \times 100 \tag{3.1}$$

$$\frac{number\ emerged}{total\ number\ of\ eggs\ deposited} \times 100 \tag{3.2}$$

Sand analyses

Moisture content

Moisture content is the ratio of the mass of water to the mass of dry soil, which can also be expressed as the percent of water on a dry-weight basis (Klute 1986). I obtained a wet mass by weighing (±0.1 g) sand samples immediately after returning to the field station (within eight hours of collection). I dried the sample to a constant mass to determine dry weight and calculated moisture using equation 3.3.

$$\frac{wet\ mass - dry\ mass}{dry\ mass} \times 100 \tag{3.3}$$

Grain size

I followed the methods described by Head (1984) to calculate grain size. I only sieved one soil type, so I used a short set of sieves (Head 1984) with mesh sizes of 2 mm, 1 mm, 0.425 mm, 0.25 mm, 0.15 mm, and 0.075 mm. I weighed the sand remaining in each sieve (±0.1 g) after a mechanical sand shaker shook the stack of sieves for 10 minutes. Before sieving the sand, I combined samples from the turtle's track to represent a larger beach width. The first sample contained sand from the water to 3.0 m up the crawl, and the second sample contained sand from the median 3.0 m of the crawl. I sieved the sand taken from the cloaca and head positions separately.

I calculate particle size with equation 3.4 and used the program GRADISTAT (Blott and Pye 2001) to calculate the mean grain size for each sample

$$\frac{mass\ passing\ the\ sieve}{total\ initial\ mass} \times 100 \tag{3.4}$$

Analyses

Nests and false crawls

I used forward stepwise logistic regression model selection to determine what beach characteristics determined whether or not a turtle nested. Prior to the analyses, I created a collinearity matrix with a cutoff of 0.85 to remove collinear variables. For the first analysis, predictors entered into the model included: beach slope, beach width, distance turtle traveled, the slope at the head position of the turtle, moisture content at the head position, and grain size at the head position. For the second analysis, I included the same variables as well as the type of beach (FSR, DR, or natural).

I measured the distance each turtle traveled in addition to the straight line measurement from the water to the egg chamber. I used a Student's *t*-test to compare nest and false crawl lengths within study sites and one-way ANOVAs to compare nest and then false crawl lengths among sites. I also calculated a straightness index, which is the distance traveled divided by the straight line distance.

I graphed the crawl transect data in a variety of ways to determine trends between nests and false crawls within and among study sites. For elevation, slope, and moisture content, I divided each crawl into quarters and averaged the sampling points within each quarter. This allowed me to examine crawls of different lengths and compare what individual turtles experienced during each quarter of their crawl. Since I combined samples for the grain size analysis, I present data from the start of the crawl, the median of the crawl, and the head position of the turtle.

To determine statistical significance, I used a Student's *t*-test to compare the values at each quarter between nests and false crawls. I also used a single factor ANOVA to compare values in each quarter among nests and then among false crawls. After all analyses, I used Holm's test to adjust the *p*-values for multiple comparisons.

Additionally, I determined the change in elevation between sampling points. I started at the head position of the turtle and moved along the transect towards the water, calculating the difference in beach height between one sampling point and the sample 1.5 m seaward. The head position served as a common reference point among crawls so that I could compare crawls of different lengths. I used the length of the shortest crawl as the length for all crawls in a study site (i.e., if the shortest crawl was 10 m, I only used the final 10 m, starting at the head, of a longer crawl).

Reproductive success

I used forward stepwise regression to determine the effects of beach characteristics on hatching and emergence success. Before running the analysis, I created a collinearity matrix with a cutoff of 0.85 to remove collinear variables. Variables entered into the model included sand moisture content, sand grain size, slope at the nest position, distance traveled, and beach width.

Results

Nests and false crawls

I analyzed data from a total of 19 nests and 7 false crawls in the two natural sites (10 nests and 5 false crawls in the first replicate, 9 nests and 2 false crawls in the second), 17 nests and 6 false crawls in the DR sites (8 nests and 2 false crawls in the first replicate, 9 nests and 4 false crawls in the second), 5 nests and 8 false crawls in the FSR:sloped site, and 9 nests and 4 false crawls in the FSR:flat site. Sample sizes for each analysis are included in figures but are sometimes smaller than that which is listed here due to problems in data collection (e.g., sand spilled during drying precluded an accurate moisture content, so that sample was removed from that analysis).

Logistic regression model selection

Both analyses resulted in R^2 values of 0.75. The best-fit models included all predictor variables, mainly as interaction terms (Tables 3.1 and 3.2). Likelihood ratio tests determined each term's contribution to the model; the most important term in the first analysis, which excluded beach type as a predictor, was the interaction of beach slope, head slope, and distance traveled ($\chi2= 32.95$). The interaction of beach type, head slope, beach width, moisture content, grain size, and distance traveled had the highest $\chi2$ (24.53) in the second analysis. In both models, the terms with a positive estimate, where higher predictors are associated with a greater likelihood of nest deposition, included interactions of several variables (Tables 3.1 and 3.2). Table 3.3 shows the $\chi2$ values of individual variables in the model; the only statistically significant predictors were head slope (p=0.03) and moisture content (p=0.03). I also chose specific models and ranked them by AICc. These also show the importance of interaction terms and are illustrated in Appendix B.

Table 3.1. Best-fit model for nest site selection excluding beach type as a predictor variable

Term	**Estimate**	**Standard Error**	**Likelihood Ratio χ2**	**Prob> χ2**
Head slope	-1.50	0.58	12.64	0.0004*
Beach slope*Head slope	0.87	0.42	15.68	<.0001*
Head slope*Moisture content	-0.73	0.39	5.99	0.0144*
Head slope*Beach width*Moisture content	-0.08	0.06	7.38	0.0066*
Grain size	-11.56	6.75	4.98	0.0256*
Beach slope*Distance traveled	-0.32	0.14	15.03	0.0001*
Beach slope*Head slope*Distance traveled	0.25	0.12	32.95	<.0001*
Grain size*Distance traveled	1.73	0.94	10.21	0.0014*
Beach slope*Beach width*Grain size*Distance traveled	0.09	0.06	9.97	0.0016*
Beach slope*Head slope*Beach width*Grain size*Distance traveled	-0.07	0.04	16.62	<.0001*

* Denotes significance at 0.05. + estimates indicate a positive relationship between the term and the chance of nesting. Head slope is the slope at the head position of the turtle while beach slope is the overall beach slope (from the water to the base of the dune) where she nested.

Table 3.2. Best-fit model for nest site selection including beach type as a predictor variable.

Term	**Estimate**	**Standard Error**	**Likelihood Ratio χ2**	**Prob> χ2**
Beach type	2.40	2.06	1.85	0.1738
Beach type*Head slope*Beach width	0.26	0.18	4.69	0.0303*
Beach type*Moisture content	-5.53	2.90	16.05	<.0001*
Beach width*Moisture content*Grain size	-0.20	0.13	4.30	0.038*
Beach type*Beach slope*Distance traveled	-0.59	0.33	7.78	0.0053*
Beach type*Beach width*Distance traveled	-0.09	0.05	5.91	0.015*
Beach type*Beach slope*Moisture content*Distance traveled	-0.75	0.38	24.53	<.0001*
Grain size*Distance traveled	0.19	0.94	0.04	0.8408
Beach type*Grain Size*Distance traveled	-2.52	1.13	8.04	0.0046*
Beach type*Head slope*Beach width* Moisture content*Grain size*Distance traveled	0.36	0.18	30.71	<.0001

*Denotes significance at 0.05. + estimates indicate a positive relationship between the term and the chance of nesting. Head slope is the slope at the head position of the turtle while beach slope is the overall beach slope (from the water to the base of the dune) where she nested. Beach type is natural, DR, or FSR.

Table 3.3. Likelihood ratio tests for predictor variables in logistic regression.

Variables	**Likelihood Ratio χ2**	**Prob> χ2**
Head slope	4.64	0.0312*
Moisture content	4.58	0.0324*
Beach type	2.89	0.2351
Distance traveled	1.73	0.1887
Beach slope	1.03	0.3099
Grain size	0.03	0.8655
Beach width	0.00	0.9518

Straightness index and distance traveled

Nesting crawls were not significantly longer than false crawls. Turtles that nested traveled a mean of 21.7 m (SD=6.9) while false crawling turtles traveled a mean of 17.2 m (SD=9.3) Nest and false crawl lengths among sites were not statistically significant. Additionally, turtles traveled in relatively straight lines from the water to the dunes, with an average straightness index of 0.94 for nests and 0.93 for false crawls (Table 3.4).

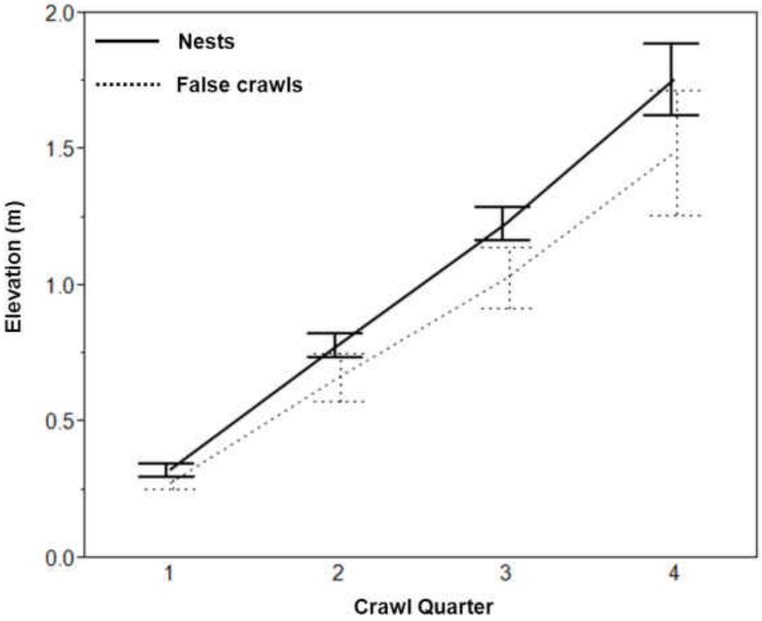
Table 3.4. Distance traveled and straightness index by beach type.

	Nests			False crawls		
	n	**Distance traveled (m)**	**Straightness index**	**n**	**Distance traveled (m)**	**Straightness index**
All natural	19	19.66	0.97	7	15.56	0.95
All dunes	17	20.84	0.95	6	12.51	0.98
FSR:flat	9	22.52	0.94	4	15.59	0.85
FSR:sloped	5	23.76	0.88	8	25.22	0.94
Average	--	21.69	0.94	--	17.22	0.93

Trend analysis: crawl quarters

Beach elevation/slope

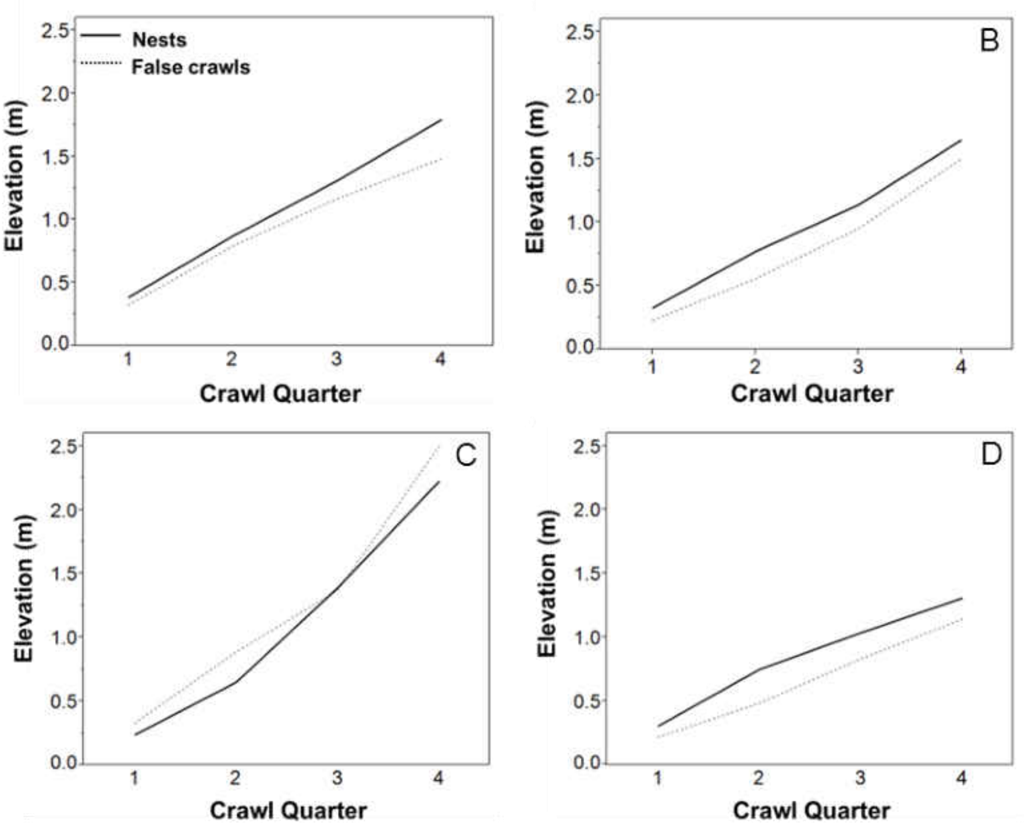
The pooled nest and false crawl data from each study site (n=6) revealed a trend of an increase in beach elevation as turtles crawled landward. There was also a trend of turtles nesting in areas of higher elevation than where they false crawled (Figure 3.2). The mean heights for nesting crawls during the first through fourth quarters, respectively, were 0.3 m (standard deviation (SD=0.1), 0.8 m (SD=0.1), 1.2 m (SD=0.1), and 1.8 m (SD=0.3). For false crawls, the mean height at each quarter, starting at one and ending at four, was 0.3 m (SD=0.1), 0.7 m (SD=0.2), 1.0 m (SD=0.3), and 1.5 m (SD=0.6). The difference in heights at nests compared to false crawls was not statistically significant in any of the quarters



Sample size = 6. Error bars show standard error

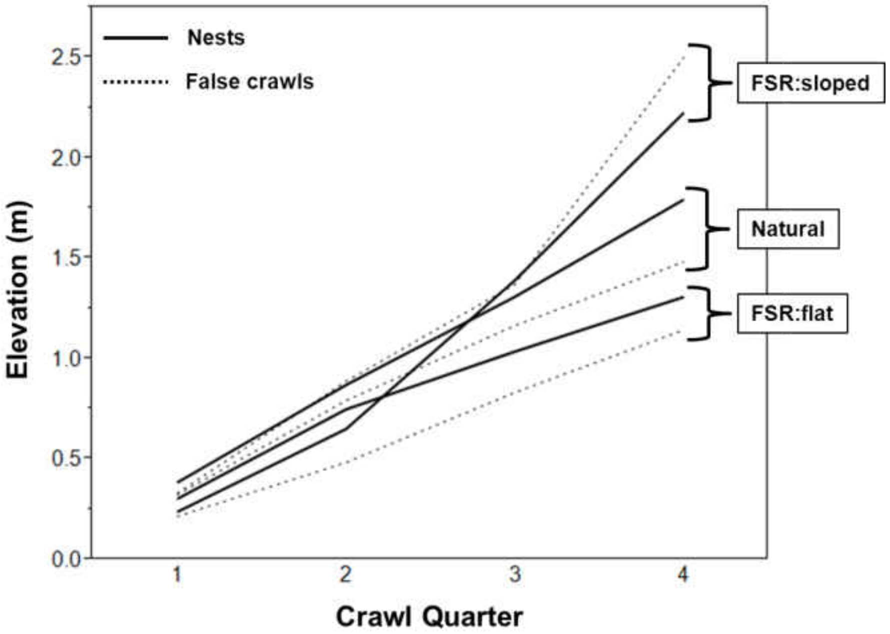
Figure 3.2. Pooled elevation of nests and false crawls at all study sites (n=6).

Figure 3.3 shows the elevation changes by treatment. The FSR:sloped site (Figure 3.3C) was the only beach where turtles false crawled at higher elevations than where they nested. Figure 3.4 illustrates the differences in elevation among the natural beaches and the FSR sites, which had the most distinct profiles. A one-way ANOVA among these three beaches revealed that there was not a statistically significant difference among nests or among false crawls in any of the quarters.



Sample size for natural (18 nests, 7 false crawls), DR (16 nests, 6 false crawls), FSR:sloped (5 nests, 8 false crawls), FSR:flat (8 nests, 4 false crawls)

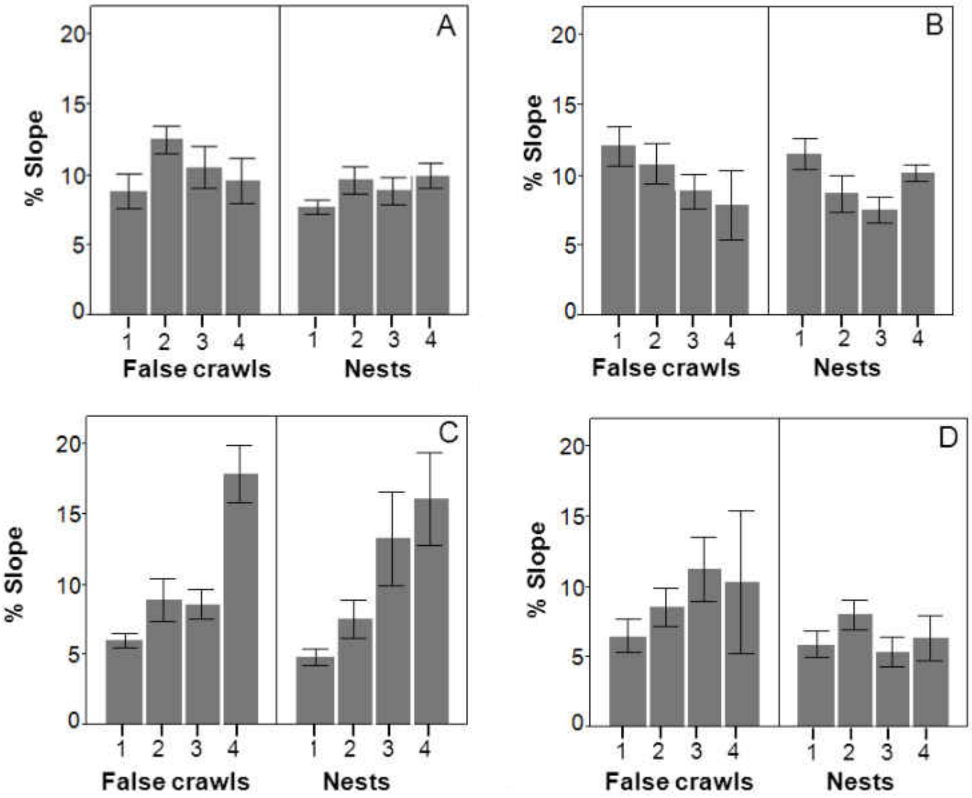
Figure 3.3 Elevation of nests and false crawls at A) natural sites, B) DR sites, C) FSR:sloped , and D) FSR:flat



Sample size for natural (18 nests, 7 false crawls), FSR:sloped (5 nests, 8 false crawls), FSR:flat (8 nests, 4 false crawls)

Figure 3.4. Changes in elevation among nests and false crawls at natural and FSR sites.

The percent slope of each crawl quarter on each treatment is illustrated in Figure 3.5 and Appendix B. For all nesting crawls, turtles emerged in areas with a mean slope of 6.7% (SD=2.4); the mean slopes in the second, third, and fourth quarters, respectively, were 9.0% (SD=4.1), 8.3% (SD=4.7), and 10.3% (SD=4.8). For false crawls, the mean slope in the first quarter was 7.2% (SD=2.6), the second was 9.8% (SD=3.5), the third was 9.8% (SD=3.4), and the fourth was 12.4% (SD=7.2).

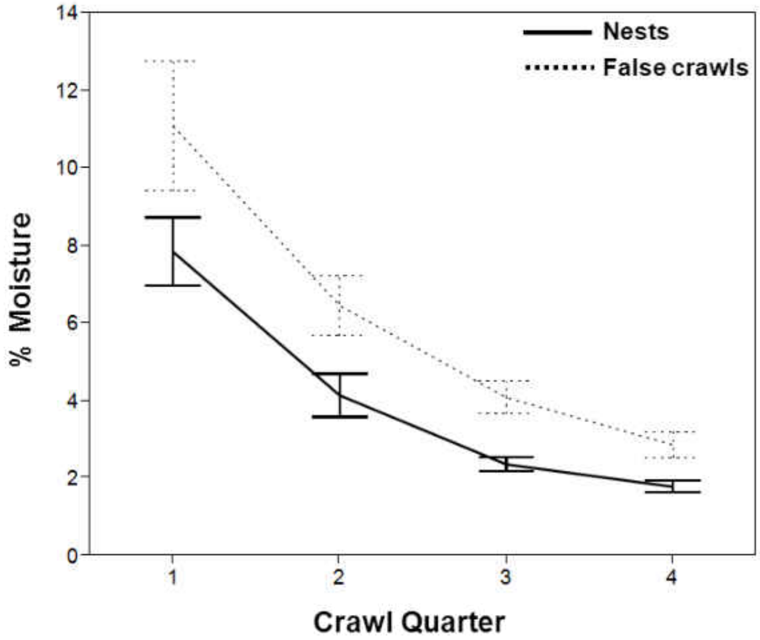


Sample size for natural (18 nests, 7 false crawls), DR (16 nests, 6 false crawls), FSR:sloped (5 nests, 8 false crawls), FSR:flat (8 nests, 4 false crawls). Error bars show standard error.

Figure 3.5. Mean percent slope for each quarter for false crawls and nests on A) natural sites, B) DR sites , C) FSR:sloped, and D) FSR:flat .

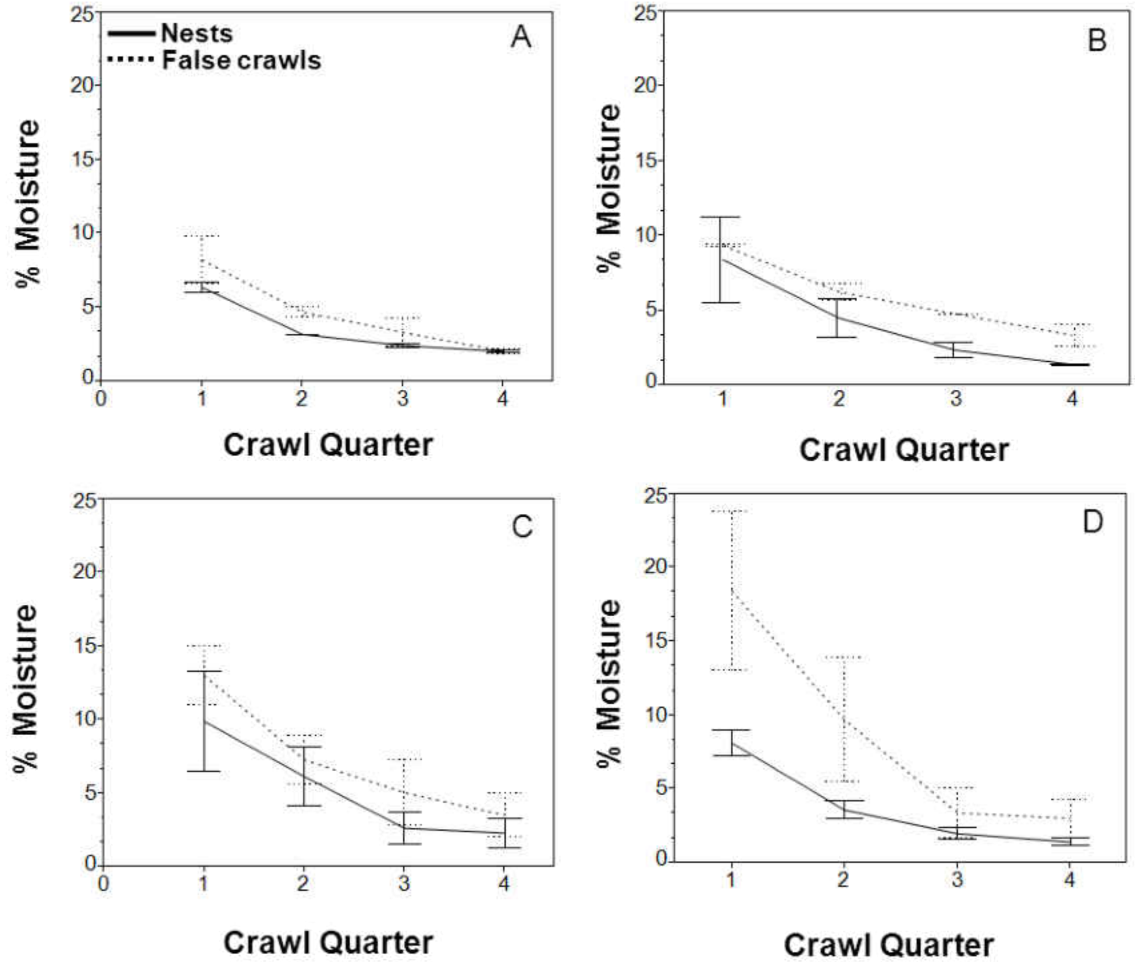
Moisture content

An analysis of pooled nest and false crawl data from each study site (n=6) revealed a trend of decreasing moisture content as turtles crawled landward, which was expected (Figure 3.6). Additionally, nests occurred in drier areas than false crawls, a trend that remained consistent in each quarter (Figure 3.6) and was statistically significant during the third (p=0.02) and fourth (p=0.04) quarters. This trend was evident in all treatments (Figure 3.7).



Sample size = 6. Error bars show standard error.

Figure 3.6. Pooled moisture content of nests and false crawls at all study sites.



Sample size for natural (19 nests, 7 false crawls), DR (17 nests, 6 false crawls), FSR:sloped (4 nests, 6 false crawls), FSR:flat (9 nests, 4 false crawls). Error bars show standard error.

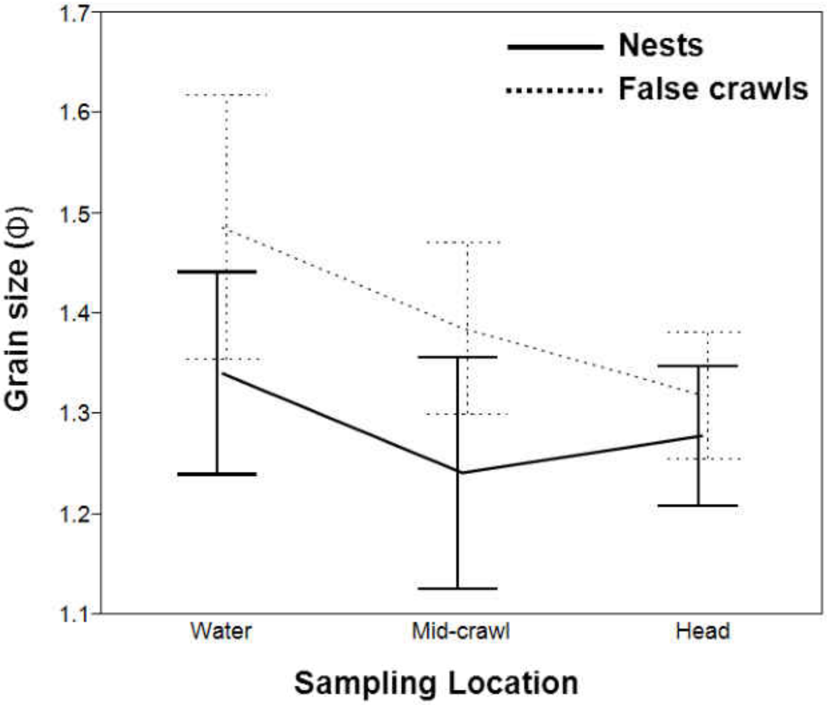
Figure 3.7. Moisture content of nests and false crawls at A) natural sites, B) DR sites, C) FSR:sloped, and D) FSR:flat.

The mean moisture contents during nesting crawls, starting in the first quarter and ending in the fourth quarter, were 7.8% (SD=2.2), 4.1% (SD=1.4), 2.4% (SD=0.4) and 1.8% (SD=0.4). False crawls had mean moisture contents, starting in the first quarter and moving to the fourth, of 11.1% (SD=4.1), 6.5% (SD=1.9), 4.1% (SD=1.0), and 2.9% (SD=0.8).

Grain size

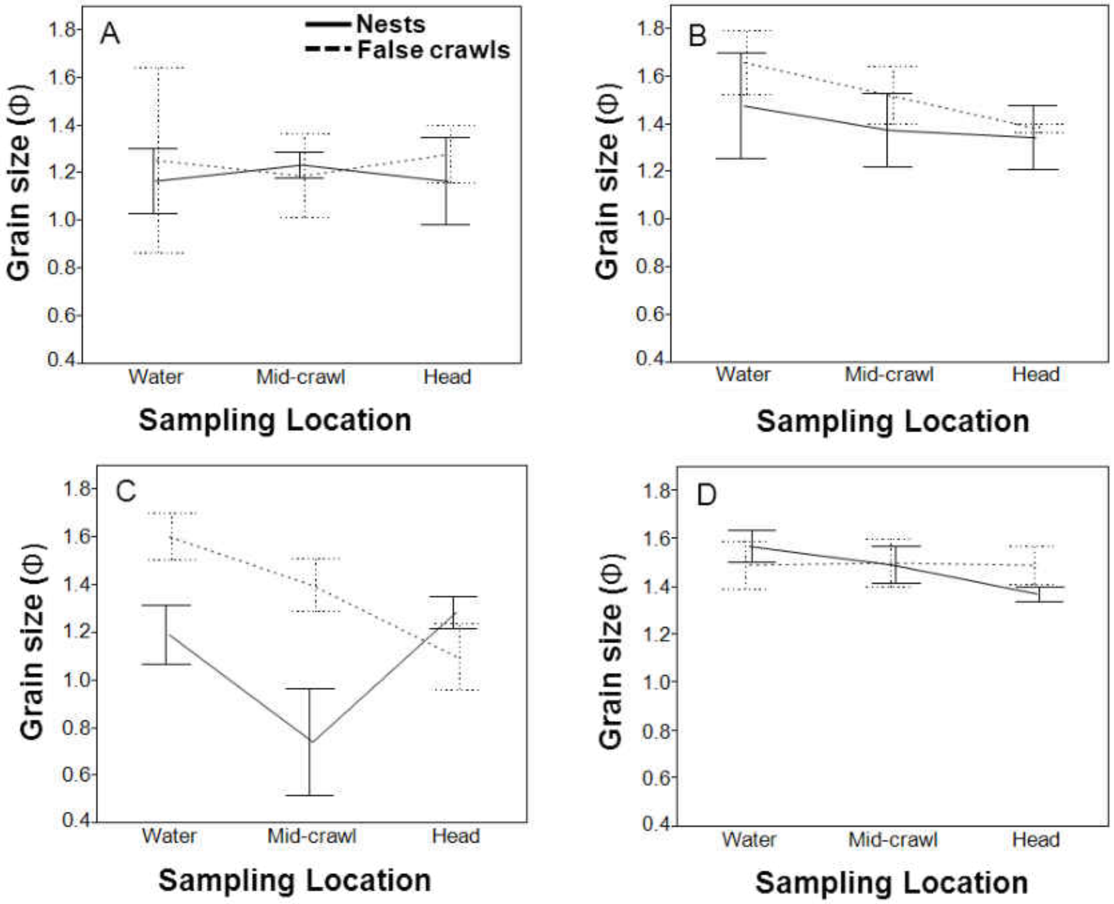
To analyze grain size, I used the Wentworth Grade Scale, which provides a description of particle size (e.g., clay) as well as measurements in mm and phi (ϕ) units. Phi is on a logarithmic scale and is commonly used because it expresses particle size in units of equal value. The grain size (diameter) increases as ϕ decreases (Flugel 2004).

The pooled nest and false crawl data from each study site (n=6) show the average grain size was larger throughout false crawls than nesting crawls, although this difference was not statistically significant (Figure 3.8). This pattern was not consistent among treatments (Figure 3.9). For nesting crawls, the sites closest to the water had an average grain size of 1.3ϕ (SD=0.2) the median site had a mean grain size of 1.2ϕ (SD=0.3) and the head position had a mean grain size of 1.3ϕ (SD=0.2). For false crawls, sites closest to the water had a mean of 1.5 ϕ (SD=0.3), the median site averaged 1.4ϕ (SD=0.2), and the head position averaged 1.3ϕ (SD=0.2).



Sample size=6. Error bars show standard error.

Figure 3.8. Pooled grain size (Φ) along nests and false crawls at all study sites.



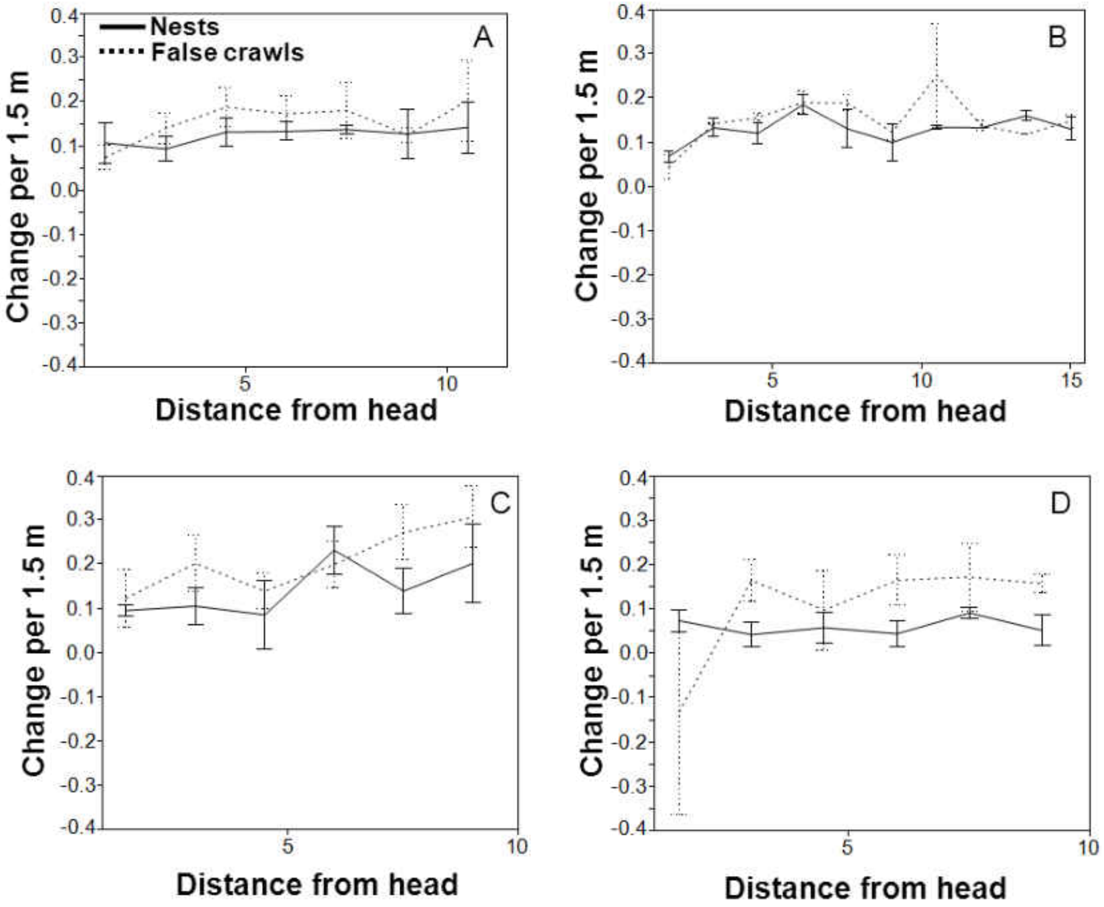
Sample size for natural (18 nests, 7 false crawls), DR (17 nests, 6 false crawls), FSR:sloped (5 nests, 8 false crawls), FSR:flat (9 nests, 4 false crawls). Error bars show standard error.

Figure 3.9. Grain size (Φ) of nests and false crawls at A) natural sites, B) DR sites, C) FSR:sloped, and D) FSR:flat site.

Trend analysis: rate of change

Elevation

In all beaches, the change in elevation in the final five meters of false crawls decreased (Figure 3.10). In nesting crawls, the change in elevation just before the nest site stayed flat or increased except in the DR beaches.



Sample size for natural (18 nests, 7 false crawls), DR (16 nests, 6 false crawls), FSR:sloped (5 nests, 8 false crawls), FSR:flat (8 nests, 4 false crawls). Error bars show standard error.

Figure 3.10 Rate of change in elevation of nests and false crawls at A) natural sites, B) DR sites, C) FSR:sloped, and D)FSR:flat.

Reproductive success

Tables 3.5 and 3.6 show the best-fit models for hatching and emergence success, respectively. The adjusted R^2 for hatching success was 0.44 and 0.45 for emergence success. I expected the two models to be similar; they had three overlapping terms, two of which were the most significant terms in both models (interaction of moisture content and nest slope and the interaction of moisture content, distance traveled, and nest slope). Positive estimates, where higher values are associated with a greater likelihood of higher reproductive success, were also the same in both models (distance traveled and the interaction of moisture content and nest slope).

Table 3.5. Best-fit model for hatching success.

Term	**Estimate**	**Standard Error**	**F Ratio**	**Prob>|t|**
Distance traveled	0.01	0.01	4.47	0.0427*
Moisture content*Distance traveled	-0.01	0.01	2.22	0.1467
Beach width	-0.01	0.00	3.29	0.0792
Moisture content*Nest slope	0.03	0.01	9.86	0.0037*
Moisture content*Distance traveled*Nest slope	-0.01	0.00	9.05	0.0052*

Nest slope is the slope at the nest location. * Denotes significance at 0.05. + estimates indicate a positive relationship between the term and hatching success.

Table 3.6. Best-fit model for emergence success.

Term	**Estimate**	**Standard Error**	**F Ratio**	**Prob>|t|**
Moisture content	-0.05	0.03	2.45	0.1277
Distance traveled	0.01	0.01	3.19	0.0843
Grain size*Distance traveled*Beach width	0.00	0.00	3.64	0.0662
Moisture content*Nest slope	0.04	0.01	17.14	0.0003*
Moisture content*Distance traveled*Nest slope	-0.00	0.00	4.98	0.0332*

Nest slope is the slope at the nest location. * Denotes significance at 0.05. + estimates indicate a positive relationship between the term and emergence success.

Discussion

Nests and false crawls

Beach shape

While the majority of sites showed a trend of nesting crawls occurring higher in elevation throughout the crawl than false crawls, the FSR:sloped site displayed the opposite trend (Figure 3.3). Additionally, the difference in elevation between crawl types and among sites was most distinct during the fourth quarter (Figure 3.4). These data indicate that there was an ideal range of nesting elevation, which was most evident towards the end of the crawl. Too much or too little height, especially during the fourth quarter of the crawl, was less conducive to nesting.

However, elevation by itself did not likely serve as a cue, but rather its relationship with beach slope. Higher elevations did not necessarily indicate steeper slopes; since I averaged elevation data by quarter, crawl distances were not explicitly taken into account. For example, at the FSR:flat site, the average elevation in nests was higher, but the slope was steeper in false crawls (Figure 3.3D, 3.5D). This was the result of shorter false crawls relative to nests; although the elevation was higher along nesting crawls, each quarter was also longer, which made the slope more gradual.

On all beaches except the FSR:sloped site, mean slope decreased between the third and fourth quarters in false crawls (Figure 3.5), which means the beach flattened out in the fourth quarter. At the FSR:sloped site, there was instead an increase in slope between the third and fourth quarters, indicating a steep rise in the beach profile. In crawls that resulted in nests, there was also an increase in slope between the third and fourth quarters, though none so drastic as the increase seen in false crawls at the FSR:sloped site. These results indicate that the last half of the crawl was important in determining whether a turtle nested. If the beach flattened out or rose too steeply during the final quarter, turtles were less likely to nest, while if the beach was steeper during the final quarter compared to the third quarter, turtles were more likely to nest,

For a fine-scale look at where these changes in beach shape occurred, I examined the difference in elevation between sampling points along the crawl transect For nests laid in the natural and FSR sites, the change in beach height between sampling points in the last five meters was relatively consistent. The fairly flat line representing nests in natural and FSR sites (Figure 3.10) indicates that the beach was rising at approximately the same rate between sampling sites towards the end of the crawl.

Conversely, the line representing false crawls slopes downward in the final five meters, illustrating the beach shape getting flatter (Figure 3.10). At the FSR:flat site, the height is negative at the final sampling point, indicating that the beach sloped backwards between the head position and the next sampling site. At the FSR:sloped site, even though the slope was steeper in the fourth quarter (Figure 3.5), the beach still flattened out towards the end of non-nesting crawls (Figure 3.10). Most of the turtles that false crawled at this site began climbing a steep dune, then turned back to the water at or near the top of the dune. The steep dune caused the slope of the final quarter to be steeper than the slope of the third quarter, but the dune rose less sharply towards the top of the dune. This is seen in the decreased change in elevation that occurred between sample sites towards the end of the crawl (Figure 3.10).

These results indicate that finding a beach slope most conducive to nesting is more complex than determining a single range of acceptable slopes. Although a more gradual slope appeared to be more conducive to nesting than a short, steep slope, there was overlap in nest and false crawl slopes throughout each crawl quarter (Appendix B). It seems that the relationship between changes in slope towards the end of the crawl is more important than the overall beach slope. For instance, if a turtle is crawling on a beach with a 5% slope, an increase to an 8% slope could provide the signal to nest. However, a turtle crawling on a beach with an 8% slope that decreases to a 5% slope would not receive the appropriate cue to nest.

These findings could clarify some contradictory results concerning beach slope in the literature. Provancha and Ehrhart (1987) described a "preferred" nesting beach, based on high and low density nesting, as steeply sloped (15.8% ±3.5%). This is contradictory to Garmestani *et al*. (2000), who found high loggerhead nesting densities on wider, flatter beaches. Both studies examined overall slopes without studying changes in slope along the beach width, which could be significant for determining if a turtle nests or not.

Sand characteristics

Moisture content and grain size did not have as much of an impact on nest site selection as beach shape. Trends across the beach width in moisture content occurred as expected, with moisture content decreasing as turtles traveled away from the water. The trend of drier sand throughout nesting crawls likely corresponds to differences in crawl lengths. False crawls were almost 5 m shorter than nesting crawls, so they were in wetter areas. It is unlikely that the gradient of decreasing moisture content served as more than a coarse scale cue. It seems reasonable that turtles could notice an obvious change in moisture content, such as that which they experience in the swash zone, where they are in wet sand and are being hit by waves, compared to the dry sand mid-way up the beach. However, it seems unlikely that they could cue into very specific changes in moisture.

Grain size naturally decreases from the water to the dune (Edwards 2001), which is the opposite of what I observed (as ϕ decreases, grain size increases). This is likely due to two reasons. The first is that I averaged my sampling points; if I had used each sample rather than combining them, it is possible that I could have observed the natural trend. Additionally, tidal cycles during data collection could have played a role. Turtles that emerged at low tide emerged in finer sand than those that emerged at higher tides, where wave action deposits more shells. Although I did not observe the trend I expected, the differences in particle size are small, never moving out of the range described in the Wentworth Scale as medium sand. As with moisture content, it seems probable that a turtle could notice large scale changes, such as the difference between shells and silt, but it seems unlikely that a turtle could notice minor changes in grain size while crawling up the beach.

While these characteristics do not appear to serve as initial nesting cues, it is likely that they play a role later in the nesting process. For example, when a turtle digs the egg chamber, sand that is too dry can collapse the chamber, which could impact whether a turtle continues digging or returns to the water before depositing eggs.

Multiple cues

The best-fit logistic regression model, excluding beach type as a predictor, included all variables, mainly as interaction terms, indicating that beach profile, width, moisture content, and grain size all served as nesting cues (Table 3.1). Although the best-fit model in the second analysis also included all variables, it had the same R^2 value, indicating that beach type by itself did not help further explain the model (Table 3.2).

Likelihood ratio tests helped tease apart the results and determined each term's contribution to the model. In both analyses, the high chisquare values associated with interaction terms (first analysis: interaction of beach slope, head slope, and distance traveled; second analysis: interaction of beach type, head slope, each width, moisture content, grain size, and distance traveled), compared to the lower chisquare values of individual predictors, indicate that interactions among variables were more important than individual predictors in nest site selection. Additionally, only slope at the head position and moisture content were significant on their own, whereas all but one interaction term (grain size and distance traveled in the second analysis) in both analyses were significant (Tables 3.1-3.3).

The positive estimates associated with interactions of beach slope, beach width, head slope, distance traveled, moisture content, grain size, and beach type indicate an increased chance of nesting as those characteristics increased. Since these are interaction terms, we cannot determine their exact relationship, but it appears that variables associated with the beach shape and width play an important role in determining if a turtle nested, in conjunction with sand characteristics, to a lesser degree.

Wood and Bjorndal (2000) suggested that turtles selecting a nesting site could follow a stepwise series of cues, passing the threshold of one characteristic before cueing into the next. Based on these results, a change in moisture content could provide the first broad-scale cue. Although it is unlikely that a turtle notices minute changes, it is likely that she could recognize a difference when she crosses from very wet sand in the swash zone into drier sand. Once a turtle passes a moisture content threshold, these results indicate that she could then cue into the shape of the beach. Increases in slope (as long as they are not too drastic), could provide the signal to nest, while decreases in slope could provide the signal to return to the water.

Reproductive success

The relationship between nest site selection and reproductive success rates is not as straightforward with marine turtles as with avian species. The beach is subject to varying environmental conditions, which can significantly impact the nesting environment throughout the approximately 50-day incubation period. While a relationship should exist between where the nest was laid and its reproductive success, I expect that other variables, such as those that affect gas exchange, are more important in reproductive success than those the nesting turtle uses to choose a nest site (Mortimer 1990).

The best-fit models for both hatching and emergences success were similar, and the most important term for both was the interaction of moisture content and slope at the nest chamber (Tables 3.5 and 3.6). There were also marginally positive estimates associated with this interaction and distance traveled. This makes intuitive sense for distance traveled, as the further landward a nest was deposited, the less chance it had of being inundated by tides, which can lower reproductive success by impeding gas exchange. The positive estimate associated with the interaction of moisture content and nest slope was less clear, as there is a range of acceptable moisture contents that preclude desiccation or inundation; however, the estimate for this term is very small (0.03 for hatching success and 0.04 for emergence success), which could take that into account. These data indicate that variables important in nest site selection do also play a role in the reproductive success of the nest.

Conclusion

I elucidated characteristics that initiate loggerhead nesting by examining nests and false crawls on beaches with varying types of construction. While the logistic regression best-fit model included all variables, I found the most distinct differences in trends between nests and false crawls in analyses of elevation and slope. The data indicate that loggerheads preferred longer, more gradual slopes to short, steep slopes. Perhaps more important than the overall slope were changes during the second half of the crawl, where false crawling turtles generally encountered a flatter beach while nesting turtles encountered a more sloped beach. On a fine-scale, changes in profile within five meters of the nest site appeared to serve as nesting cues, with a decreased rate of change generally resulting in false crawls. Other variables could play a role in nest site selection on a more broad-scale; a gradient in decreasing moisture content further from the ocean could provide an initial cue, and once the turtle reaches drier sand, she cues into changes in slope. Variables important in nest site selection, specifically the slope, distance traveled, and moisture content were also important in determining reproductive success.

This study was the first to provide data about loggerhead nest site selection by studying both successful and unsuccessful nesting attempts on beaches with different templates. As such, it provides valuable insight into how to nourish beaches in a manner more conducive to loggerhead nesting; most notably by providing more slope mid-beach as turtles enter the crucial third and fourth quarters of the crawl. This study provides the framework for more research that continues to examine differently shaped beaches to try to determine the relationship among the beach slopes most conducive to nesting.

CHAPTER 4: GENERAL DISCUSSION

Loggerheads

Since the 1980s, studies have documented a temporary decrease in loggerhead nesting success after full-scale restoration (Raymond 1984, Steinitz *et al*. 1998, Herren 1999, Rumbold *et al*. 2001, Brock *et al*. 2009). However, none have examined the effects of alternate template designs on nesting success or determined the mechanism behind this decline. Without learning why nesting loggerheads are impacted by an altered shoreline, we do not have the data needed to engineer beaches in a more "turtle-friendly" manner.

My first study showed that full-scale and dune restoration affected nesting loggerheads to different degrees. There was a significant difference in deltas, due to a decreased nesting success rate at engineered sites, during the years of construction and one year post-construction for both designs. Effect sizes between the two engineered sites were similar during the years of construction, but the effect size during the first year post-construction was significantly stronger after full-scale restoration than after dune restoration. This indicates that loggerheads were sensitive to changes in both engineered beaches, but something about full-scale restoration caused them to be negatively affected for longer than they were after dune restoration.

The objective of the second study was to provide the mechanism behind the decreased nesting success rates by determining what beach characteristics serve as nesting cues. I found that beach elevation and slope were the most important nesting cues. When each crawl was divided into quarters, loggerheads nested more often in areas with longer, more gradual slopes, and the slope of the first half of the crawl did not appear to be as important as the slope at the end of the crawl. In all study sites, there was an increase in slope between the third and fourth quarters of crawls that resulted in nests, whereas there was generally a decrease in slope between the third and fourth quarters of unsuccessful nesting attempts. The slope itself may not have been as important as the change in slope; if the beach slope kept increasing after the turtle completed three-quarters of the crawl, the turtle was more likely to nest. It seems likely that the turtles cue into a different characteristic(s) during the beginning of the crawl, only cueing into slope after passing a threshold from the prior characteristic(s) (Wood and Bjorndal 2000). My results indicate that the initial signal could be moisture content; once the turtle reached drier sand than what was found in the swash zone, she cued into slope. However, other variables that I did not examine could also be important (i.e., sand temperature) (Wood and Bjorndal 2000).

This study helped elucidate the mechanism behind the decrease in nesting success rates observed in the first study. If increases in slope were key to initiating the start of the nesting process, the flat berm built during full-scale restoration provided little opportunity for an increase in slope. Alternately, dune restoration more closely followed the shape of a natural beach, which could explain the smaller effect size one year post-restoration. A better understanding of the relationship between slopes that initiate nesting would provide data needed to build dunes that are more conducive to loggerhead nesting. Although full-scale restoration beaches are generally built with little to no slope, a more sloped beach could provide habitat more favorable for loggerhead nesting. Increasing the slope mid-beach, when turtles enter the crucial second half of the crawl, could provide the appropriate nesting cue. This study provides the framework for more research to design experiments with the purpose of finding slopes that are the most conducive to loggerhead nesting.

Both studies also examined hatching and emergence success. The first analysis showed that neither type of restoration caused a significant change in either measure of reproductive success. Other studies have documented varying impacts on reproductive success post-construction (reviewed in Brock *et al*. 2009). Although there were no changes in reproductive success, I did have a small sample size.

In the second analysis, I determined if characteristics that served as nesting cues were important in reproductive success. Since a turtle has a limited ability to assess how the environment will change during incubation, it has been suggested that a gravid female may choose a nest site based on her survival rather than that of her offspring (Bjorndal and Bolten 1992). Model selection found the best-fit models included all terms that were also included in nest site selection, with the interaction of moisture content and slope at the nest chamber as the most significant term. These results indicate that there is overlap in beach characteristics that serve as nesting cues and those that result in higher reproductive success.

Green turtles

This was only the second study to examine the impacts of full-scale restoration on green turtle nesting and reproductive success (Brock *et al*. 2009) and the first to look at the impacts of dune restoration. There was no pattern to changes in green turtle nesting success rates after dune restoration. Similar to loggerhead results, something about the full-scale restoration was less conducive to nesting than dune restoration; during the five seasons between full-scale restoration projects, nesting success rates never recovered statistically. This lack of a tendency for nesting success rates to recover between projects could result in permanently altered nesting patterns; after an initial full-scale restoration project, beaches are re-engineered every three to ten years (Weggel 1995). It is critical that an experiment similar to the one I did for loggerheads is performed to determine how to engineer beaches that do not impact green turtle nesting so negatively.

There was not a significant change in hatching or emergence success rates post-restoration. However, as with loggerheads, the sample size was very small.

Summary

Results from these analyses of loggerhead nesting provide data needed to start experimenting with methods to engineer more “loggerhead-friendly” nesting beaches. I also showed that green turtle nesting patterns could be altered if a design more conducive to green turtle nesting is not developed. Both studies fill gaps in the literature concerning beach restoration and provide the framework for additional studies to continue providing data about the relationship between nesting turtles and beach characteristics.

APPENDIX A: TEMPORAL AUTOCORRELATION

Methods

In Chapter 2, I compared nesting and reproductive success rates at a Control (natural beach) compared to two Impact sites (FSR and DR). As part of the nesting success analysis, I used GS+ (Gammadesign software, version 9) to test for temporal autocorrelation in the historical dataset (1997-2001). Temporal autocorrelation occurs when measured variables are more similar when closer in time and less similar when further apart in time (Legendre 1993). I expected to find similar results among the three sites; however, this was not the case.

Results

Figures 5.1 and 5.2 illustrate temporal autocorrelation rates that occurred in the three study sites from 1997-2001. For both loggerheads and green turtles, there was a clear pattern of autocorrelation present in the Control site at approximately 20 days. However, this pattern was not present in either Impact site for either species.

A.

B.

C.

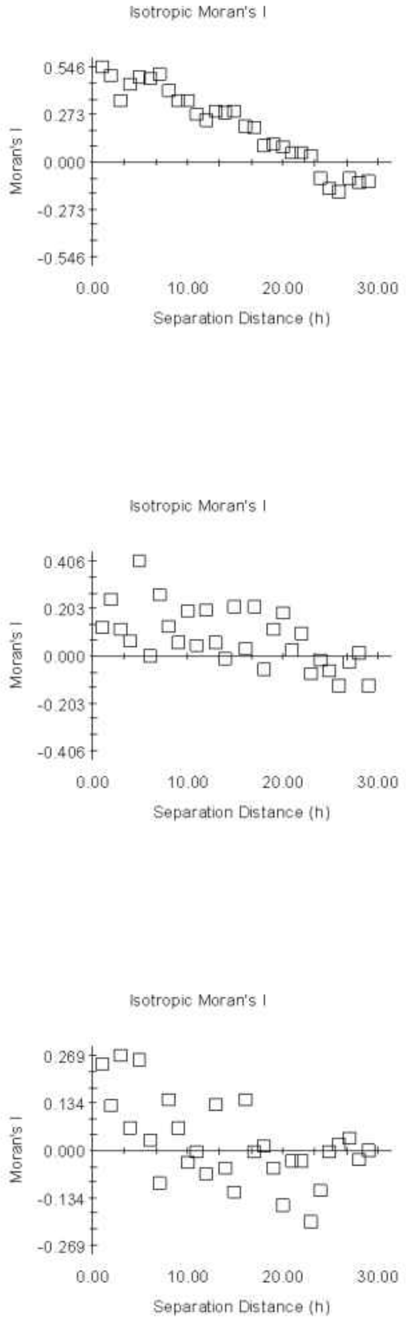


Figure 5.1. Historical loggerhead nesting success rate autocorrelation results at each study site: A) Control, B) DR, and C) FSR

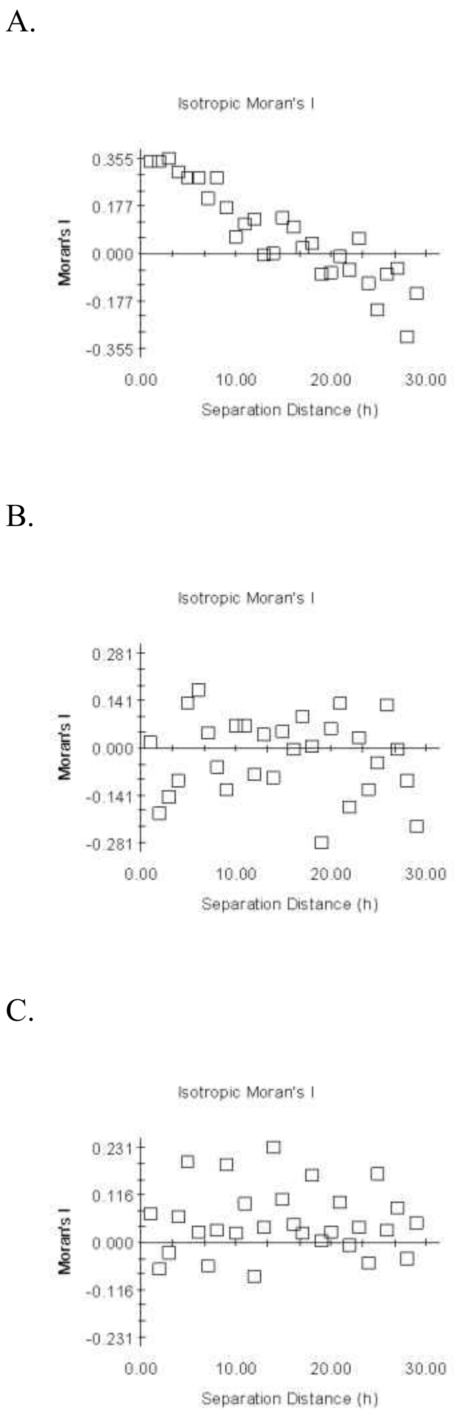


Figure 5.2. Historical green turtle nesting success rate autocorrelation results at each study site: A) Control, B) DR, and C) FSR

Discussion

The test for temporal autocorrelation yielded some unexpected results, as one would expect to find similar degrees of autocorrelation among the three sites prior to restoration. The main difference between the Control and the two Impact sites during the historical time period is the degree of development along the coastline. The shoreline along the Control has been less developed than the other two sites, consisting mainly of single-family residences interspersed with patches of vegetated, undeveloped areas. The FSR and DR sites have historically been more highly developed areas fronting condominiums, hotels, and single family residences. Since temporal autocorrelation was only present in the less developed site, it is possible that unnatural factors in the developed areas, such as a human influence, interrupted the nesting pattern, causing the difference in results.

People on the beach can impact marine turtle nesting by approaching turtles prior to egg deposition, which can cause a non-nesting emergence. In addition, although Witherington (1992) found no direct effects of mercury vapor lights on whether loggerheads and green turtles nested after emerging above the high tide line, he did note the possibility of an indirect effect of lighting. On a well-lit beach, turtles are more visible and more likely to be approached by people; conversely, turtles are more aware of people in their line of sight. Both people and artificial lighting are more prevalent in the highly developed FSR and DR sites, making it possible that these human influences interrupted the natural nesting pattern and ensuing temporal autocorrelation that was evident in the Control.

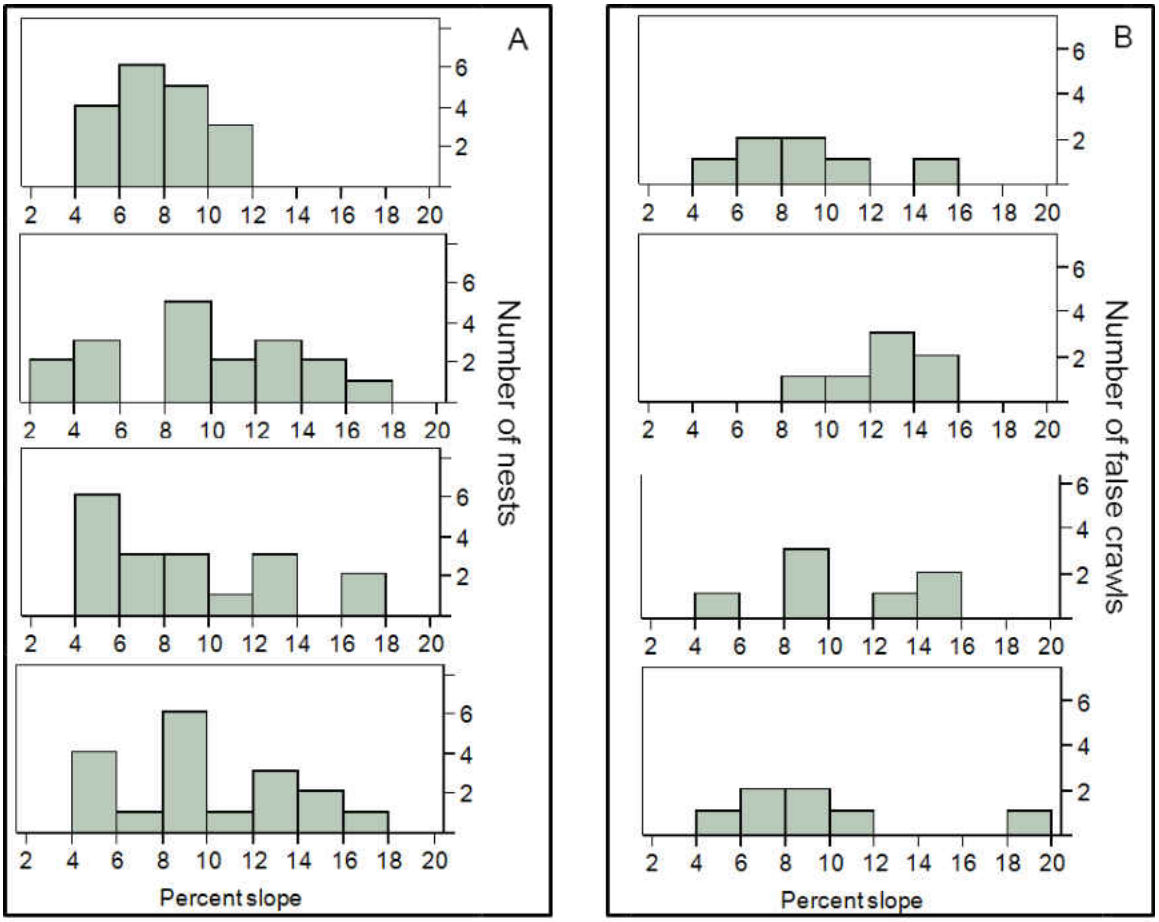
APPENDIX B: CHAPTER 3 ADDITIONAL TABLES AND FIGURES

Table 6.1. Top five models for nest site selection excluding beach type as a predictor variable

Models	**AICc**	**Prob>χ2**
Moisture content*Grain size*Head slope*Distance traveled	82.8568	0.3597
Grain size*Distance traveled	84.5295	0.0012*
Moisture content*Grain size	84.5896	0.0556
Moisture content*Head slope*Distance traveled	87.3221	0.6635
Moisture content	87.4952	0.0324*

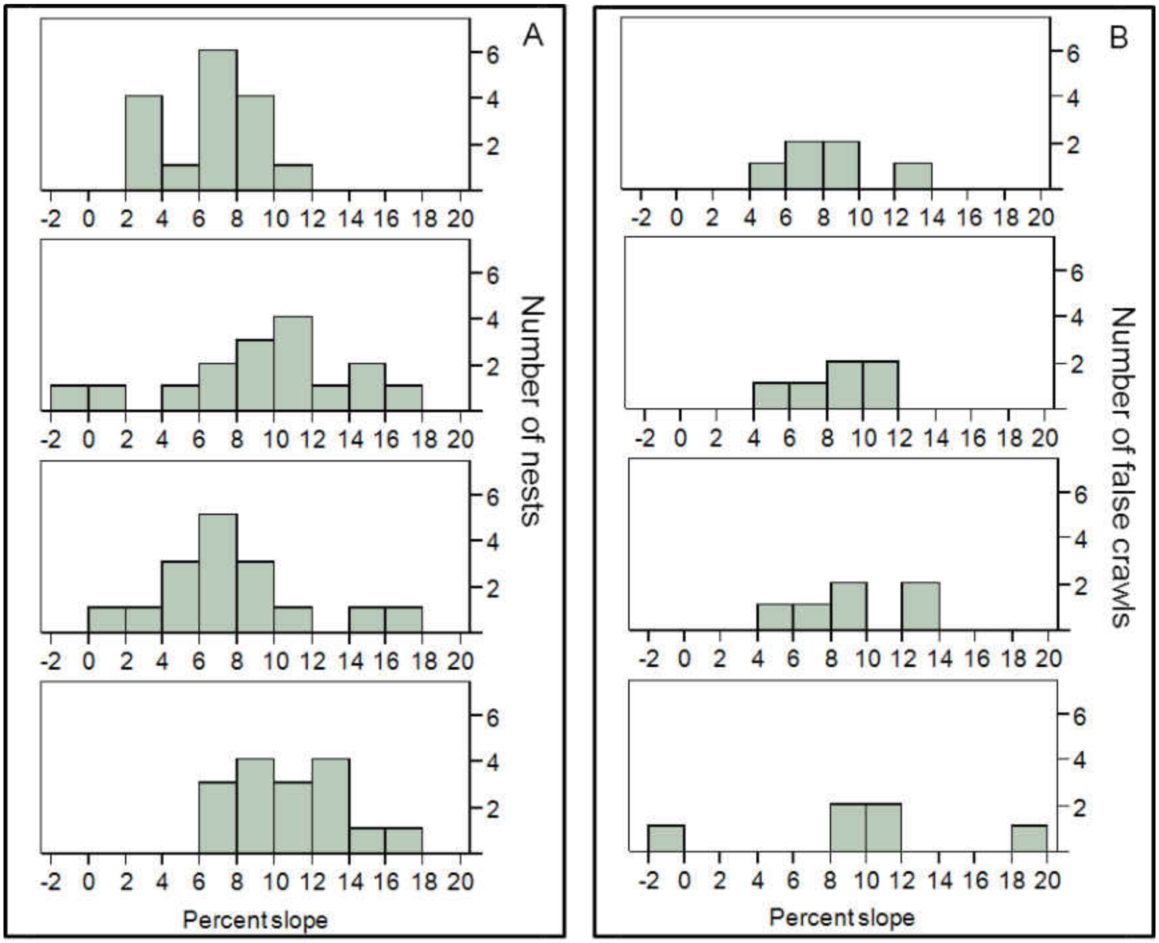
Table 6.2. Top five models for nest site selection including beach type as a predictor variable

Models	**AICc**	**Prob>χ2**
Beach type*Head slope*Moisture content	85.6449	0.0907
Beach type*Head slope*moisture content*grain size *Distance traveled	85.8628	0.0005*
Beach type*Head slope*Moisture content *Distance traveled	86.8033	0.2344
Beach type*Moisture content*Grain size	87.1235	0.1901
Moisture content	87.4952	0.0324*



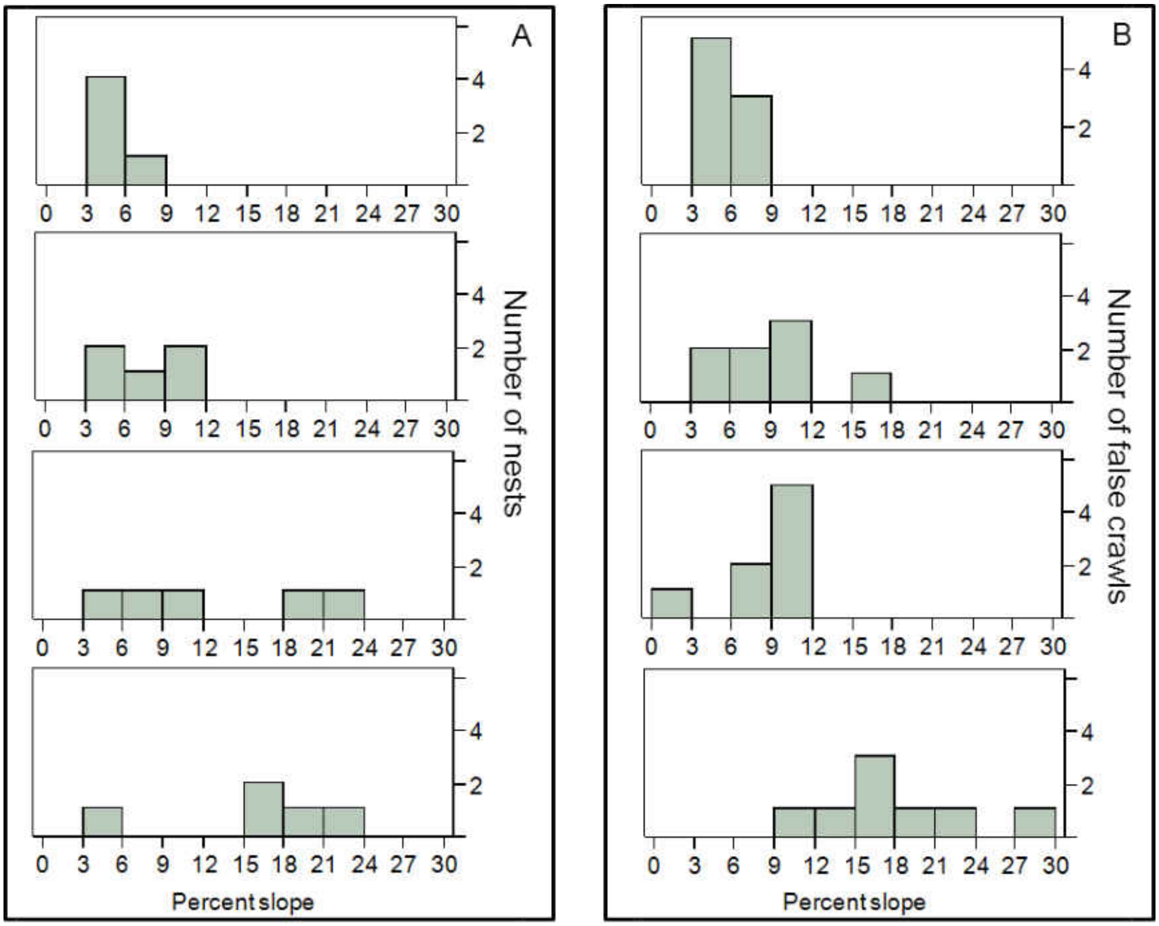
Histograms start with the 1st quarter at the top and continue in ascending order with the 4th quarter at the bottom.

Figure 6.1. Percent slopes for each quarter for A) nests and B) false crawls laid on natural beaches.



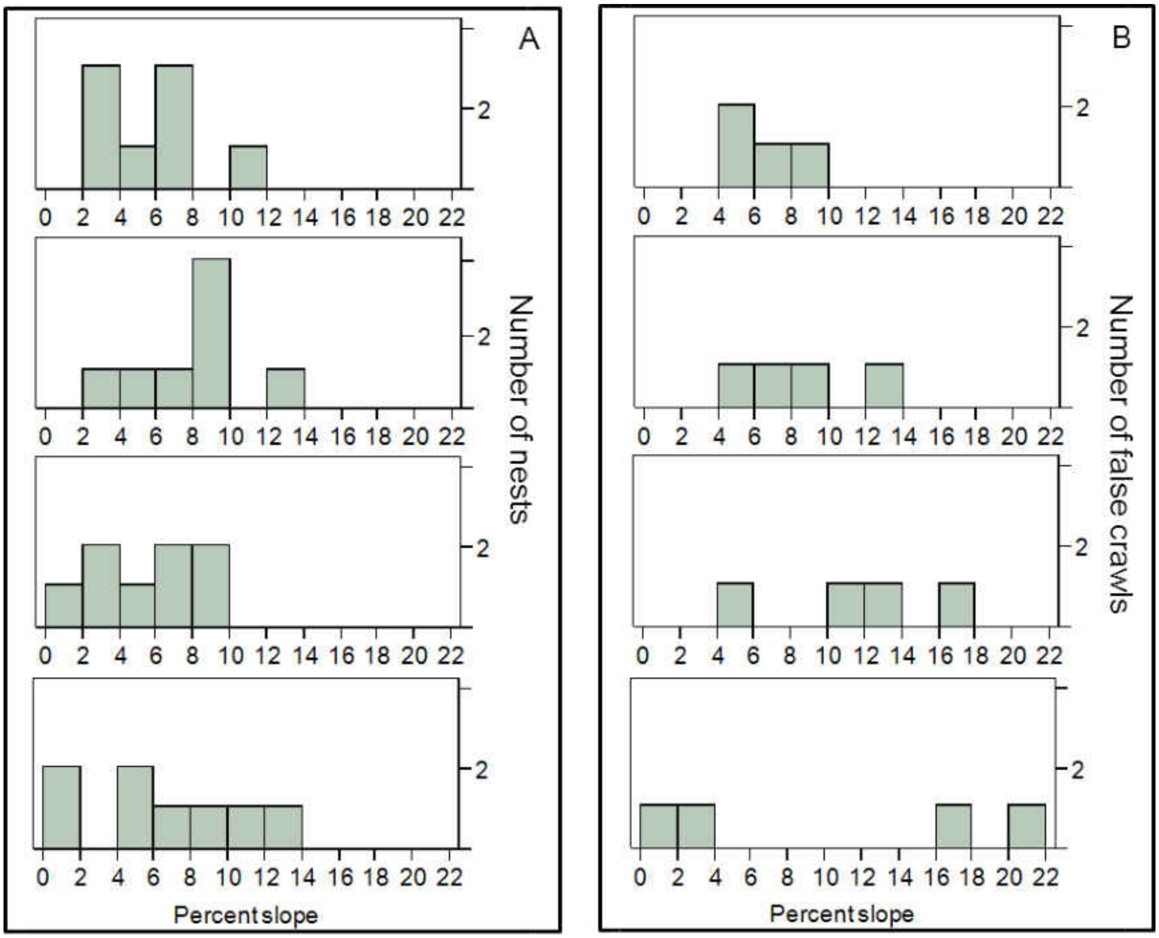
Histograms start with the 1st quarter at the top and continue in ascending order with the 4th quarter at the bottom.

Figure 6.2. Percent slopes for each quarter for A) nests and B) false crawls laid on DR beaches



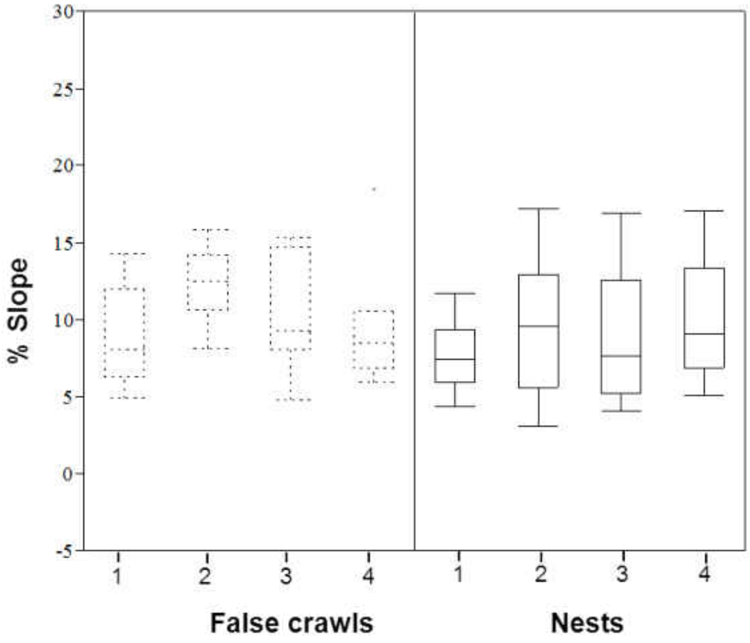
Histograms start with the 1st quarter at the top and continue in ascending order with the 4th quarter at the bottom.

Figure 6.3. Percent slopes for each quarter for A) nests and B) false crawls laid in the FSR:sloped site.



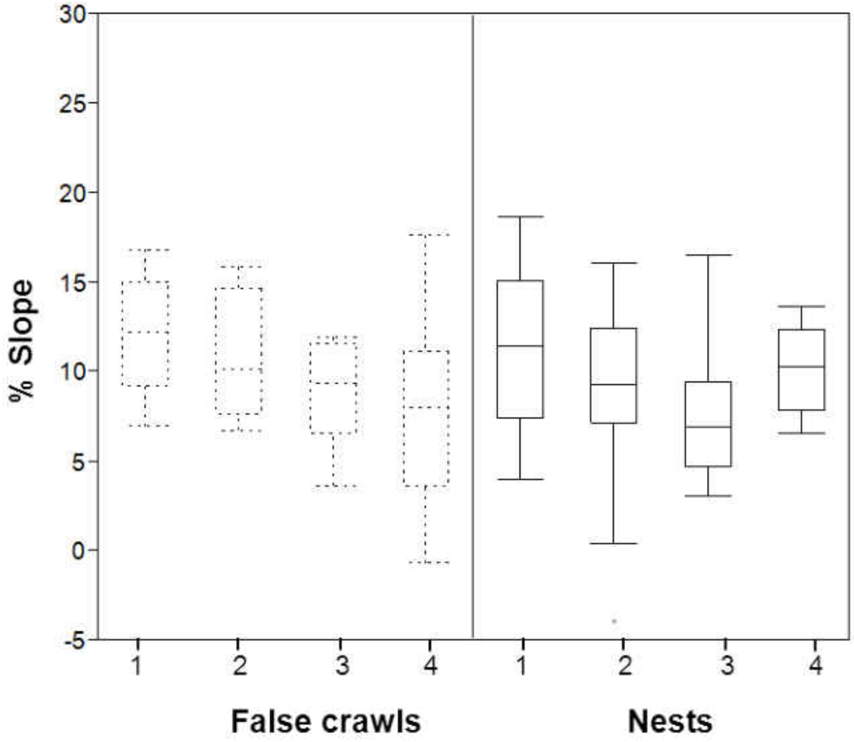
Histograms start with the 1st quarter at the top and continue in ascending order with the 4th quarter at the bottom.

Figure 6.4. Percent slopes for each quarter for A) nests and B) false crawls laid in the FSR:flat site.



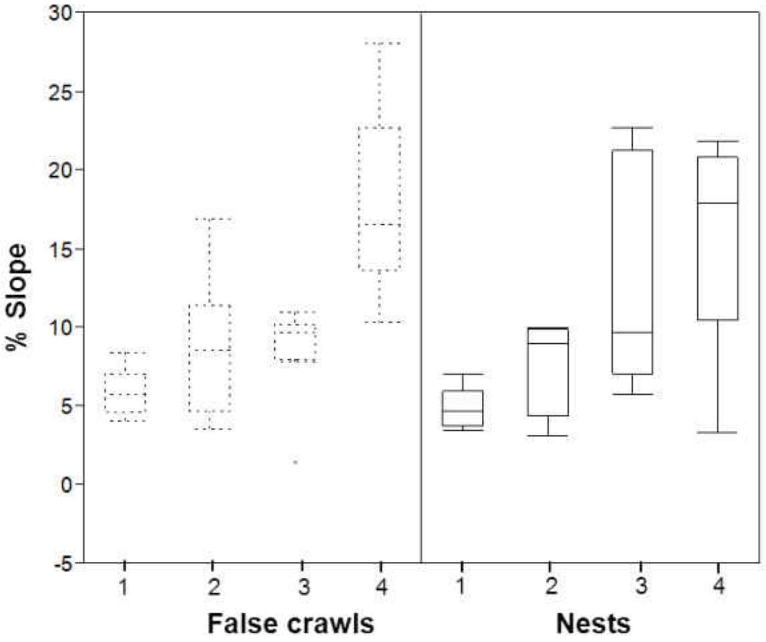
The boxes represent the middle quartiles, the line is the median, and the whiskers show the first and fourth quartiles. Single points show outliers.

Figure 6.5. Mean percent slope for each quarter for false crawls and nests laid on natural beaches.



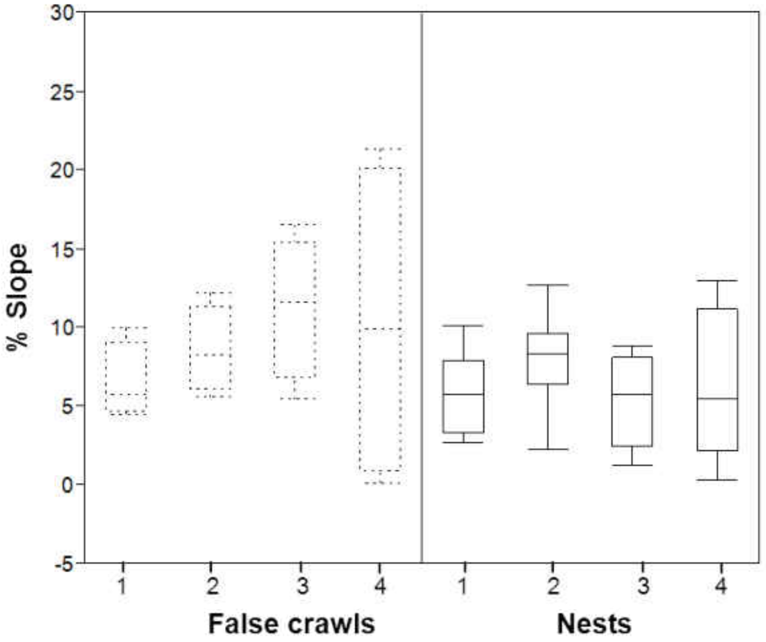
The boxes represent the middle quartiles, the line is the median, and the whiskers show the first and fourth quartiles. Single points show outliers

Figure 6.6. Mean percent slope for each quarter for false crawls and nests laid on DR beaches.



The boxes represent the middle quartiles, the line is the median, and the whiskers show the first and fourth quartiles. Single points show outliers.

Figure 6.7. Mean percent slope for each quarter for false crawls and nests laid at the FSR:sloped site.



The boxes represent the middle quartiles, the line is the median, and the whiskers show the first and fourth quartiles. Single points show outliers.

Figure 6.8. Mean percent slope for each quarter for false crawls and nests laid at the FSR:flat site.

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