THE EFFECT OF BEACH NOURISHMENT ON LOGGERHEAD SEA TURTLE (*Caretta caretta*) NESTING IN SOUTH CAROLINA

by

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A thesis submitted in partial fulfillment of the degree requirements for the
Master of Science in Environmental Studies at the
Graduate School – College of Charleston

December 2004

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ACKNOWLEDGEMENTS

I would like to thank my primary advisor, Dr. Robert Van Dolah, for his advice and guidance throughout my thesis research. I would also like to thank Dr. Mike Katuna, Sally Murphy, and Alan Shirey, my other committee members, for their help throughout many aspects of my graduate career. Partial funding was provided by the Army Corps of Engineers, Charleston District and funding for data loggers was supplied by South Carolina Department of Natural Resources.

I would also like to thank all of the employees and volunteers working on the turtle projects on Debordieu Beach, Kiawah Island, Hunting Island and Hilton Head Island. They were willing to share their data and time to help with my research. I especially would like to thank Betsy Brabson on Debordieu Beach, Jack Hamilton and Jim Jordan on Kiawah Island, Amanda Howard on Hunting Island, and Kim Washok-Jones and Ginger Martin on Hilton Head Island. I would also like to thank everyone at the Army Corps of Engineers, Charleston District for their support, Charlotte Hope of SCDNR for providing contact information for all of the turtle folks in South Carolina, and Mike Forte and the BERM project at Coastal Carolina University for providing all beach profile data. I would also like to thank Lisa McLean and Marty Levisen at SCDNR for helping with the grain size analysis and George Rierkerk for the use of statistical software. Finally, I would like to thank my family and friends for all of their understanding and support.

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ABSTRACT

Loggerhead sea turtles, *Caretta caretta*, nest on South Carolina beaches. Many of these beaches are periodically nourished as a temporary solution to fight beach erosion, improve shoreline stabilization, protect beachfront property, and restore habitat. Beach nourishment has the potential to help sea turtle populations by increasing nesting habitat that would otherwise be unavailable, but it can also change parameters of the natural beach that may affect nesting and reproductive success. This study determined the effects of nourishment on nesting loggerhead turtles in South Carolina. The study had three components: 1) to determine if nourishment affected nest density, false crawl density, and the nest to total crawl ratio by examining historic nesting data; 2) to determine if a partial nourishment project on Hunting Island, SC altered physical properties of the beach; and 3) to determine if beach slope influenced nest site selection.

Historic nesting and false crawl densities were significantly different between the nourished beaches and the Kiawah control beach, precluding meaningful comparisons among these beaches. Comparison of nesting and false crawl densities among nourished and control sections of the same beach showed no significant differences that could be related to nourishment. On one nourished beach, Debordieu, the nest to total crawl ratio increased after nourishment to levels comparable or above control sections of the beach. On another nourished beach, Hilton Head, the nest to total crawl ratio decreased after the nourishment and was not comparable to the control beach until three years after nourishment. Differences may be due to the amount of nesting habitat available prior to the nourishment, differences in the study sites, or differences in the nourishment projects.

Significant differences were found in sand temperature, compaction, grain size, and moisture content between the nourished and reference beaches on Hunting Island, SC. The nourished sand was warmer, more compact, had a coarser and wider grain size distribution, and had less moisture than the reference beach. However, many of these differences were small and may not be biologically meaningful. Differences found in temperature and compaction may have the potential to be biologically meaningful. One relationship was found between beach slope and total crawl density. However it was not biologically meaningful.

INTRODUCTION

All genera of sea turtles located in the Atlantic Ocean (*Caretta, Chelonia, Dermochelys*, *Eretmochelys*, *and Lepidochelys*) are listed as threatened or endangered by the U.S. Endangered Species Act (ESA) of 1973 (Meylan *et al.* 1995). The loggerhead, *Caretta caretta*, was listed under the threatened category of the ESA on July 28, 1978 (Federal Register, Volume 40, Number 98). There are two loggerhead subpopulations primarily nesting on the southern coastline of the United States, extending from North Carolina to southwest Florida (TEWG 2000 and Ehrhart *et al.* 2003). Another small nesting subpopulation is located on the Florida Panhandle (TEWG 2000 and Ehrhart *et al.* 2003). The southern Florida subpopulation appears to be stable or slightly increasing, with a 3.6% increase seen annually from 1989 to 1998 (TEWG 1998 and TEWG 2000). However, the northern subpopulation, extending from northern Florida to North Carolina has been declining since the early 1980's (Hopkins-Murphy *et al.* 2001). South Carolina alone has shown a 5% annual decrease between 1980 and 1987 (Hopkins-Murphy and Murphy 1988). This trend has continued with South Carolina loggerhead nest production falling to 3,000 nests per season by the end of the 1990's, compared to 5,600 nests per season as recently as 20 years ago (Sally Murphy pers. comm., Ehrhart *et al.* 2003). Due to the decrease seen in the northern subpopulation, it has become increasingly important to monitor this group's population dynamics.

Human activity on nesting beaches directly threatens all sea turtles and degrades their nesting habitat (Iocco 1998). Reduced availability and suitability of nesting habitat due to coastal development, beach modification, and erosion, among other factors, can adversely effect turtle populations (Hopkins and Richardson 1984). Beach nourishment is the placement of beach fill as a temporary engineering solution to erosion (Crain *et al.* 1995). Beach fill can be obtained from inland sources; estuaries, lagoons, or inlets on the backside of a beach; sandy shoals in navigation channels; nearshore ocean waters; or offshore ocean waters (Green 2002). The fill is placed on a beach and is graded to the desired profile. The primary goals of beach nourishment are to: increase shoreline stabilization, protect beachfront property, increase recreational areas, and restore habitat (Rumbold *et al.* 2001). However, it can also have adverse effects, disrupting existing biological communities in the subaerial, intertidal, and shallow subtidal zones of beaches (NRC 1995).

Beach nourishment has great potential to help threatened and endangered sea turtle populations by providing increased or improved nesting habitat that would otherwise be unavailable, especially in areas where beaches have eroded to the point where little nesting habitat was available prior to the nourishment (Ernest and Martin 1999). Crain *et al.* (1995) noted that turtle crawl and nesting numbers often increase after nourishment. While the quantity of nesting habitat is not a problem, the quality of beach habitat may be altered in ways that could adversely affect turtle nesting (Crain *et al.* 1995). Nourishment can alter a beach's sand density, compaction, shear resistance, moisture content, slope, sand color, grain size, grain shape, sand mineral content, and gas exchange (Nelson and Dickerson 1988a, Crain *et al.* 1995, and NRC 1995). Previous studies have found nourishment increased sand compaction (Raymond 1984, Ryder 1993, Steinitz *et al.* 1998, Ernest and Martin 1999, and Scianna 2002), moisture content (Ackermann 1991, Ackermann *et al.* 1992, Broadwell 1991, Ernest and Martin 1999, Herren 1999, and Parkinson *et al.* 1994), and sand temperature (Ackermann *et al.* 1992, Ernest and Martin 1999, Mihnovets 2003, and Mihnovets and Godfrey 2004) and altered grain size (Steinitz *et al.* 1998, Ernest and Martin 1999, and Herren 1999) and sand color (Mihnovets 2003, Mihnovets and Godfrey 2004).

These altered parameters may affect nesting females by altering their nest site selection, nest-chamber geometry, nest concealment (Crain *et al.* 1995), and may also influence the incubating environment of a nest, which may affect hatchling success (Rumbold *et al.* 2001) and hatchling sex ratios (Nelson and Dickerson 1988a and Ackermann 1991). Large scarps often form on recently nourished beaches, which can impede turtles from reaching nesting areas, increasing the number of false crawls (Raymond 1984, Ryder 1993, Crain *et al.* 1995, NRC 1995, Steinitz *et al.* 1998, Ernest and Martin 1999, Herren 1999, and Rumbold *et al.* 2001) or causing turtles to lay nests in unsuitable locations (below the escarpment) where nests have a greater potential to be overwashed (Steinitz *et al.* 1998 and Herren 1999).

Nest site selection influences both the proportion of crawls resulting in nests and reproductive success. Therefore, it is important to determine how beach nourishment affects loggerhead nest site selection. Before that can be done, the environmental cues used for nest site selection must first be understood. Nest site selection for sea turtles can be divided into three phases: beach selection, emergence of the female, and nest placement. Although it is not entirely clear how loggerheads select nesting beaches, each site typically meets specific requirements. It needs to be easily accessible from the ocean, be high enough to avoid being inundated frequently by high tides, have enough cohesive sand to allow nest construction, and the sand must facilitate gas diffusion and have temperatures conducive to egg development (Mortimer 1990). The turtle's beach selection and emergence may rely on these beach characteristics and other offshore cues (Wood and Bjorndal 2000). After a beach is selected and a female emerges, a specific nest site is chosen. In the absence of disturbance, loggerheads tend to lay nests in non-random patterns (Hays and Speakman 1993 and Mellanby *et al.* 1998). However, nest site selection is not completely understood and many of the studies on nest site selection have been contradictory (Miller *et al.* 2003).

Studies by Kikukawa *et al.* in 1998 and 1999, found that out of the 23 characteristics studied, the most important parameters in nest site selection were compaction of the sand, followed by distance from the nearest human settlement. Others have found that artificial lighting on the beachfront reduces the number of loggerheads relative to areas with little or no artificial lighting (Witherington 1992 and Ehrhart *et al.* 1996). In the Florida Keys, nesting turtles avoided areas backed by tall Australian pines (Schmelz and Mezich 1988). However, on an urban beach in Boca Raton, FL nests tended to be clustered in front of tall buildings, perhaps because they help block out the artificial lighting of the city (Salmon *et al.* 1995). Studies by Stoneburner and Richardson (1981) found an abrupt increase in sand temperature was associated with the onset of digging after turtles crawled up a beach. However, Wood and Bjorndal (2000) found no correlation between temperature changes and successful nesting events. Instead, they found that beach slope appeared to have the greatest influence on nest site selection (Wood and Bjorndal 2000). Other studies on loggerheads and hawksbills have also found beach slope to be a cue for nest site selection (Provancha and Ehrhart 1987, Horrocks and Scott 1991, and Wood 1998). In general, loggerheads seem to favor moderately sloped, narrower beaches backed by high dunes (Caldwell 1959). When beaches are nourished, they tend to be wider and flatter, which may influence nest placement. However, turtles may use multiple cues during the selection process (Wood 1998) and all of the environmental cues involved in nest site selection are still being determined.

Since beach nourishment can change physical and environmental parameters, it is important to determine what factors affect nest site selection, the proportion of crawls resulting in nests, and hatching success as well as how altered nesting substrates may affect all of these processes. This will help determine how to perform beach nourishment and other shoreline modification projects with the least effects on sea turtles. The main objective of my research was to determine if beach nourishment has a significant effect on loggerhead turtle nesting and beach characteristics in South Carolina. Most studies looking at beach nourishment effects on sea turtle nesting have been conducted in Florida on loggerheads from the south Florida subpopulation. There is a need for studies to be conducted on beach nourishment effects on nesting loggerheads in the northern subpopulation. To evaluate the possible effect of beach nourishment on nesting loggerheads in South Carolina, this study was divided into three components.

1) The objective of the first component was to determine if beach nourishment has an effect on the density of nests, false crawls (abandoned nesting attempts or non-nesting emergences), and the nest to total crawl ratio (number of nests/total

number of crawls) by examining historical data available for South Carolina beaches.

H_0: Beach nourishment has no significant affect on loggerhead nesting density, false crawl density, and the nest to total crawl ratio.

H_1: Beach nourishment has a significant affect on loggerhead nesting density, false crawl density, and the nest to total crawl ratio.

2) The objective of the second component was to determine if a recent partial nourishment project on Hunting Island (January - March 2003) altered physical properties of the beach.

H_0: Beach nourishment has no significant affect on sand temperature, compaction, color, grain size, and moisture content.

H_2: Beach nourishment has a significant affect on sand temperature, compaction, color, grain size, and moisture content.

3) The objective of the third component was to determine if beach slope influences nest site selection, perhaps leading to information regarding a potential “turtle-friendly” slope future nourishment projects could be based upon.

$H_{0:}$ Beach slope has no significant affect on loggerhead nest site selection on Kiawah and Hilton Head Island in South Carolina.

H_3: Beach slope has a significant affect on loggerhead nest site selection on Kiawah and Hilton Head Islands in South Carolina.

METHODS

Study Sites

Three beaches were chosen for the historical component of the project: Debordieu Beach, SC; Hilton Head Island, SC; (both nourished beaches); and Kiawah Island, SC (no true nourishment project; Figure 1). Debordieu Beach and Hilton Head Island were chosen since historical nesting data was available before and after nourishment operations. Kiawah Island served as a control beach because it represented a non-nourished natural beach system. All of these beaches are classified as either developed, when the entire zone contains human habitation, or mixed use, when developed areas are mixed with some natural beach. All three study sites had at least some residential homes and condominiums in close proximity to nesting beaches (Hopkins-Murphy *et al.* 2001). When analyzing nesting data, only the most recent nourishment projects were used due to constraints in reliable turtle nesting data.

Hunting Island was chosen for the second component of the project because it was the only beach nourished in the region during the time frame of my research. It was a small project, however, it was typical of a normal beach nourishment project. Kiawah and Hilton Head were used for the beach slope component of the project because complete nesting and beach profile data were readily available.

Debordieu Beach, SC

Debordieu Beach consists of a gated community with single-family residential homes and condominiums. The northern portion of the beach has dune fields and approximately twelve private homes. The southern portion of the beach is undeveloped and owned by the University of South Carolina (Hopkins-Murphy *et al.* 2001). There is a sea wall along the center of the beach that is approximately one third of the length of the beach (Hopkins-Murphy *et al.* 1999) and is an area of high erosion (Betsy Brabson pers.comm.). Debordieu was nourished in 1990 and 1998 (King 1999). The 1998 nourishment project is used in this analysis. This nourishment occurred in the winter and early spring of 1998, prior to the 1998 nesting season (Betsy Brabson pers. comm.). Approximately 250,000 cubic yards of sand were placed on the beach with the fill being trucked in from an inland source (King 1999). The nourished area of the beach was not tilled after the 1998 nourishment (Betsy Brabson pers. comm.).

Hilton Head, SC

Hilton Head is the largest barrier island on the South Carolina coast, with approximately 18.5 km of beach on the Atlantic Ocean and 7.2 km of beach on Port Royal Sound (Hopkins-Murphy *et al.* 1999). It contains gated communities, private homes, condominiums, and multi-story ocean front hotels. There are small pocket beaches on the northeast side of the island facing Port Royal Sound (Hopkins-Murphy *et al.* 2001). Hilton Head was nourished in 1981, 1990, 1997, and 1999 (King 1999). The 1997 nourishment project was used in this analysis. The 1997 nourishment was a large project placing approximately 2,961,700 cubic yards of sand onto the island's Atlantic shoreline and approximately 421,300 cubic yards on the Port Royal Sound shoreline (Olsen Associates, Inc. 1999). The beach fill for the Atlantic shoreline came from two offshore borrow sites: Joiner Banks shoals seaward of the north section of the island and Gaskin Banks seaward of the central portion of the island. The beach fill for the Port Royal shoreline came from the relocation of a marginal tide channel adjacent to the Port Royal shoreline. The nourished areas were interspersed throughout the beach. The 1999 beach nourishment was small, placing approximately 200,000 cubic yards of sand on the southern portion of the island (Olsen Associates, Inc. 1999). To make the interpretation of results simpler the area of beach nourished by the 1999 project was excluded from the analysis. The nourished areas of the beach in both 1997 and 1999 were not tilled after the nourishment projects were completed (Kim Washok-Jones pers. comm.).

<u>Kiawah Island, SC</u>

Kiawah Island is a gated, residential resort with 16 km of ocean facing beach. It is comprised of private homes, several golf courses, multi-story condominiums, and a county park. The beach is wide, flat, and fairly stable with well-developed dune fields. Homes are required to be 20-30 feet landward from the primary dune system (Hopkins-Murphy *et al.* 1999, Hopkins-Murphy *et al.* 2001, and Scianna 2002). In some areas, the beach is backed by multi-story condominiums and the Kiawah Inn. The southern part of the beach is a County Park with paid beach access and no beachfront structures (Hopkins-Murphy *et al.* 1999). Kiawah Island has never had a true beach nourishment project, although some limited beach scraping operations have been done on a short portion of the island. Therefore, Kiawah Island was used as one of the control beaches.

Hunting Island, SC

Hunting Island, SC is owned by the South Carolina Department of Parks, Recreation, and Tourism. It has approximately 6.4 km of highly erosional, ocean facing beach that is littered with fallen trees, remnants of a highway, and exposed marsh peat and stump (Hopkins-Murphy *et al.* 1999). There are a few cottages located adjacent to the nesting beach on the south end of the island and a campground located at the north end. Overall the beach is classified as mixed use, in large part due to the approximately 800,000 visitors per year (Hopkins-Murphy *et al.* 2001).

Hunting Island was nourished in 1968, 1971, 1975, 1980, 1991, and 2003 (King 1999). The 2003 nourishment project was analyzed for this portion of the research. This project was a partial nourishment, with approximately 230,200 cubic yards of sand placed in one section of the beach. It was done primarily to save a road that was overwashed and in danger of completely washing out (Alan Shirey pers.comm.). The study area was physically similar to nesting habitat that would be created by a normal beach nourishment operation. The sand for the nourishment came from an inlet that was dredged at the south end of the island. The project began January 15, 2003 and was completed March 6, 2003. Prior to nourishment, that portion of the beach was almost completely submerged at high tide, providing essentially no nesting habitat for sea turtles and could not be used as a control beach in this study. Instead, I used the southern end of the island as a control for measuring beach characteristics. This control location was chosen because it was the only place on the island (besides the newly nourished area) that was not submerged at high tide and because it had not been nourished in the recent past so it represented a natural beach system. The following beach characteristics were measured on both the nourished and control beaches: sand temperature, compaction, color, grain size, and moisture content.

Historical Study

Historical Evaluation Parameters

When evaluating the historical nesting data, three parameters were used, all of which influence overall nesting success. The parameters were: nest density, defined as the number of successfully laid clutches per unit distance; false crawl density, defined as the number of crawls per unit distance where no clutch was laid; and nest to total crawl ratio (number of nests/total number of crawls) per unit distance. The unit of distance used to calculate these densities varied for each study site, depending on the length of the beach and the size of the nourishment project being analyzed.

Turtle nesting data from each of the study sites has been obtained from permittees and compiled by the South Carolina Department of Natural Resources. During the turtle nesting season (approximately mid - May to early August) volunteers and employees walk the beaches looking for nests and false crawls. The location of each nest or false crawl is recorded based on its relationship to permanent beach markers located on each beach. The distance between beach markers varies for each study site. However, all of the markers are divided into 0.1, 0.2, or 1.0 mile increments, allowing for comparisons among beaches. To calculate densities, the number of nests, false crawls, or nest to total crawl ratio was calculated as a number per unit distance based on the beach markers. The unit distance was selected as large as possible to try and increase the number of nests per segment. However, the unit distance had to be small enough to give a minimum of three segments within each nourished area for statistical purposes.

Historical Study Comparisons

I made three comparisons for each of the nourished beaches. The first approach compared a nourished portion of each study site with the Kiawah Island beach control site that represented a non-nourished natural beach system. The second approach compared a nourished area of each beach with a control area (representing a non-nourished natural beach system) within that same beach. This comparison is possible because each of the nourishment projects analyzed in this study was only a partial nourishment. Many studies have found that nourished beaches typically return to their "natural" state from one to three years after the completion of the nourishment project (Crain *et al.* 1995, Steinitz *et al.* 1998, and Ernest and Martin 1999). Each control area for this comparison had not been nourished for at least three years prior to the project analyzed. The third approach compared changes within the nourished area on each of the study sites before vs. after nourishment. A minimum of three years of pre- and post-nourishment data was used, although there are some exceptions due to gaps in the turtle data. Each of the three comparisons was made for each nesting parameter at all study sites. Differences were statistically compared using two-way and one-way ANOVAs or Kruskal-Wallis one-way ANOVA test on ranks when ANOVA assumptions were not met. When differences were found, Tukey's all pairwise method of multiple comparisons was used to identify the source(s).

Beach Characteristic Study

Sand Temperature

Two HOBO Water Temp Pro® data loggers were used to record temperature. One was placed in a nourished beach and one was placed in a beach segment that was not nourished. The data loggers were buried in approximately 45 cm (~18 inches) of sand. This depth was chosen because it approximates mid-clutch depth for an average loggerhead nest (Dodd 1988) and is midway between the two depths (30 and 60 cm) that have been consistently monitored for temperature in hatchling sex ratio studies (Mrosovsky and Provancha 1989 and Mrosovsky and Provancha 1992). Sediment temperature was recorded every hour for an 8-week period, starting July 12, 2003 and ending September 11, 2003. The data loggers were moved within each of the study regions (nourished and control) every two weeks, to get a better estimate of the overall sediment temperature throughout each site. To compare temperatures in the nourished and control area, average daily temperatures were first computed and then compared for the four two-week periods and overall using paired t-tests or Wilcoxon Signed Rank Tests when t-test assumptions were not met.

Sand Compaction

Compaction measurements were taken with a Durham Geo-Enterprises, Model S-214® portable static cone penotrometer (measuring compaction in psi – pounds per square inch). It is important to note that when using the cone penotrometer, readings are influenced by the mass and technique of the person collecting measurements (Ferrell *et al.* 2003). In this study, the same person took all compaction measurements and the highest reading that could be obtained accurately was 800 psi. Therefore, when readings were higher than 800 psi they were recorded as greater than 800 psi, but 800 psi was the number used when conducting the statistical analyses. This may downplay some of the differences between the compaction levels on the nourished and control beach.

Compaction measurements were taken at 3 depths: ~ 15 cm (~6 in.), ~30 cm (~ 12 in.), and ~45 cm (~18 in.) and at three zones on the beach: upper (on the upper portion of the berm a few meters before the tree line), lower (above the previous high tide wrack line), and middle (between the two previous sites), in accordance with the Army Corps of Engineers methodology. Measurements were taken every 500 feet, giving a total of 5 stations per region. Each measurement was based on an average of three replicate measurements taken at approximately the same place. Measurements were taken on June 22, 2003 and on May 24, 2004. Two-way ANOVA tests were used to determine significance between treatment (nourished or control) and location (upper, lower, middle) at each depth (15, 30, and 45 cm) for each year's data. When differences were found Duncan's method for multiple comparisons was used to record the source(s).

<u>Sand Color</u>

Differences in sand color differences were detected using a Munsell Color chart. Samples were collected at every site where compaction readings were taken in 2003 (45 samples each from the nourished and control beaches). Color was determined while sand samples were wet. Specific colors were assigned numeric values and a three-way ANOVA (treatment, beach location, and depth) with rank values was used to determine significant differences between the nourished and control beaches.

Sand Grain Size

Samples for the sand grain size analysis were collected at every site where compaction readings were taken in 2003 (45 samples each from the nourished and control beaches). Grain size distributions were measured from an approximately 50 g subsample. Each sample was separated into sand, silt, and clay components. Sand was separated by washing the subsample through a 0.062 mm sieve. Clay and silt were separated using a pipette analysis. The samples were then dried in a drying oven at 90ºC and weighed to the nearest 0.001 g. The remaining sand was then sieved through a nest of sieves with mesh sizes of 4.00, 2.83, 2.00, 1.41, 1.00, 0.71, 0.50, 0.35, 0.25, 0.177, 0.125, 0.088, and 0.063 mm (-2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0Φ) using a mechanical shaker. Sieve contents were weighed to the nearest 0.01g. Mean grain size and sorting were calculated with a spreadsheet obtained from SCDNR. All calculations were based on the moment method (Folk 1974). Kruskal Wallace one-way ANOVA on ranks tests were used to compare mean grain size in the nourished and control beach. Two sample Kolmogorov-Smirnov tests were used to compare control and nourished grain size distributions.

Sand Moisture Content

Samples for the moisture content analysis were collected at every site where compaction readings were taken in 2003 (45 samples each from the nourished and control beaches). Samples were collected in Ziploc bags to avoid moisture loss in transit to lab. The samples were then placed in a refrigerator until analyzed. Moisture content was analyzed from approximately a 50 g subsample. Samples were weighed and then dried in a drying oven at 75˚C for at least 48 hours and then weighed again. The ratio of water loss to dry mass multiplied by 100 represented the moisture content of the sample. Two-way ANOVA tests were used to determine significance between treatment (nourished or control) and location (upper, lower, middle) at each depth (15, 30, and 45 cm). When differences were found, Duncan's method for multiple comparisons was used to record the source(s). Rainfall should not have skewed the results. Since Hunting Island is only 5000 acres, when rainfall occurred both sites would most likely have been affected. The Hunting Island Park Staff reported no incidences of storms covering only a portion of the island to me.

Beach Profile/Slope Study

Beach profile data was obtained from Coastal Carolina University's Center for Coastal Marine and Wetland Studies' Beach Erosion and Monitoring program (BERM). The BERM program compiles beach profile data annually. Profiles are taken at permanent beach monuments located along the South Carolina coastline. The horizontal monument position is recorded in North Atlantic Datum 1983 State Plane U.S. survey feet and the elevation data is recorded in North Atlantic Vertical Datum 1988 in feet.

This study compared the relationship between crawl numbers (the number of nests plus the number of false crawls) and beach slope on Kiawah and Hilton Head. These two beaches were chosen because they provided adequate nesting and beach profile data. The year 1999 was chosen for analysis because it was a high nesting year for loggerheads across the southeast U.S. and because profiles of Kiawah and Hilton

Head were taken in the late spring close to loggerhead nesting season. Kiawah profiles were taken in April 1999 and Hilton Head profiles were taken in May 1999. Since the profiles were taken near or during the nesting season it can be reasonably assumed that the profiles throughout the entire nesting season were similar to those measured.

Four beach variables were determined for each beach monument location: maximum profile height, average slope from mean high water (MHW) to mean low water (MLW), maximum slope from MHW to MLW, and average subtidal slope from MLW out to 1500 feet from the permanent monument. To determine values for the four variables, graphs of each profile were used. Maximum height was determined by the point of highest elevation above sea level on each profile. When calculating the three other beach variables, slopes were calculated for every 25 ft. segment along each profile and averaged. Elevations were rounded to the nearest 0.25 feet in slope calculations. This was done to account for any surface irregularities. Average slope from MHW to MLW was calculated over the distance from MHW to MLW. Average subtidal slope was calculated over the distance from MLW to 1500 feet from the permanent monument. Maximum slope was determined as the largest slope per 25 feet in the MHW to MLW region.

Each beach, Kiawah and Hilton Head, was divided into one mile segments. For each segment the number of nests and false crawls were added to provide a total number of crawls per mile segment. The small area of Hilton Head nourished in 1999 was excluded from the analysis to make interpretation of the results simpler. There were one to four beach monuments located in each mile segment. All four variables (maximum height, MHW to MLW slope, subtidal slope, and maximum slope from MHW to MLW) were calculated for each mile segment. For mile segments containing more than one monument, beach profile data for that segment was calculated by averaging the values from all beach transects within that mile.

Scatterplots were made to determine the relationship between crawl number and maximum height, MHW to MLW slope, subtidal slope, and maximum slope from MHW to MLW. Linear regressions were performed to determine if any of the relationships were significant.

RESULTS

Historical Study

Results are listed as follows: 1) the comparison between the nourished beach segment with the unnourished Kiawah control beach; 2) the comparison between the nourished beach segment with a control site on the same beach, and 3) the pre- and post-nourishment comparison of the nourished beach.

Debordieu Beach

All nest densities, false crawl densities, and the nest to total crawl ratios for Debordieu Beach are based on the number of nests or false crawls per 0.4 mile. This distance was chosen due to the size of the nourishment project.

Nesting Density

1) The mean nesting density on the nourished portion of Debordieu Beach was 3.3 nests/0.4 mile versus 9.4 nests/0.4 mile on Kiawah Island. Significant differences were seen between beaches, with Debordieu Beach having significantly lower nesting densities overall ($p < 0.001$; Figure 2). No significant differences were seen between years ($p = 0.728$). Significant differences were seen between pairwise comparisons in all but two years, 1995 and 2001, with Kiawah Island having significantly higher nesting densities. A lot of natural variation was seen between the two beaches with no clear patterns. Therefore, when analyzing

nesting density on Debordieu Beach, I relied more heavily on the other two comparisons.

2) The mean nesting density on the control portion of Debordieu Beach was 3.2 nests/0.4 mile versus 3.3 nests/0.4 mile on the nourished portion. No significant differences were seen between these sections of the beach overall ($p = 0.903$). Significant differences were seen over time ($p = 0.021$) with the highest nesting densities occurring in 1995. No significant differences were seen between pairwise comparisons, however some trends were apparent. The nesting density on the nourished portion of the beach declined two years prior to the nourishment when compared with the control beach. Nesting densities were comparable with the control beach during the nesting seasons following nourishment (Figure 3).
3) The mean nesting density on the nourished portion of Debordieu three years pre-nourishment was 3.5 nests/0.4 mile versus 2.5 nests/0.4 mile three years post-nourishment. No significant differences were seen between three years pre- and post-nourishment. However, nesting density in 1995 was significantly higher than nesting densities in each of the following years ($p = 0.045$; Figure 4).

False Crawl Density

1) The mean false crawl density on the nourished portion of Debordieu Beach was 3.9 false crawls/0.4 mile versus 6.2 false crawls/0.4 mile on Kiawah Island. Significant differences were seen between beaches with Debordieu Beach having significantly lower false crawl densities ($p < 0.001$; Figure 5). No significant differences were seen between years ($p = 0.607$). Significant differences were seen in pairwise comparisons with Kiawah Island having significantly higher nest

densities. A lot of natural variation was seen between the two beaches with no clear patterns. Therefore, when analyzing false crawl density on Debordieu Beach, I relied more heavily on the other two comparisons. No false crawl data was available for Kiawah Island in 1995.

2) The mean false crawl density on Debordieu Beach's control beach was 3.3 false crawls/0.4 mile versus 3.9 false crawls/0.4 mile on the nourished beach. No significant differences were seen between beaches (p = 0.465) or between years (0.064). Significant differences were seen between pairwise comparisons in 1995 with the nourished beach having higher false crawl densities (Figure 6).

3) The mean false crawl density on the nourished portion of Debordieu three years prior to nourishment was 4.9 false crawls/0.4 mile versus 3.25 false crawls/0.4 mile three years post-nourishment. No significant differences were seen between the three years pre- and post-nourishment periods. False crawl densities in 1995 were higher than the densities in each of the following years but this difference was not significant (p = 0.195; Figure 7).

Nest to Total Crawl Ratio

1) The mean nest to total crawl ratio on Debordieu Beach's nourished beach was 55.1% versus 60.4% versus on Kiawah Island. No significant differences were seen between beaches (p = 0.267) or between years (p = 0.083; Figure 8). However, significant differences were seen between pairwise comparisons in 1997 and 2001. In 1997, Kiawah Island had significantly higher nest to total crawl ratios. In the four nesting seasons following nourishment, ratios on Debordieu Beach were comparable or higher than Kiawah Island's. In 2001, the

nest to total crawl ratio was significantly higher on Debordieu Beach than Kiawah Island (Figure 8). Nest to total crawl ratios could not be calculated for Kiawah in 1995.

2) The mean nest to total crawl ratio on Debordieu Beach's control beach was 51.6% versus 55.1% on the nourished beach. Overall no significant differences were seen between beaches (p = 0.641), between years (p = 0.731), or between pairwise comparisons, but trends similar to the Kiawah Island comparison were seen (Figure 9). The proportion of crawls resulting in nests on the nourished beach was lower the nesting season prior to nourishment when compared to the control beach, but not significantly so. The nest to total crawl ratio increased after nourishment and was comparable or higher than that on the control beach in subsequent years (Figure 9). While these changes were also not significantly different, the change does suggest improvement in turtle nesting success that may be related to nourishment.

3) The mean nest to total crawl ratio on Debordieu Beach's nourished beach three years prior to nourishment was 43.3% versus 63.7% three years post-nourishment. No significant differences were seen between the three year pre- and post-nourishment periods or between years (p = 0.155; Figure 10).

<u>Hilton Head Island</u>

All nest densities for the Hilton Head Island comparisons are based on the number of nests or false crawls per 1.0 mile. This distance was chosen due to the size of the nourishment project, which allowed a greater unit length to be used for each segment, thereby increasing the number of turtle nests or false crawls per unit distance.

Nesting Density

1) The mean nesting density on the nourished portion of Hilton Head Island was 10.1 nests/mile versus 23.7 nests/mile on Kiawah Island. Significant differences were seen between beaches with Hilton Head Island having significantly lower nesting densities ($p < 0.001$; Figure 11). Significant differences were seen between years ($p = 0.007$), with 1999 having higher nesting densities than all other years. Significant differences were seen between pairwise comparisons in all years except 1995, with Kiawah Island having significantly higher nesting densities. A lot of natural variation was seen between the two beaches with no clear patterns. Therefore, when analyzing nesting density on Hilton Head Island, I relied more heavily on the other two comparisons.

2) The mean nesting density on Hilton Head Island's control beach was 11.2 nests/mile versus 10.2 nests/mile on the nourished beach. No significant differences were seen between beaches ($p = 0.320$), between years ($p = 0.055$), or between pairwise comparisons. However, in 1997, the year of the nourishment, nesting densities on both the nourished and control portions of the beach dropped substantially (Figure 12).

3) The mean nesting density on Hilton Head Island's nourished beach three years prior to nourishment was 11.3 nests/mile versus 10.9 nests/mile three years post-nourishment. No significant differences were seen between the three year pre- and post-nourishment periods or between years on the nourished beach ($p = 0.648$; Figure 13).

False Crawl Density

1) The mean false crawl density on Hilton Head's nourished beach was 9.8 false crawls/mile versus17.8 false crawls/mile on Kiawah Island. Significant differences were seen between beaches with Hilton Head Island having significantly lower false crawl densities ($p = 0.007$; Figure 14). Significant differences were also seen between years ($p = 0.001$), with 1999 having higher false crawl densities than all other years. Significant differences were seen between pairwise comparisons in 1996, 2000, and 2001 with Kiawah Island having significantly higher nesting densities. A lot of natural variation was seen between the two beaches, with no clear patterns oberved. Therefore, when analyzing false crawl density on Hilton Head Island, I relied more heavily on the other two comparisons. False crawl densities were not available for Kiawah Island in 1995.
2) The mean false crawl density on Hilton Head Island's control beach was 8.0 false crawls/mile versus 9.8 false crawls/mile on the nourished beach. No significant differences were seen between beaches ($p = 0.099$; Figure 15). Significant differences were seen between years ($p < 0.001$) with 1999 having higher false crawl densities than all other years. Significant differences were seen between pairwise comparisons in 1997 and 1999 with the nourished portion of the beach having significantly higher false crawl densities (Figure 15).
3) The mean false crawl density on the nourished section of Hilton Head Island was not available in 1994. Therefore, the three-year pre- versus post-analysis could not be done. However, when comparing the false crawl densities on the

nourished beach between years, significant differences were found with false crawl densities in 1999 significantly higher than all other years ($p = 0.008$; Figure 16).

Nest to Total Crawl Ratio

1) The mean nest to total crawl ratio on Hilton Head Island's nourished beach was 50.2% versus 60.0% on Kiawah Island. Significant differences were seen between beaches with Hilton Head Island having significantly lower nest to total crawl ratios ($p < 0.001$; Figure 17). No significant differences were seen between years ($p = 0.066$). Significant differences were seen between pairwise comparisons in 1997, 1998, and 1999 with Kiawah Island having higher nest to total crawl ratios. Nest to total crawl ratios could not be calculated for Kiawah Island in 1995.

2) The mean nest to total crawl ratio on Hilton Head's control beach was 61.4% versus 50.2% on the nourished beach. Significant differences were seen between beaches with the control beach having significantly higher nest to total crawl ratios ($p = 0.001$; Figure 18). Significant differences were also seen between years ($p = 0.024$) with 1997 having higher ratios than all other years. Significant differences in pairwise comparisons were seen in 1997 and 1999 with the control beach having higher nest to total crawl ratios (Figure 18).

3) The mean nest to total crawl ratio on Hilton Head Island's nourished beach was not available in 1994. Therefore, the three-year pre- versus post- analysis could not be done. No significant differences were found when comparing the nest to total crawl ratio on the nourished beach between years ($p = 0.05$; Figure 19).

Beach Characteristic Study

<u>Sand Temperature</u>

A large variation in sand temperature was seen over the sampling period, ranging from 25.1˚C to 31.6˚C on the nourished beach and ranging 25˚C to 31.2˚C on the control beach (Figure 20). Mean temperature over the entire sampling period was 29.3˚C for the nourished beach and 28.9˚C for the control beach. The nourished beach had significantly higher temperatures in the overall 8-week period ($p = <0.001$), period 1 ($p = <0.001$), and period 3 ($p = <0.001$). No significant differences were seen in periods 2 and 4 (Table 1).

<u>Sand Compaction</u>

Sand compaction levels increased with depth on both the nourished and control beaches. Compaction values were highest on the mid-berm on both the nourished and control beaches compared to the upper berm and above mean high water zones (Figures 21 - 26). In 2003, the nourished beach was significantly more compact than the control beach at 15 cm ($p = 0.008$; Figure 21). No significant differences were seen in compaction values between beach locations ($p = 0.355$). However, highest compaction values were seen mid-berm. The U.S. Fish and Wildlife Service uses 500 psi as a compaction threshold (U.S. Fish and Wildlife Service, unpublished). In 2003, compaction values at 15 cm on the control beach were all lower than 500 psi. However, compaction values on the nourished beach at 15 cm were above 500 psi mid-berm. No significant differences were seen between the nourished and control beaches at 30 cm (p = 0.863) or 45 cm (p = 0.218) or between zones at 30 cm (p = 0.085) or 45 cm (p = 0.130; Figure 22 and 23.)

By 2004, no significant differences were seen in sand compaction between the nourished and control treatments or beach zones at any depth ($p > 0.05$). This was due to decreases in compaction values on the nourished beach and increases in compaction values on the control beach, in both the upper and middle zones. However, all compaction values on the control beach were still under 500 psi. On the nourished beach, mean compaction values on the upper berm and above mean high water zones increased in 2004, but compaction decreased slightly on the mid-berm. Compaction values mid-berm and above mean high water were still above 500 psi in 2004 (Figures 24 – 26).

Sand Color

Two sand colors were found on the nourished and control beaches: light olive and gray (5Y 6/2) and light gray hue (5Y 7/2). Each color was found among all treatment groups, zones, and depths. Significant differences were not found between treatment groups or locations for 15, 30, and 45 cm.

Sand Grain Size

Mean grain size of all samples collected on the nourished and control beaches consisted of fine sand. Each sample contained less than two percent clay and silt. Grain particle size distributions at the upper, middle, and lower zones and at 15, 30, and 45 cm were all similar. Mean grain size of the nourished beach was 2.27 Φ and was 2.79 Φ on the control beach. Significant differences in mean grain size were seen between the nourished and control beaches (p = <0.001) with the control beach having a finer grain size (Figure 27). Mean grain size data for all samples on the nourished and control beaches can be found in Appendix 1. Significant differences were also seen between grain size distributions (p = 0.01), with the nourished beach having a wider distribution (Figure 28; Table 2).

Sand Moisture

Moisture content of the samples generally increased with depth. However, a larger difference was seen between the moisture content at 15 cm than with the moisture contents at 30 cm and 45 cm. Samples held the most moisture in the above mean high water zone, while the upper and mid-berm zones were comparable (Figures 29 - 31). Significant differences were seen in moisture content between the nourished and control treatments at 15 cm (p = 0.026), with the control sand holding more moisture. No significant differences were seen between zones at 15 cm (p = 0.458) or between treatments and zones at 30 cm (p > 0.05), but significant differences were seen at 45 cm between treatments (p = <0.001) and zones (p = 0.002). The control sand and the lower site had significantly more moisture.

Beach Profile/Slope Study

Overall Hilton Head Island beach profiles had greater topographic relief than Kiawah Island profiles. However, little difference was seen within or between study sites when comparing MHW to MLW slope, subtidal slope, and maximum slope from MHW to MLW. The only parameter that varied significantly within a site and between beaches was maximum profile height. The average maximum beach profile height for Hilton Head Island was 32.7 feet and Kiawah Island was 13.38 feet. Mean slope from MHW to MLW for Hilton Head Island was –0.0228 ft/25 ft and Kiawah Island was –0.0216 ft/ 25ft. Mean subtidal slope for Hilton Head Island was –0.0097 ft/25 ft and for Kiawah Island was –0.0092 ft/25 ft. Maximum slope from MHW to MLW was –0.0411 ft/25 ft for Hilton Head Island and –0.0417 ft/25 ft for Kiawah Island.

On Hilton Head Island, no significant relationships were found between turtle crawl number and the four slope parameters (Figures 23 – 35). On Kiawah Island, a significant relationship was found between turtle crawl number and mean subtidal slope ($p = 0.031$, $r^2 = 0.5651$). Gradual slopes had more turtle crawls (Figure 39). No significant relationships were found between crawl number and mean maximum beach height, crawl number and mean slope from MHW to MLW, and crawl number and mean maximum slope from MHW to MLW (Figures 36 - 38).

DISCUSSION

Historical Study

Nesting densities on all beaches examined in this study were indicative of cyclical trends of loggerhead nesting observed by others in the southeastern USA (Hopkins-Murphy *et al.* 2001 and TEWG 2000). These cyclical patterns are due, in part, to re-migration intervals. The mean observed re-migration interval for loggerheads is 2.5 to 3.0 years (Schroeder *et al.* 2003), indicating that there should be fluctuations in nesting numbers that are dependent, in part, on the number of turtles that are remigrating in a given season. This cyclical fluctuation must be considered when analyzing the historical data.

Female loggerhead turtles often place more nests at some beaches than others. The reasons they prefer beaches is not always obvious (Steinitz *et al.* 1998). When comparing nesting and false crawl densities on the two nourished beaches and Kiawah Island, significant differences were seen between the beaches, with no consistent patterns observed among years and beaches. Therefore, when analyzing the effects of nourishment on turtle nesting activities on Debordieu Beach and Hilton Head Island, I relied more on the within beach comparisons and the pre- versus post-nourishment comparisons than on the inter-beach comparisons when considering the total number of nests and total number of false crawls observed.

Ryder (1993) suggested that a better indicator of the quality of the nourished beach, as a nesting habitat, would be the proportion of crawls resulting in nests. These ratios rely on proportional data, not absolute densities. Since proportional data avoids some of the problems I encountered in comparing nesting and false crawl densities among beaches, this measure of nesting success was able to be used for comparison of Kiawah Island and the two nourished beaches.

<u>Debordieu Beach</u>

On Debordieu Beach, nest densities on the nourished portion of the beach declined two years prior to the nourishment project when compared to the control beach. Nesting densities increased the nesting season immediately after nourishment on both the nourished and control beaches. The fluctuations observed in nest density were similar to fluctuations in nesting numbers throughout the state, which suggest that the number of females breeding each year may have influenced the increased trend in nesting density during this period. However, the increase seen on the nourished beach probably would not have occurred without the nourishment project. Volunteers for Debordieu's turtle monitoring program observed a narrowing of the beach due to erosion prior to nourishment (Betsy Brabson, pers.comm.), so it is reasonable to assume the nourishment contributed at least partially to the increased number of nests observed through an increase in the nesting habitat available.

Similar increases were also seen in Debordieu Beach's nest to total crawl ratio. The nesting season prior to nourishment, nest to total crawl ratios on the nourished portion of Debordieu Beach were significantly less than ratios observed at Kiawah Island

and the control section of Debordieu Beach. In the nesting season immediately after nourishment and for the next four nesting seasons, the nest to total crawl ratios increased to levels greater or comparable than those observed on Kiawah Island, a historically good nesting beach, and the control portion of Debordieu Beach. This provides stronger evidence that the improved nesting on Debordieu Beach following nourishment was probably due at least, in part, to the nourishment project.

In the mid-1980's, Debordieu constructed a sea wall because the area in front of many homes was experiencing high rates of erosion (Betsy Brabson, pers. comm.). The 1998 nourishment project was approximately 1.7 miles long and approximately half of the area nourished was in front of the sea wall. Prior to the 1998 nourishment, there was no available nesting habitat at high tide for turtles in front of the sea wall (Betsy Brabson, pers. comm.). It can be assumed the nourishment project increased the amount of nesting habitat available on Debordieu Beach. Ernest and Martin (1999) and Crain *et al.* (1995) also noted nesting numbers often increased after nourishment projects, especially in areas where no nesting habitat was available prior to the nourishment or where beaches were severely eroded.

Overall, few statistically significant patterns were found in the historical analysis on Debordieu Beach. This lack of statistical significance may be due in part to the small sample size and high variability of nests and false crawls within each 0.4 mile segment. The segments in the Debordieu analyses were small due to the size of the nourishment project. When segment length increased, as in the Hilton Head Island analyses, more significant patterns were seen. Therefore, the patterns observed on Debordieu Beach could have been statistically significant if the nourishment project had allowed for a larger segment size to be used for counting the number of turtle nests and false crawls.

Hilton Head Island

During the nesting season prior to nourishment, nest densities were lower on the nourished section of the Hilton Head Island beach when compared to the control section. Nesting densities increased on the nourished and control beaches after nourishment. Like Debordieu Beach, the increases in nest density were similar to fluctuations in nesting numbers throughout the state, suggesting that these increases were probably partially attributed to the number of females breeding each year, not simply due to the nourishment project.

When the nest to total crawl ratios were compared, the ratios on the nourished portion of Hilton Head Island were significantly less than those on Kiawah Island during the nourishment and two nesting seasons after nourishment. Effectively similar patterns were seen when comparing the nourished and control sections of Hilton Head Island. Significant differences were seen between the two beaches and the nest to total crawl ratios decreased during the nourishment and up to two years after the nourishment was complete, suggesting that the nourishment project on Hilton Head Island did not have immediate positive effects. After three years, both the between beach comparison (with Kiawah) and the within beach comparison of nest to total crawl ratios on the nourished beach were comparable to the control beaches, indicating that nourishment may have been beneficial to turtles in the long term.

It is important to note that the 1997 Hilton Head Island nourishment occurred during the turtle nesting season. Nesting densities decreased substantially in 1997 on both the nourished and control areas, probably due in large part to the disturbance from this project. The nourished areas were interspersed throughout the nesting beach, so both the control and nourished portions of the beach were affected. However, false crawl densities on the nourished portion of the beach were significantly higher and nest to total crawl ratios were significantly lower than on the control beach. Therefore, the nourishment project probably affected the entire nesting beach, with more harm done in the nourished areas.

The decrease in nest to total crawl ratios observed during nourishment and the two years following nourishment may be, at least in part, due to berm scarps formed after the nourishment project. Monitoring reports from a previous nourishment project on Hilton Head in 1990 found that high scarps occurred frequently and persisted for a year after the project's completion (Van Dolah *et al.* 1992). Steinitz *et al.* (1998) also observed it took approximately one year for a nourished beach to stabilize so that high scarps would not form. Berm scarps have been found to impede turtles from reaching nesting areas, increasing the number of false crawls and decreasing the proportion of crawls resulting in nests (Raymond 1984, Ryder 1993, Crain *et al.* 1995, NRC 1995, Steinitz *et al.* 1998, Ernest and Martin 1999, Herren 1999, and Rumbold *et al.* 2001). It could be reasonably assumed that scarps, similar to the ones formed after the 1990 nourishment project, could have formed after the 1997 nourishment project and persisted up to two years after the project's completion, influencing the nest to total crawl ratio.

After analyzing the results from the historical study on Debordieu Beach and Hilton Head Island, it is clear that generalizations cannot be made about the affects that nourishment projects have on nesting sea turtles. The different results seen after nourishment on Debordieu Beach and Hilton Head Island could be due to a number of reasons. First, the analysis compares densities of different nesting parameters, but it does not take into account differences among the nesting beaches. The two nourished beaches in this study are not identical and parameters other than the nourishment project could have affected the proportion of crawls resulting in nests. For example, both beaches have development adjacent to their nesting habitat. However, the development on Debordieu Beach is primarily residential homes, whereas some of the development on Hilton Head Island is commercial hotels and businesses. It could be hypothesized that Hilton Head Island has more artificial lighting and perhaps, more people on the beach at night, both of which could affect the proportion of crawls resulting in nests (Salmon *et al.* 1995, Kikukawa *et al.* 1998, and Kikukawa *et al.* 1999). Variation in results may also be due to the unique nature of each nourishment project. For example, each project got fill material from different locations. The beach fill for the Debordieu Beach nourishment project was brought in from an inland source, while the fill for the Hilton Head Island project was pumped from offshore borrow sites. These differences may have affected turtle nesting activities. Every nesting beach and beach nourishment project is unique, so to determine the affect of beach nourishment on sea turtle nesting activities, each case must be studied individually.

Effects of Nourishment on the Physical Characteristics of Hunting Island

Previous studies have found changes in physical properties of beaches due to beach nourishment (Raymond 1984, Broadwell 1991, Ackermann *et al.* 1992, Ryder 1993, Steinitz *et al.* 1998, Herren 1999, Ernest and Martin 1999, Rumbold *et al.* 2001, Scianna 2002, Mihnovets 2003, and Mihnovets and Godfrey 2004). On Hunting Island, significant differences were found in sand temperature, compaction, mean grain size, grain size distribution, and moisture content between the nourished and control beaches. Some of these differences have the potential to influence nest to total crawl ratios and alter the nest environment (Raymond 1984, Crain *et al.* 1995, Steinitz *et al.* 1998, Rumbold *et al.* 2001, and Carthy *et al.* 2003).

<u>Nesting Success</u>

Increased compaction has been found to decrease the proportion of crawls resulting in nests, alter nest-chamber geometry, and alter nest concealment (Crain *et al.* 1995). Higher shear resistance nearly always results after the completion of a nourishment project (Nelson and Dickerson 1989). Other locations have found that nourished beaches remain unnaturally hard for up to seven years, depending on weather and wave conditions along with the quality of the fill (Moulding and Nelson 1988).

During the nesting season immediately after nourishment on Hunting Island, the nourished beach was significantly more compact than the control beach at 15 cm depth in the sand. Harder sand surfaces at nourished beaches often induce turtles to abort nesting attempts (Crain *et al.* 1995 and Rumbold *et al.* 2001). Although no significant differences were found between compaction values and beach location, the largest difference in compaction values were found on the middle of the berm, where most loggerheads place nests (Steinitz *et al.* 1998).

Studies at Jupiter Island, FL found beach hardness values persisted for three summers after nourishment (Steinitz *et al.* 1998). Ryder (1993) found a decrease in beach hardness one year after nourishment near the surf zone, but no decrease in the middle of the beach. The U.S. Fish and Wildlife Service suggests tilling on beaches where compaction values exceed 500 psi in multiple adjacent areas, to help reduce surface compaction values (USFWS unpublished). In 2003, compaction values at a 15 cm depth on the nourished beach mid-berm at Hunting Island exceeded the U. S. FWS threshold, potentially influencing turtle nesting activities.

Significant differences in compaction values lasted less than a year on Hunting Island. In 2004, a year after the nourishment was complete, no significant differences were seen between compaction values on the nourished and control beaches. However, compaction values on the nourished beach both mid-berm and above mean high water still exceeded the 500 psi USFWS compaction threshold and may still potentially affect turtle nesting activities. However, it is important to note that studies used to determine this compaction threshold were conducted in Florida, where beaches primarily consist of carbonate sand (Nelson and Dickerson 1987 and Nelson and Dickerson 1988b). South Carolina beaches consist of primarily siliceous material. South Carolina and Florida beaches differ in many physical characteristics, including mean grain size, porosity, and compaction. Therefore, compaction threshold values may vary by geographic region. Until a similar study is done to determine the compaction threshold in South Carolina, it is hard to determine the biological significance of the compaction differences found.

Nest Environment

Although some sand characteristics are crucial to nest survival (Packard and Packard 1988), females apparently choose nesting sites without control to most of them (i.e. sand grain size, shape, and distribution; hydric properties; pore spacing; and mineral content; Mortimer 1982 and 1990). Therefore, a beach can be attractive to females as a nesting site, but contain sands, which are less than optimal for nest survival (Steinitz *et al.* 1998).

At Hunting Island, differences were found between mean grain size, grain size distribution, moisture content, and temperature on the nourished and control beaches. Although these differences were statistically significant, some of them were slight and may not be biologically meaningful.

Statistically significant differences were found between mean grain sizes on Hunting Island with the control beach having a finer grain size. Loggerheads most commonly nest in sands with a mean particle diameter of 0.5 – 0.25 mm (1.0 Φ to 2.0 Φ), but they have also been found to nest in finer and coarser media (Hughes 1974, Mann 1979, and Foley 1998). Mean grain size on both the control (2.27 Φ) and nourished (2.79 Φ) beaches was finer than sand most commonly used by loggerheads. However, both grain sizes found were typical of South Carolina beaches and were within in the range of substrates in which loggerheads can successfully nest (Mortimer 1990 and Carthy *et al.* 2003). Significant differences were also seen in grain size distributions, with the nourished beach having a larger distribution. This is primarily attributed to the large amount of shell hash found on the nourished beach (Appendix 1). Although there were statistically significant differences between mean grain size and grain size distribution on Hunting Island's beaches, the differences were small and most studies have found little or no evidence that nest fate differed between nourished and control beaches with different grain sizes (Broadwell 1991 and Ernest and Martin 1999). Therefore, the differences seen in mean grain size and grain size distributions were probably not biologically meaningful.

Moisture content on Hunting Island's nourished beach was statistically lower than on the control beach. The largest differences seen in moisture content occurred in the above mean high water zone. Although some of these differences may be due to the substrata and physical characteristics of the control beach, it is also important to note that specific locations on the nourished and control beach may have also played a role. On the nourished beach, the above mean high water zone was on the top of a large scarp formed after the nourishment project. On the control beach, this zone was located above the wrack line. During high spring tides, it is possible this area was overwashed, which may also have influenced the larger moisture content found on the control beach.

Ehrhart (1995) hypothesized that substrates containing more moisture, have reduced space between grains, impeding gas exchange between the eggs and the sand. In an experimental study, McGehee (1990) demonstrated that egg viability was reduced when beach sand contained more moisture than found under natural conditions. Broadwell (1991) observed greater hatching success on beaches with higher moisture contents. Although there were statistically significant differences in the moisture content on the control versus nourished portions of Hunting Island, the differences were small and probably are not biologically meaningful. Both beaches held enough moisture so eggs would not desiccate, but not enough moisture to impede gas exchange (Caldwell *et al.* 1959, McGehee 1990, Broadwell 1991, Ackerman 1997, and Foley 1998).

Beach fill used in nourishment projects may also have the potential to affect sand temperatures. On Hunting Island temperatures on the nourished beach were significantly higher than temperatures on the control beach overall and for two out of the four periods measured. Sea turtles have temperature dependent sex-determination (TSD) with higher temperatures resulting in females and lower temperatures resulting in males (Yntema and Mrosovsky 1980). The incubation period for loggerheads is approximately 55 days (McGehee 1979) with the thermosensitive period for sexual differentiation occurring during the middle third of incubation (Mrosovsky and Pieau 1991). Temperatures during this two and a half to three week period most heavily influence hatchling sex ratios. Pivotal temperatures for loggerhead sea turtles in the southeast U.S. are approximately 29ºC (Mrosovsky 1988). Pivotal temperatures are the constant incubation temperatures giving a 1:1 sex ratio (Wibbels 2003). Temperature differences, even tenths of a degree Celsius, around this pivotal temperature have the potential to greatly affect hatchling sex ratios (Wibbels 2003 and Mrosovsky 1988). Although temperature differences were approximately only 0.5˚C and 1.0˚C on Hunting Island, many of these differences, especially those seen in period 3, occur near the pivotal temperature and may have the potential to affect hatchling sex ratios.

Although temperature differences observed on Hunting Island had the potential to be biologically meaningful, estimating the effect on sex ratios from this data is difficult. In this study, sand temperature was recorded, not nest temperature. Developing sea turtle nests are generally warmer than the surrounding sand (Godfrey *et al.* 1997 and Broderick *et al.* 2001), perhaps due to metabolic heating (Herren 1999). If the temperatures found on Hunting Island in the sand are similar to those found in nests, the differences might have the potential to alter sex ratios.

It is also important to note that significant differences in temperature did not persist for the entire 8-week period, or for longer than one two-week interval in the Hunting Island study. Since temperature differences did not last the entire thermosensitive period, it is difficult to conclude what affect these temperature differences would have had on sex ratios. Also it is important to note that the accuracy of the Hobo Water Temp Pro® data loggers was limited to +/-0.2˚C. After accounting for the error in the data loggers, only the differences between temperatures in period three were equal or greater than 0.5˚C.

Although specific physical differences in the nest environment may alter nest survival, interactions between several physical factors will ultimately determine how substrata affect sea turtle nest fate (Ackermann 1997). It is likely that loggerheads, like green turtles, nest worldwide in a variety of substrates that can vary considerably in water content, grain size, color, and porosity (Mortimer 1990). Therefore, some of the differences observed in mean grain size, grain size distribution, moisture content, and temperature on Hunting Island were small and may not be biologically meaningful with regard to turtle nesting. However, if sand temperatures are similar to nest temperatures, the temperature differences found on Hunting Island have the potential to be biologically meaningful affecting hatchling sex ratios. Also, if the compaction threshold identified by the U. S. FWS based on studies in Florida is applicable in South Carolina, the increased compaction values found on the nourished portion of Hunting Island also have the potential to be biologically meaningful affecting the proportion of crawls resulting in nests.

Slope Study

The mechanisms loggerheads use in nest site selection are not well understood (Dodd 1988). Proximal cues may be used to indicate where to place nests. Possible proximal cues include sand temperature (Stoneburner and Richardson 1981), moisture (Iocco 1998 and Wood 1998), and beach slope (Provancha and Ehrhart 1987, Wood 1998, and Wood and Bjorndal 2000). Slope may be a reliable indicator because it is less variable over time than temperature and moisture (Wood 1998). After other thresholds, such as moisture and temperature, are surpassed, beach slope is one environmental factor that may reliably indicate to the female the location of elevated nesting habitat (Wood 1998).

Significant relationships were found on Kiawah Island between average subtidal slope and turtle crawl numbers. Although this relationship was statistically significant, it probably was not biologically meaningful because it was based on a very small sample size and a large amount of variation was seen between crawl numbers and their corresponding slopes. Many data points had nearly identical crawl numbers, but different slope values and the significant relationship found was driven by one outlying point. When this data point was removed, no relationship was found. Other studies that have found slope to be a significant factor in nest site selection have not relied on historic beach profiles to determine a relationship. Instead, they have measured slopes of actual crawls during nesting seasons (Provancha and Ehrhart 1987 and Wood and Bjorndal 2000).

One reason significant relationships may not have been found in this study may be due to constraints in the beach profile data. Average slopes from MHW to MLW and subtidally did not differ substantially within or between the study sites. The lack of a large range in slope within the zones may explain the lack of clear or strong patterns in this study. The one parameter that varied considerably in the historic beach profile data was maximum profile height. Maximum profile height was defined as the highest elevation point on each beach profile above mean sea level and it varied substantially over the mile segments used to determine crawl numbers. Beach profile data was measured at permanent beach monuments. However, the monuments were not evenly spaced along the coastline. Some mile segments would contain only one monument, while others contained four. Maximum elevation values changed substantially over a mile. So while elevations can be averaged for segments containing more than one monument, there was high variability of elevation over the mile increment. Thus, averaging values does not give an accurate picture of the elevation that turtle would likely have seen when approaching the nesting beach.

Finally, it should be noted that a portion of all turtle beach crawls occur at or near high tide, when intertidal slopes would not be likely to have an influence on beach selection by turtles. This, combined with the other factors noted above and the lack of large differences in slopes among the beach segments analyzed undoubtedly contributed to the lack of any clear patterns observed in this portion of the study.

CONCLUSION

Based on the historical analysis, I found that generalizations cannot be made on the effects of nourishment on nesting sea turtles. On Debordieu Beach, the nourishment appeared to have an immediate positive effect on turtle nesting success and turtle nesting habitat. This immediate positive impact did not appear to occur on Hilton Head Island. Although nest density increased after nourishment, these increases were not statistically significant and nest to total crawl ratios decreased up to two years after the nourishment. Three years after the nourishment project was complete, ratios were comparable to those found on the control beach segment. While the nourishment seemed to have an immediate adverse effect on turtle nesting activities on Hilton Head Island, the nourishment may have had a positive effect in the long term based on the findings of this study and the fact that the beach would have been even more severely eroded with time if no nourishment had been done.

Numerous studies, including this one, have found beach nourishment alters physical characteristics of beaches. In this study, statistically significant differences were found between sand temperature, sand compaction, mean grain size, grain size distributions, and moisture content. These differences have the potential to influence nest site selection, the proportion of crawls resulting in nests, and the nest environment. However, only the temperature and compaction differences in this study had the potential to be biologically meaningful. As with the historical study, it is hard to make generalizations about the effects of beach nourishment on physical beach characteristics.

The effects will depend on the fill used in the nourishment project, and different fills are used seasonally and geographically in nourishment projects, depending upon availability.

This study found that beach nourishment has the potential to significantly affect loggerhead sea turtle nesting in South Carolina, but the effects were not consistent among beaches. Every nesting beach and nourishment project is unique; therefore assessments of nourishment's effect on turtles must be done on a case by case basis until more definitive data are available. Future studies should further evaluate the effects of sand compaction and sand temperature on sea turtle nesting activities in South Carolina. A better understanding of these two variables will give a broader understanding of beach nourishment's potential effects on nesting sea turtles in South Carolina.

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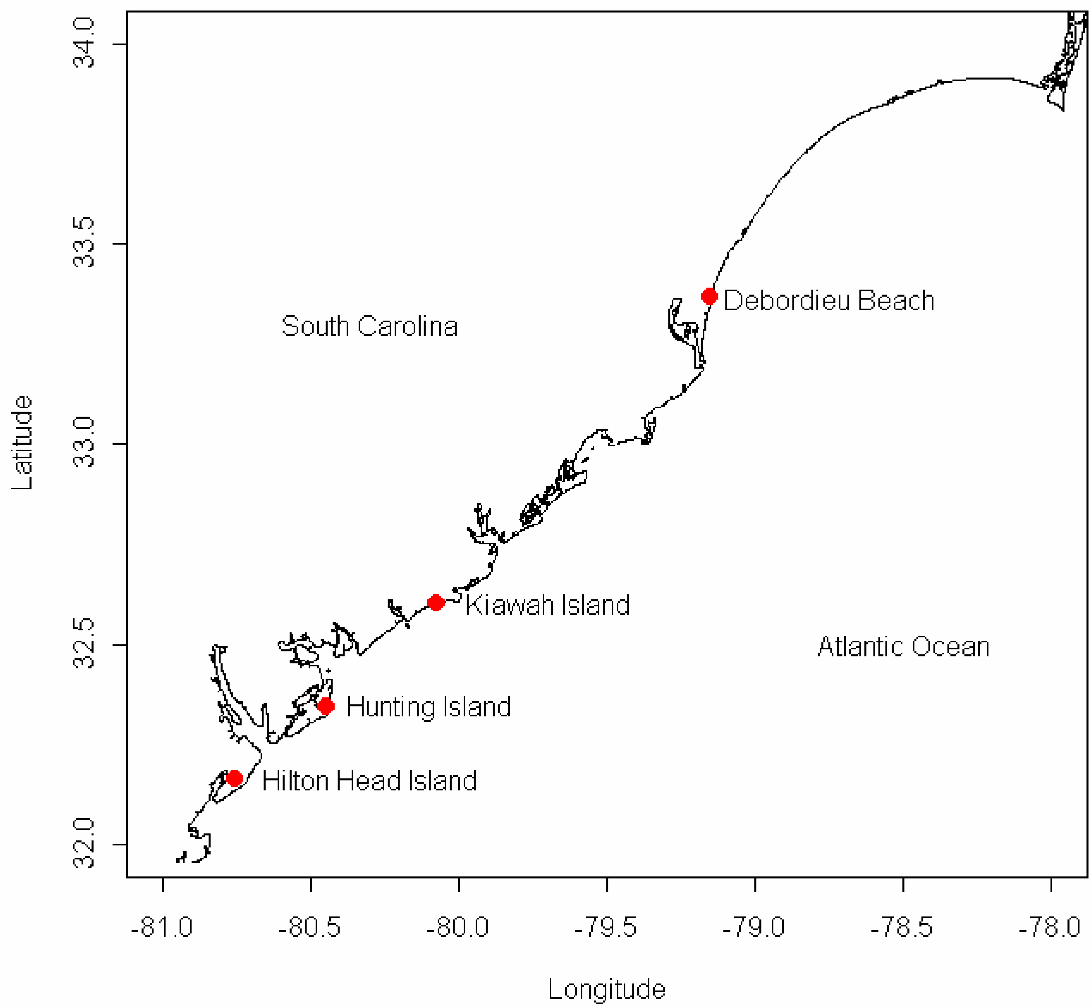
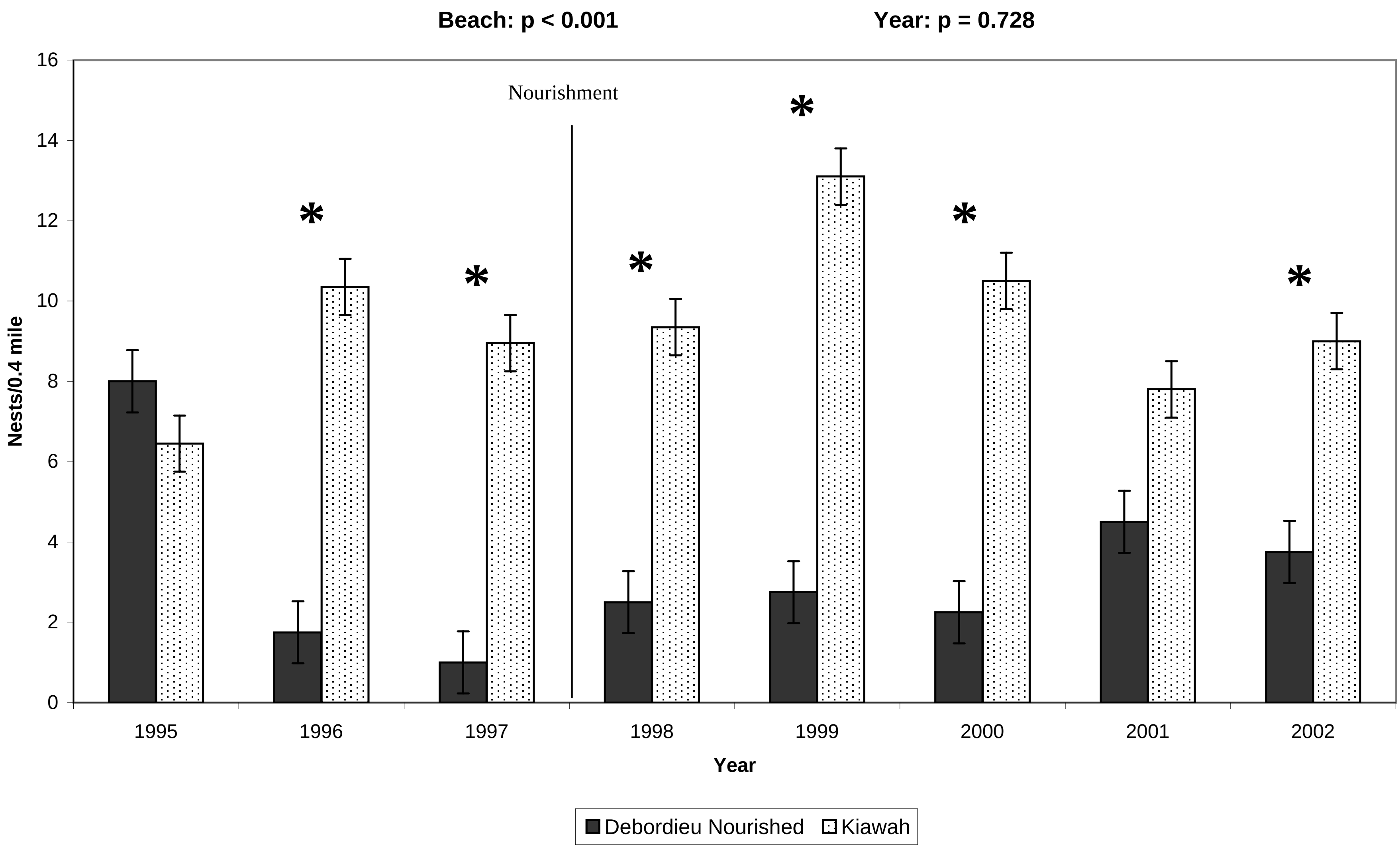
Figure 1. Study sites in South Carolina. Debordieu Beach, Kiawah Island, and Hilton Head Island were used in the historical study. Hunting Island was used in the beach characteristics study. Kiawah Island and Hilton Head Island were used in the beach profile/slope analysis.



South Carolina
Debordieu Beach
Kiawah Island
Atlantic Ocean
Hunting Island
Hilton Head Island
Latitude
34.0
33.5
33.0
32.5
32.0
-81.0
-80.5
-80.0
-79.5
-79.0
-78.5
-78.0
Longitude

Figure 2. Nesting density on Debordieu Beach versus Kiawah Island (control) from 1995 – 2002. Asterisks indicate significant differences between pairwise comparisons.



Beach: p < 0.001
Year: p = 0.728
Nourishment
Nests/0.4 mile
Year
1995
1996
1997
1998
1999
2000
2001
2002
Debordieu Nourished
Kiawah

Figure 3. Nesting density on Debordieu Beach's nourished versus control beaches from 1995 – 2002.

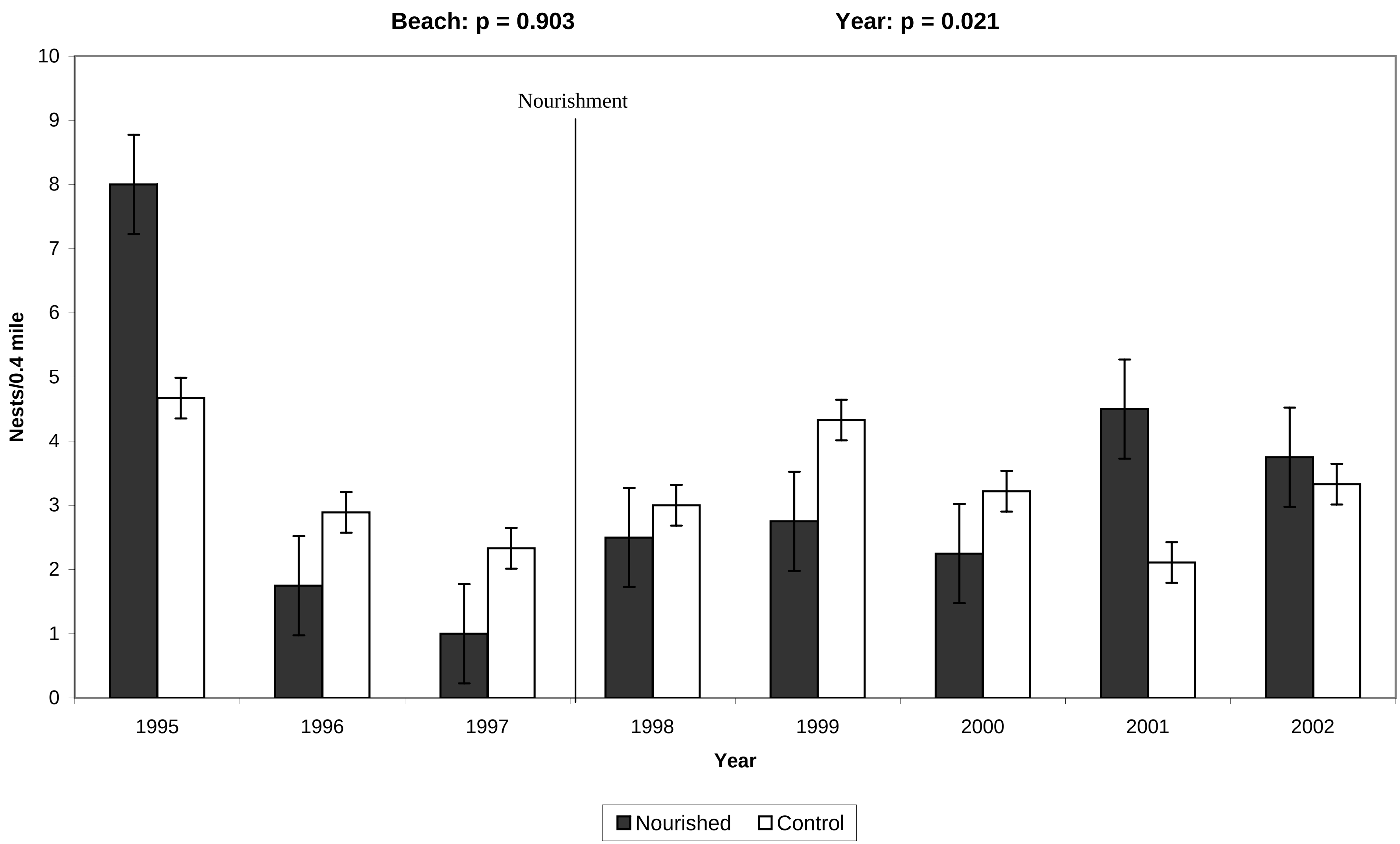
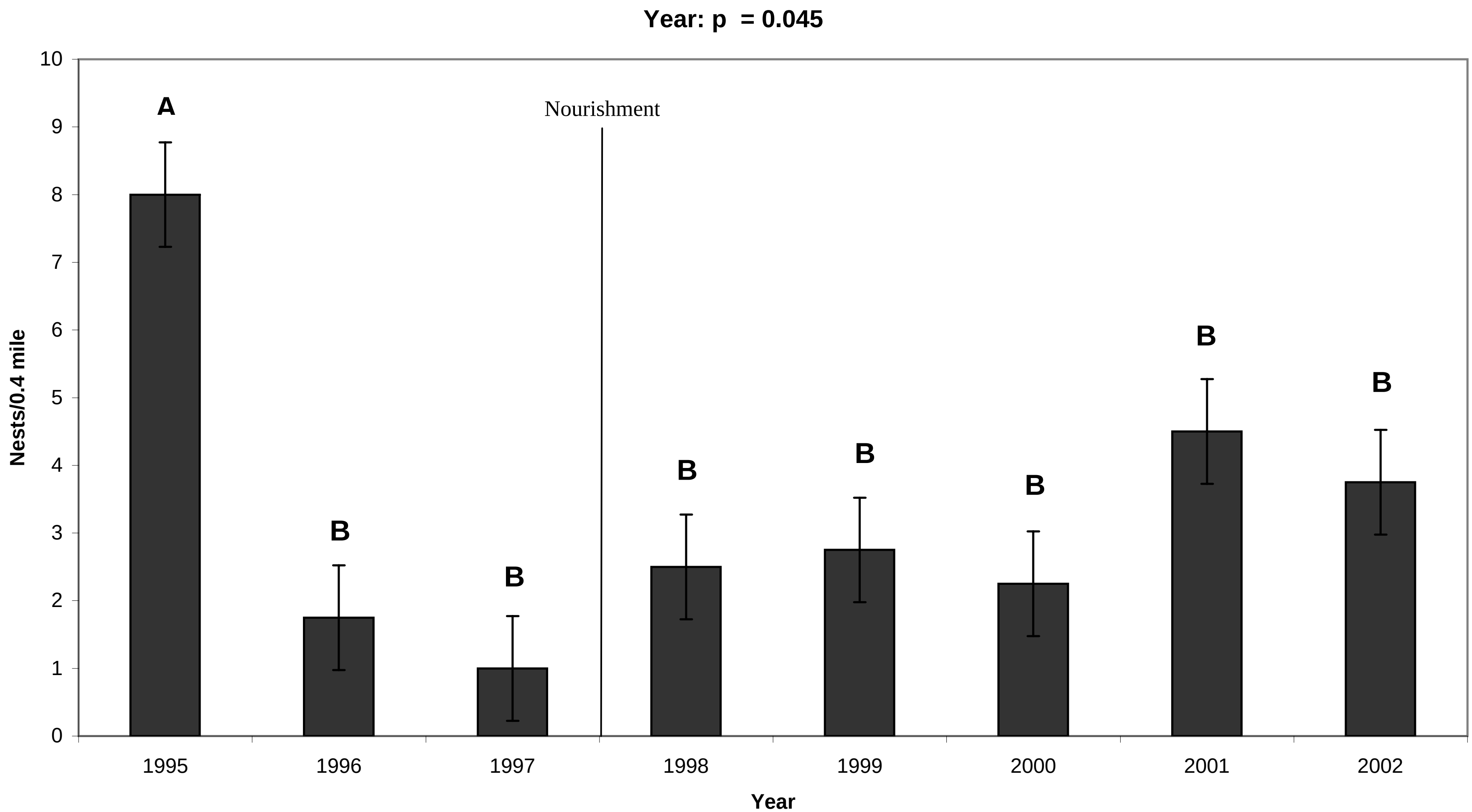
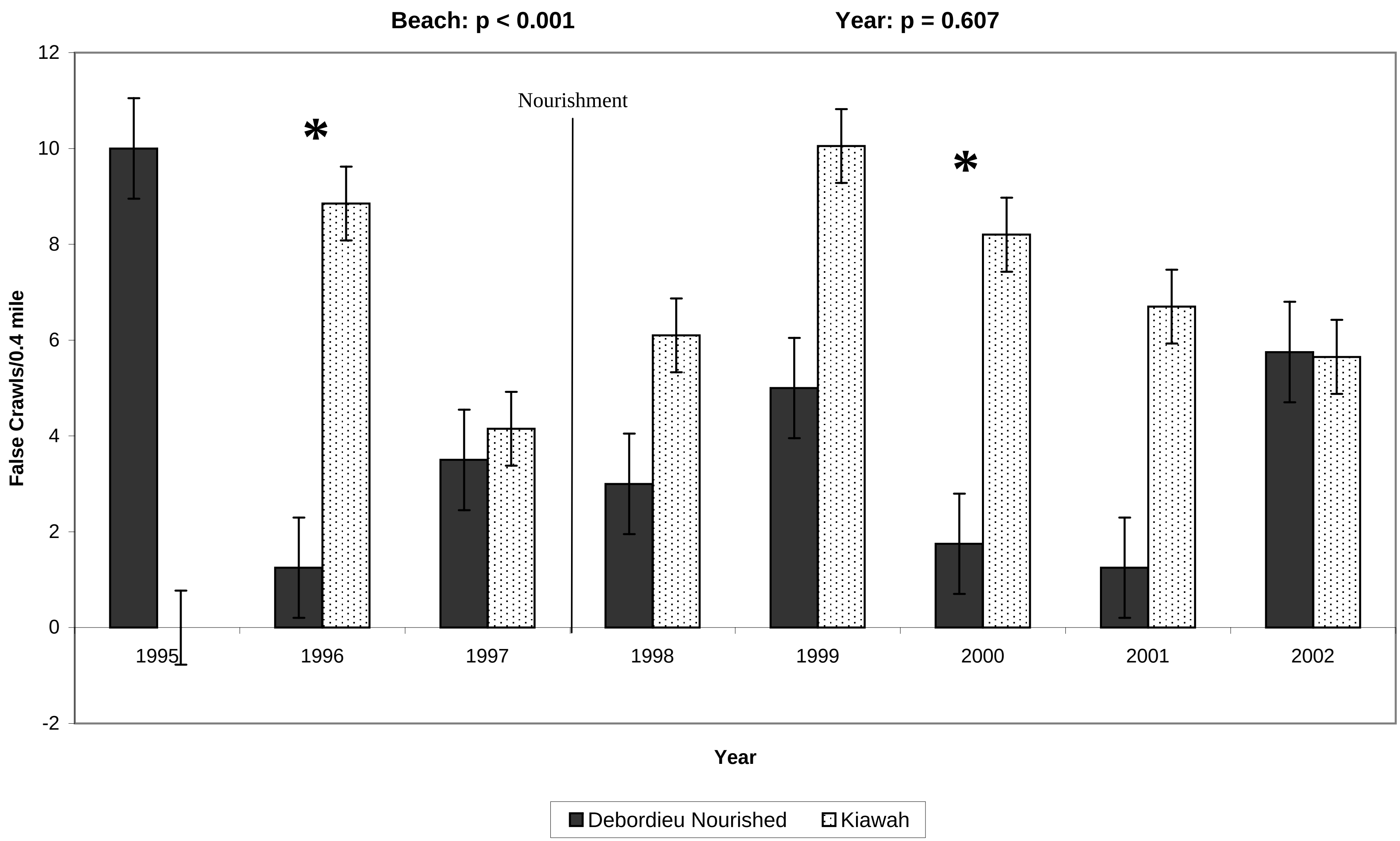

Beach: p = 0.903
Year: p = 0.021
Nourishment
Nests/0.4 mile
0
1
2
3
4
5
6
7
8
9
10
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 4. Nesting density on Debordieu Beach's nourished area pre- versus post-nourishment from 1995 – 2000. Letters indicate significant differences between years.



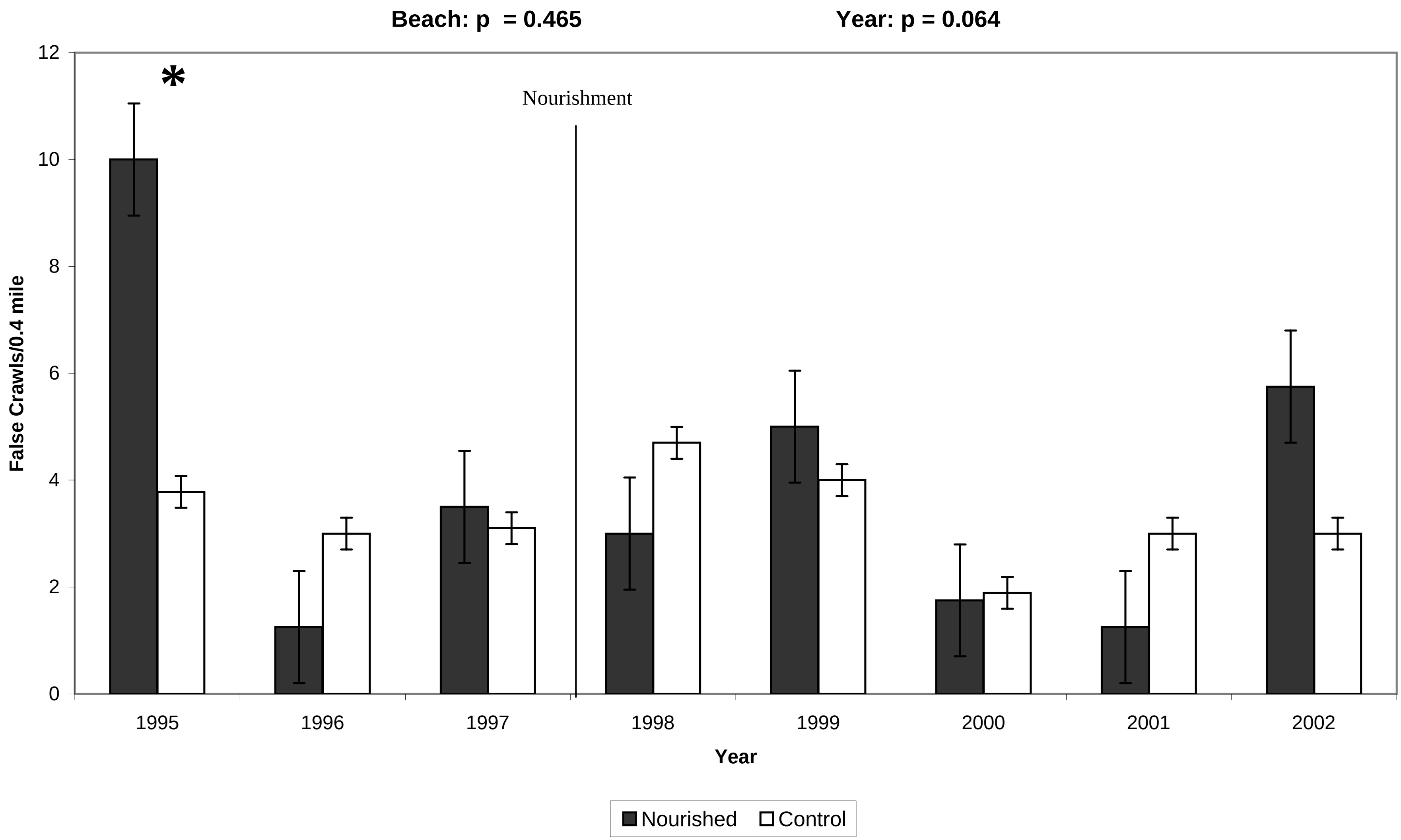
Year: p = 0.045
10
9
8
7
6
5
4
3
2
1
0
Nests/0.4 mile
A
B
B
B
B
B
B
B
Nourishment
1995
1996
1997
1998
1999
2000
2001
2002
Year

Figure 5. False crawl density on Debordieu Beach versus Kiawah Island (control) from 1995 – 2000. Asterisks indicate significant differences between pairwise comparisons.



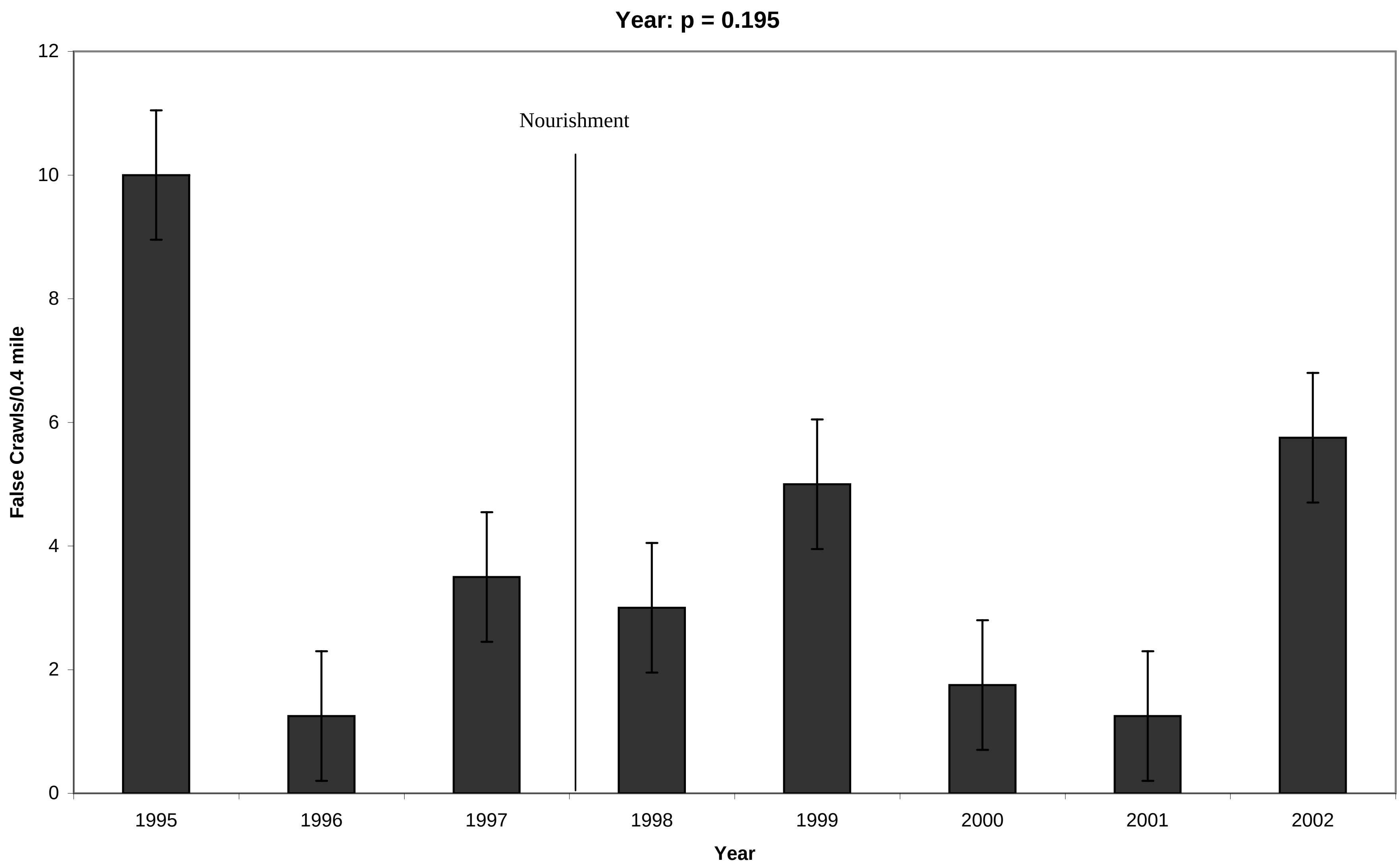
Beach: p < 0.001
Year: p = 0.607
Nourishment
*
*
12
10
8
6
4
2
0
-2
False Crawls/0.4 mile
1995
1996
1997
1998
1999
2000
2001
2002
Year
Debordieu Nourished
Kiawah

Figure 6. False crawl density on Debordieu Beach's nourished versus control beaches from 1995 – 2000. Asterisks indicate significant differences between pairwise comparisons.



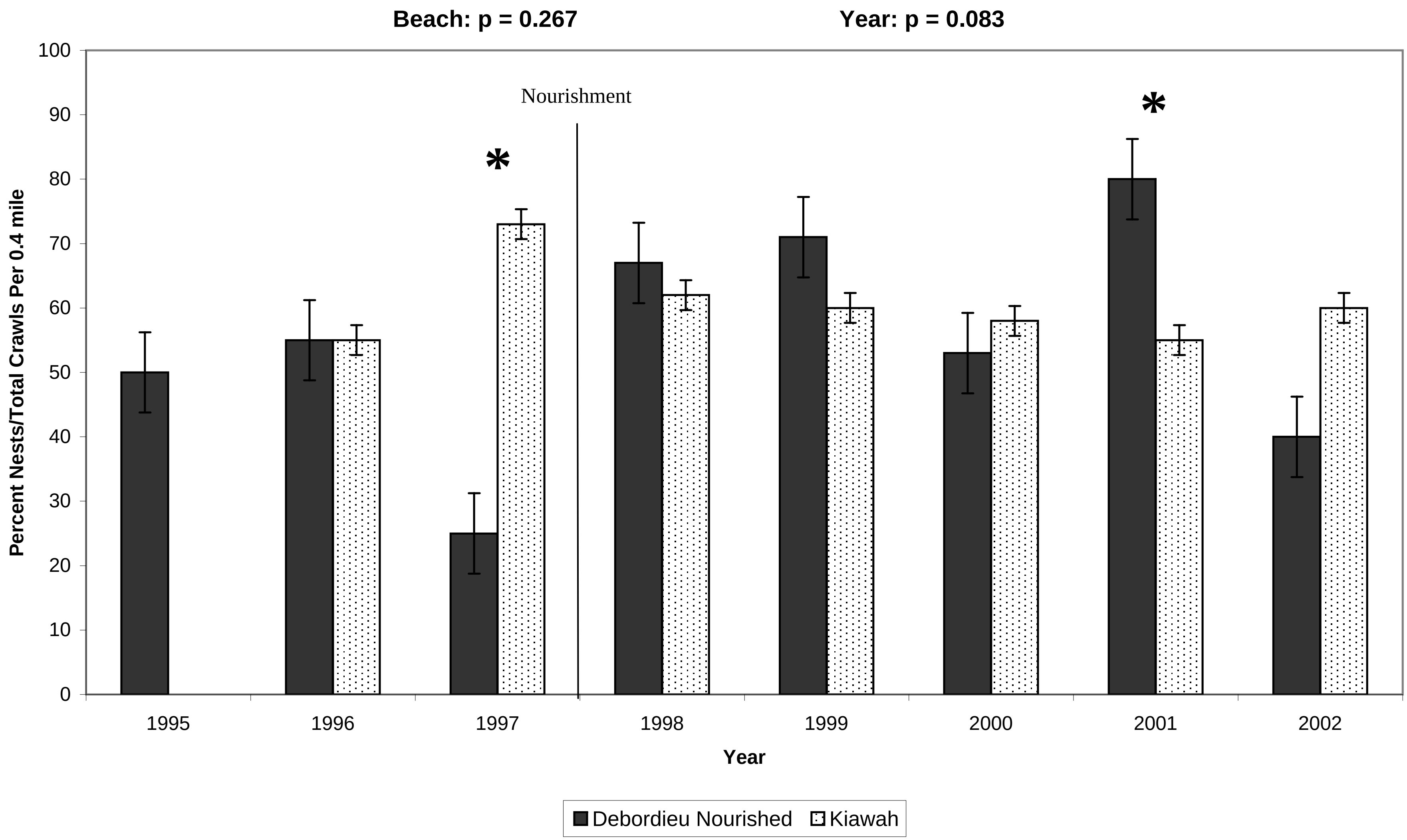
Beach: p = 0.465
Year: p = 0.064
*
Nourishment
False Crawls/0.4 mile
0
2
4
6
8
10
12
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 7. False crawl densities on Debordieu Beach's nourished area pre- versus post-nourishment from 1995 – 2000.



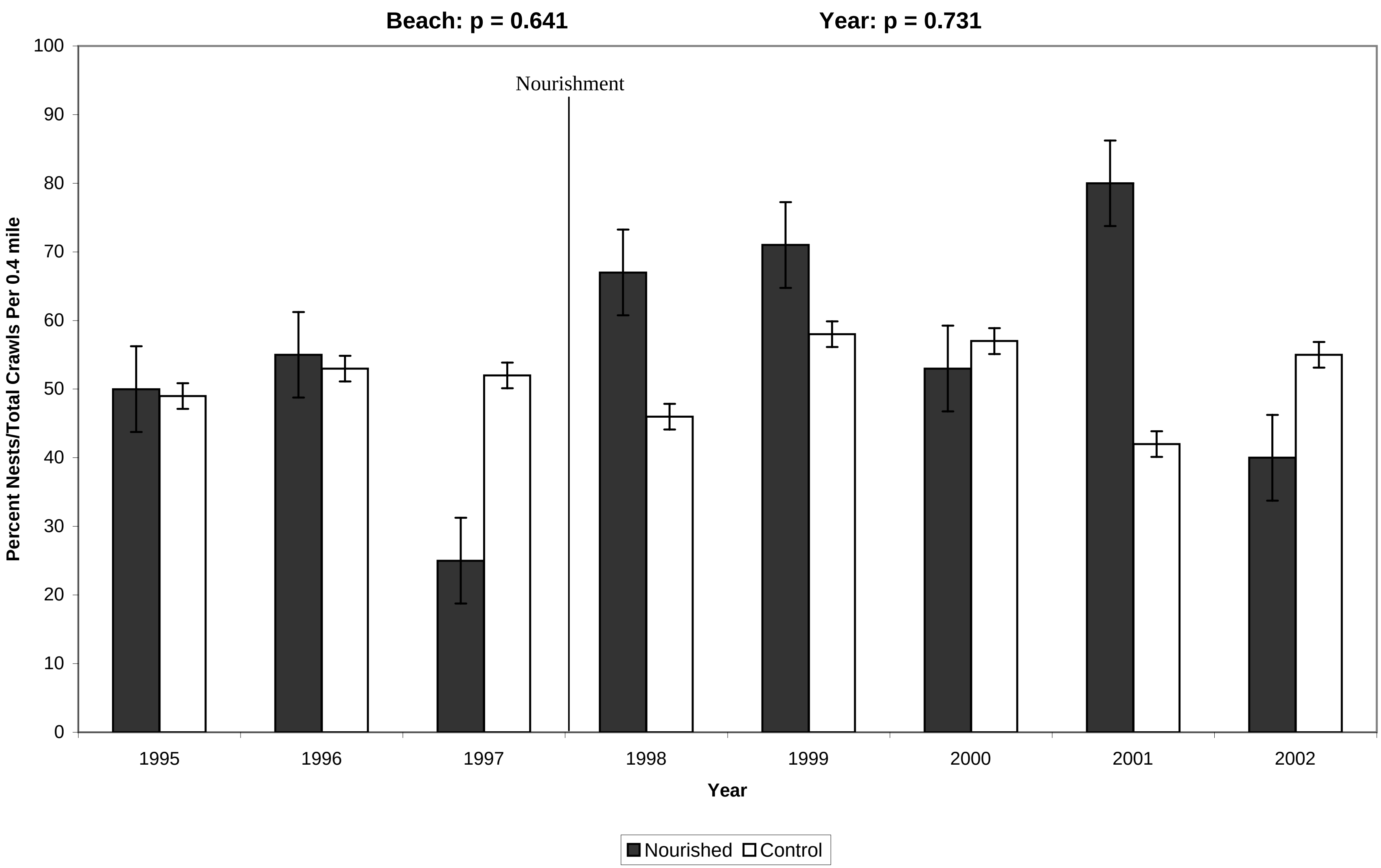
Year: p = 0.195
Nourishment
False Crawls/0.4 mile
Year
0
2
4
6
8
10
12
1995
1996
1997
1998
1999
2000
2001
2002

Figure 8. Nest to total crawl ratio on Debordieu Beach versus Kiawah Island from 1995 – 2000. Asterisks indicate significant differences between pairwise comparisons.



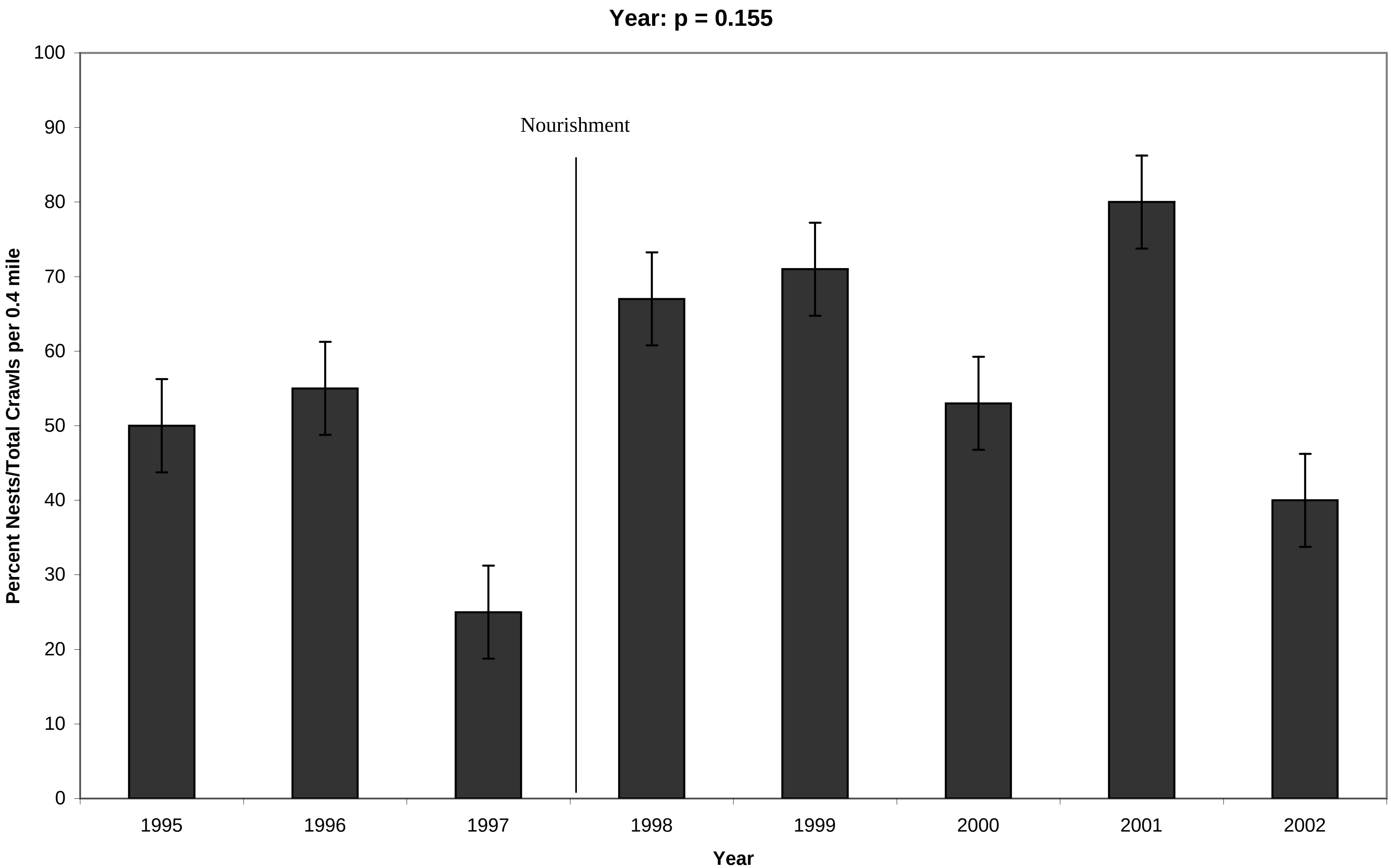
Beach: p = 0.267
Year: p = 0.083
Nourishment
*
*
Percent Nests/Total Crawls Per 0.4 mile
100
90
80
70
60
50
40
30
20
10
0
1995
1996
1997
1998
1999
2000
2001
2002
Year
Debordieu Nourished
Kiawah

Figure 9. Nest to total crawl ratio on Debordieu Beach’s nourished versus control beaches from 1995 – 2000. Asterisks indicate significant differences between pairwise comparisons.



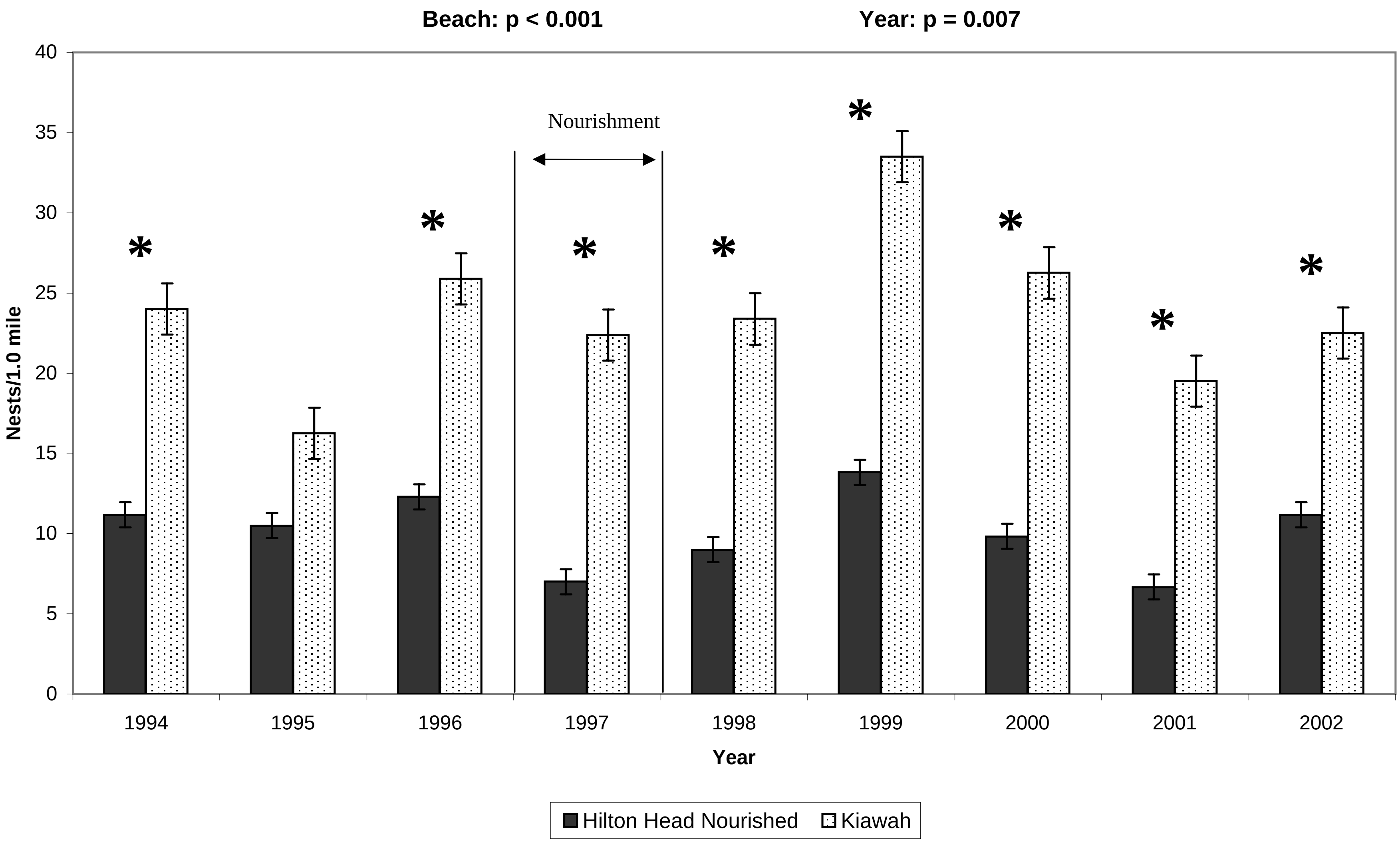
Beach: p = 0.641
Year: p = 0.731
Nourishment
Percent Nests/Total Crawls Per 0.4 mile
100
90
80
70
60
50
40
30
20
10
0
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 10. Nest to total crawl ratios on Debordieu Beach's nourished area pre- versus post- nourishment from 1995 – 2000.



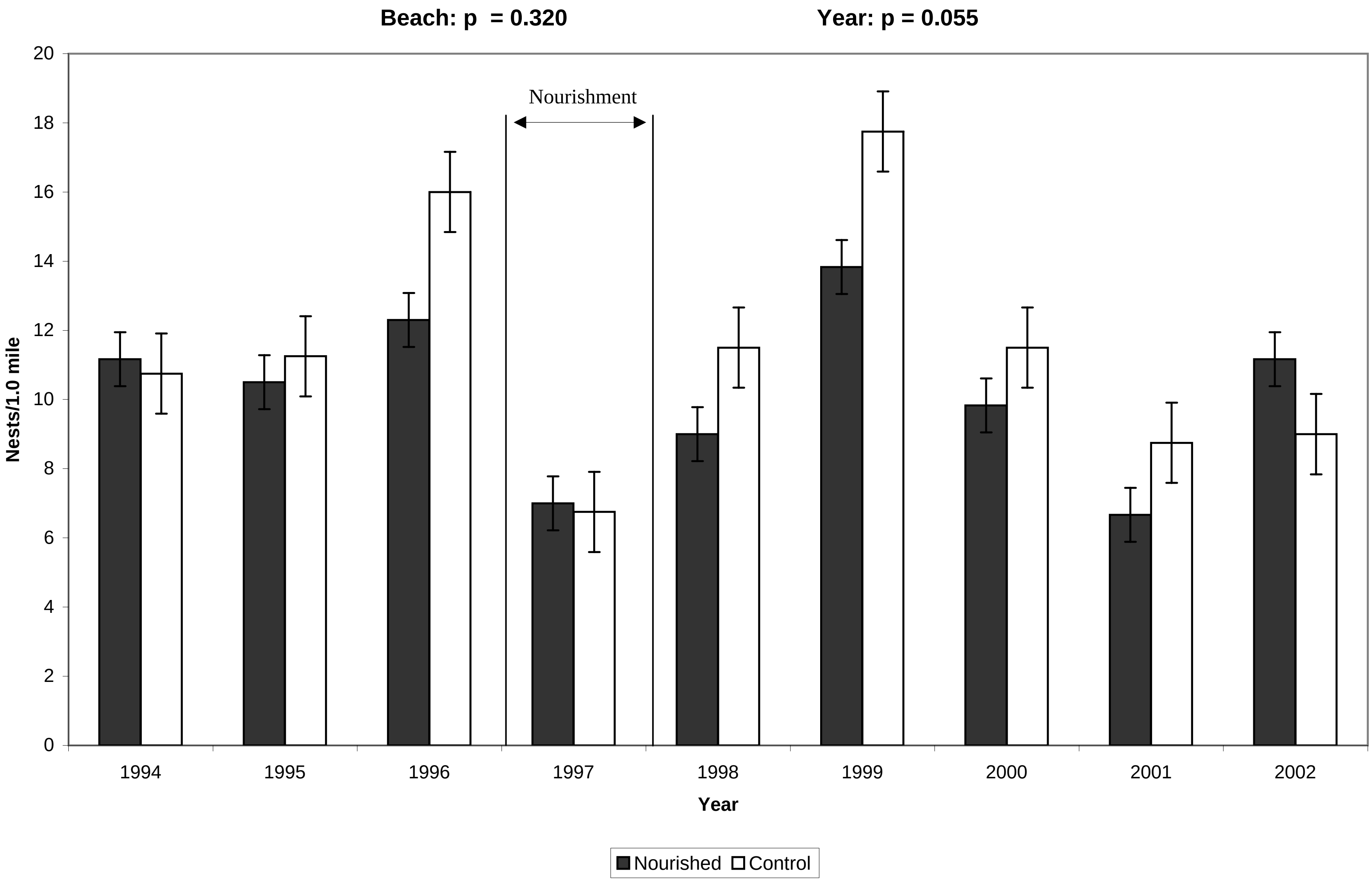
Year: p = 0.155
Nourishment
Percent Nests/Total Crawls per 0.4 mile
100
90
80
70
60
50
40
30
20
10
0
1995
1996
1997
1998
1999
2000
2001
2002
Year

Figure 11. Nesting densities on Hilton Head Island versus Kiawah Island (control) from 1994 – 2002. Asterisks indicate significant differences between pairwise comparisons.



Beach: p < 0.001
Year: p = 0.007
Nourishment
Nests/1.0 mile
40
35
30
25
20
15
10
5
0
1994
1995
1996
1997
1998
1999
2000
2001
2002
Year
Hilton Head Nourished
Kiawah

Figure 12. Nesting densities on Hilton Head Island's nourished versus control beaches from 1994 – 2002.



Beach: p = 0.320
Year: p = 0.055
Nourishment
Nests/1.0 mile
0
2
4
6
8
10
12
14
16
18
20
1994
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 13. Nesting densities on Hilton Head Island's nourished area pre- versus post- nourishment from 1994 – 2002.

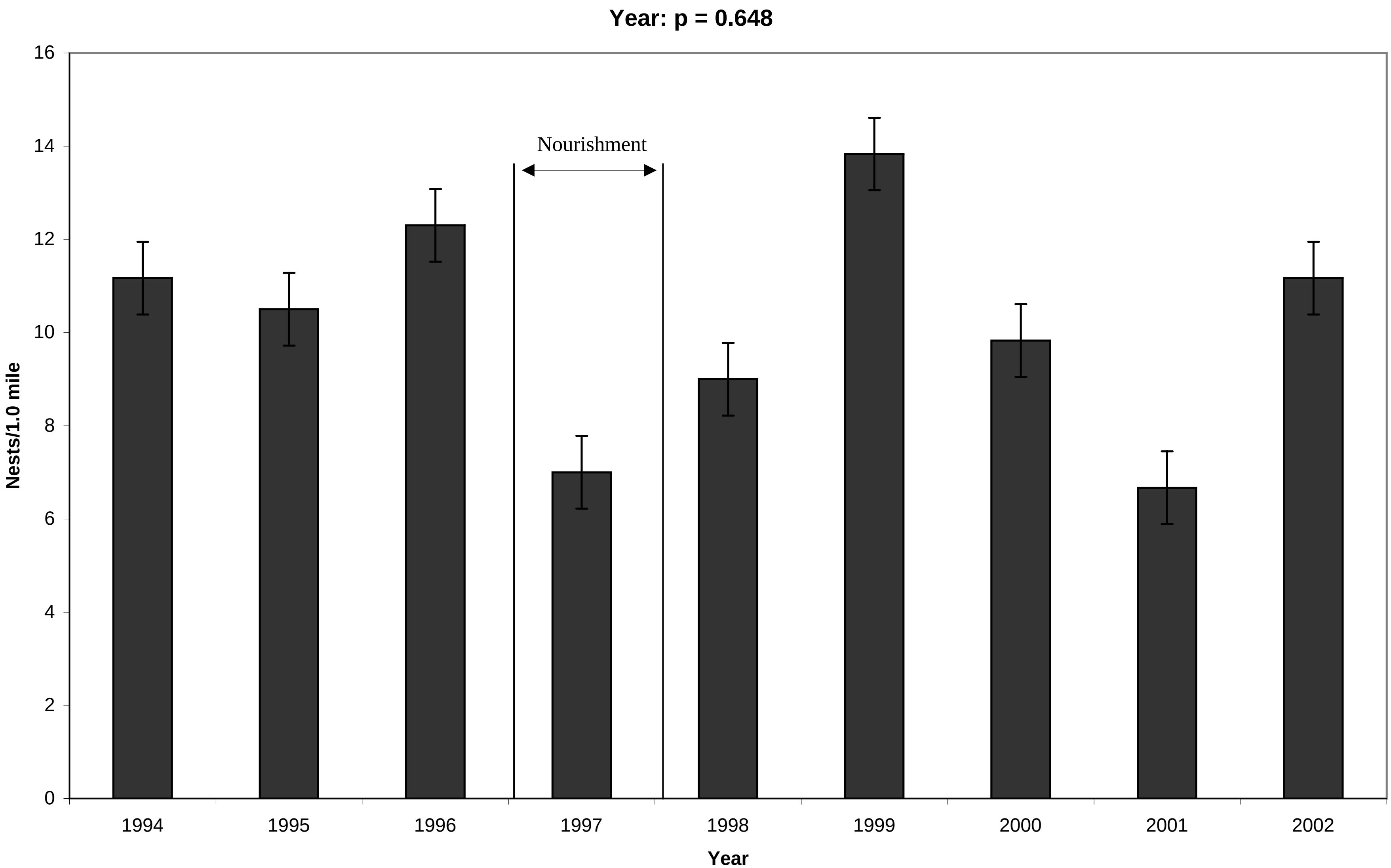

Year: p = 0.648
Nourishment
Nests/1.0 mile
Year
0
2
4
6
8
10
12
14
16
1994
1995
1996
1997
1998
1999
2000
2001
2002

Figure 14. False crawl densities on Hilton Head Island's nourished beach versus Kiawah Island (control) from 1995 – 2002. Asterisks indicate significant differences between pairwise comparisons.

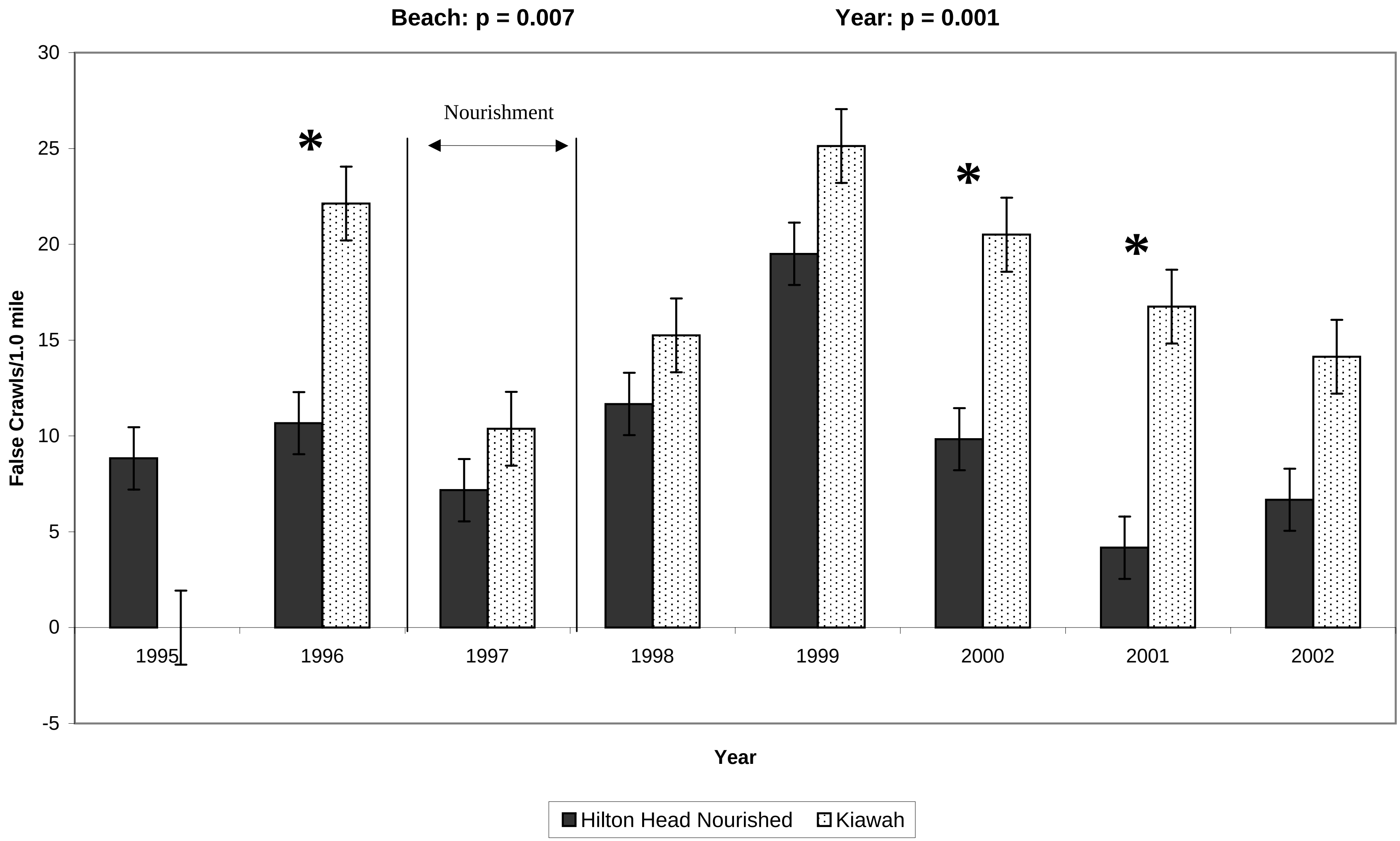
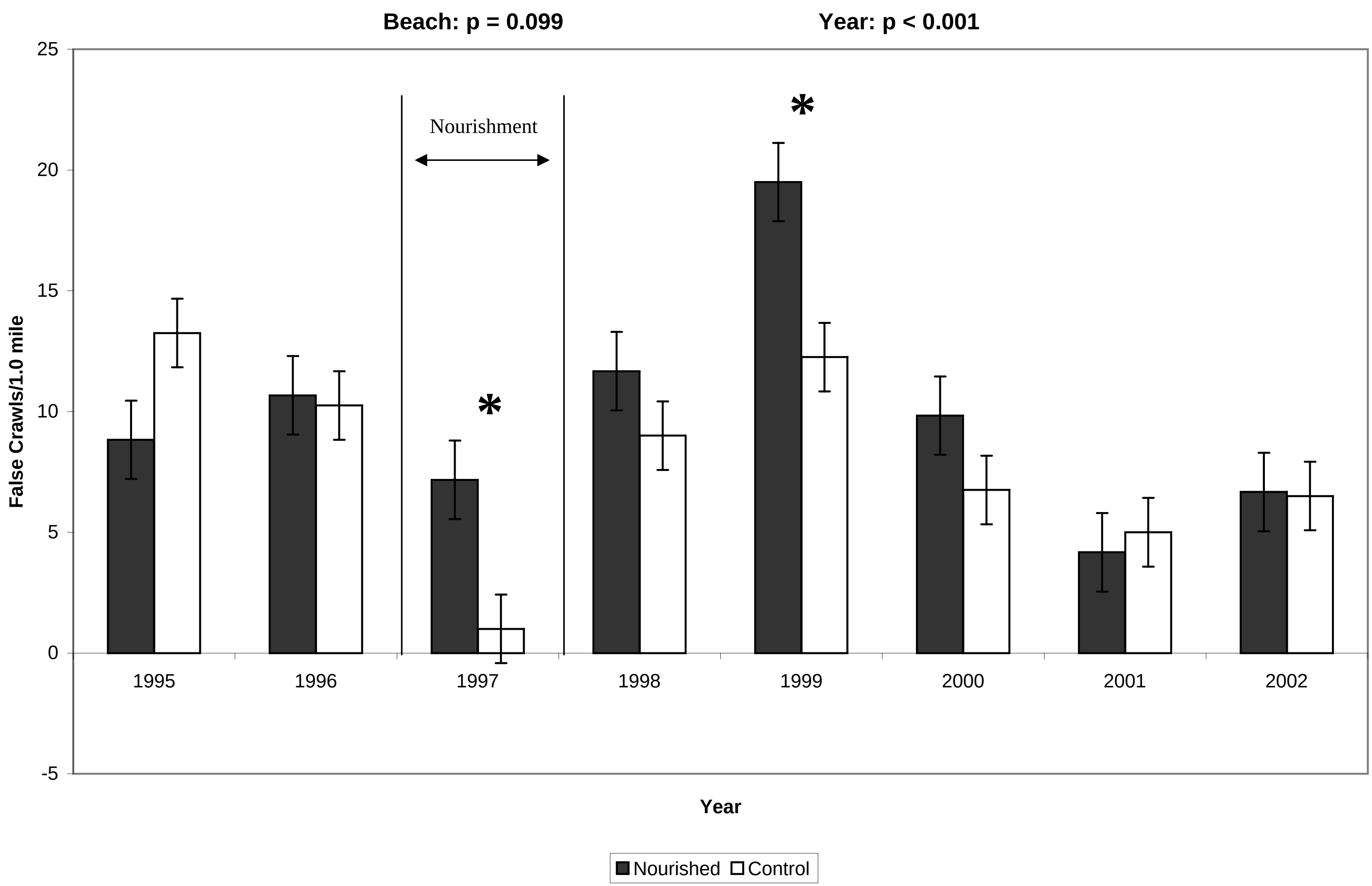
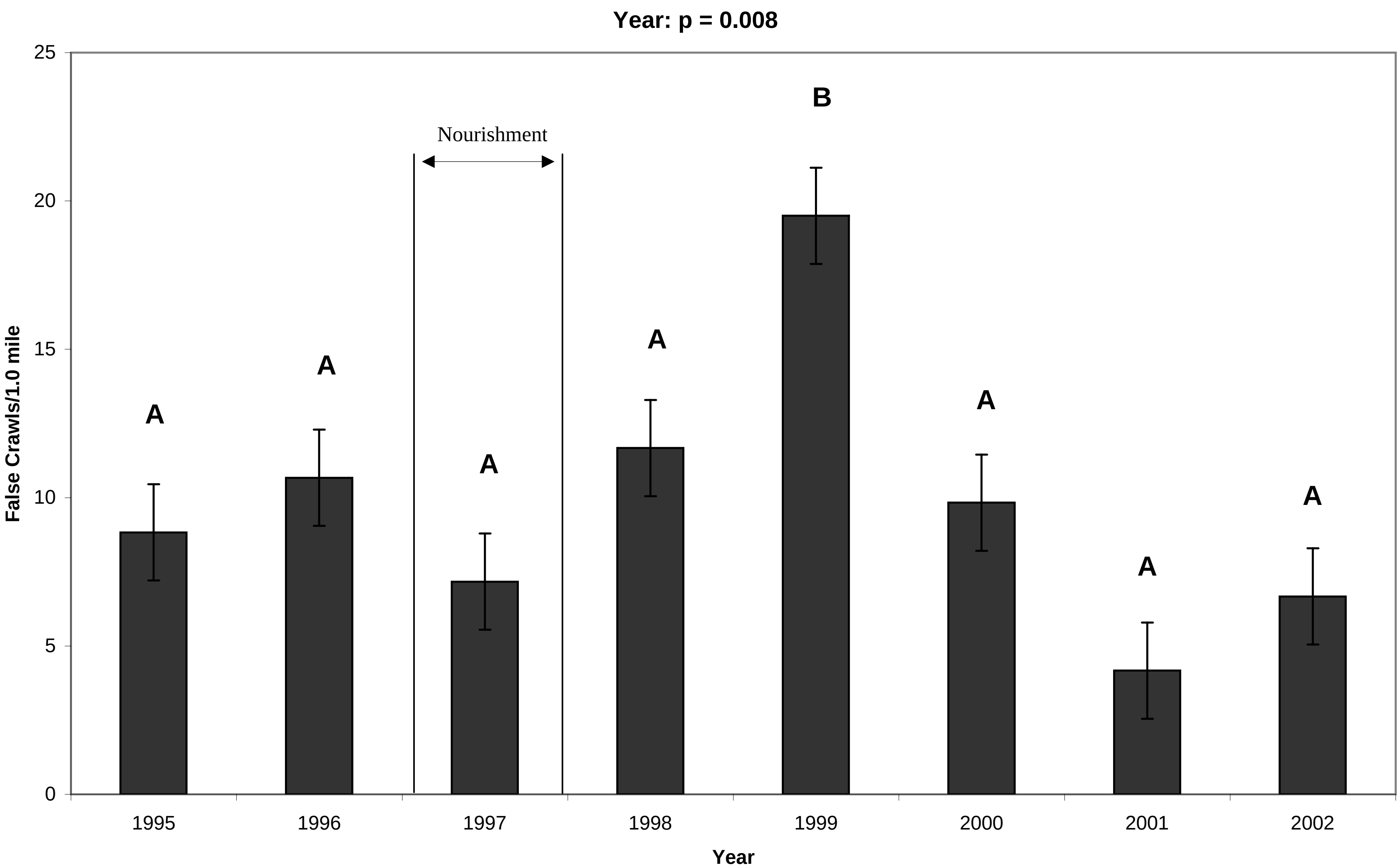

Beach: p = 0.007
Year: p = 0.001
Nourishment
*
30
25
20
15
10
5
0
-5
False Crawls/1.0 mile
1995
1996
1997
1998
1999
2000
2001
2002
Year
Hilton Head Nourished
Kiawah

Figure 15. False crawl densities on Hilton Head Island's nourished versus control beaches from 1995 – 2002. Asterisks indicate significant differences between pairwise comparisons.



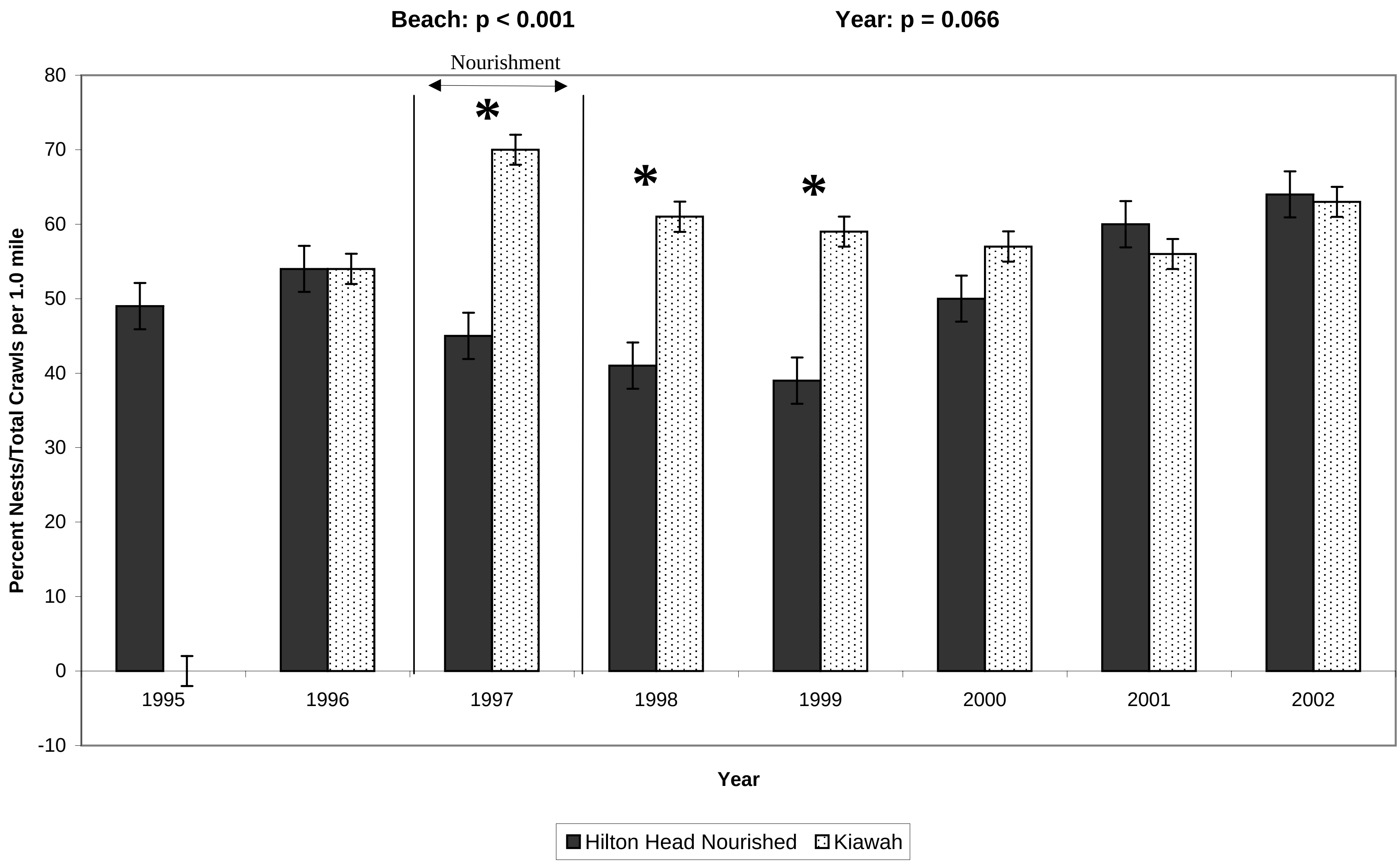
Beach: p = 0.099
Year: p < 0.001
False Crawls/1.0 mile
25
20
15
10
5
0
-5
Nourishment
*
*
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 16. False crawl densities on Hilton Head Island's nourished area pre- versus post-nourishment from 1995 – 2002. Letters indicate significant differences between years.



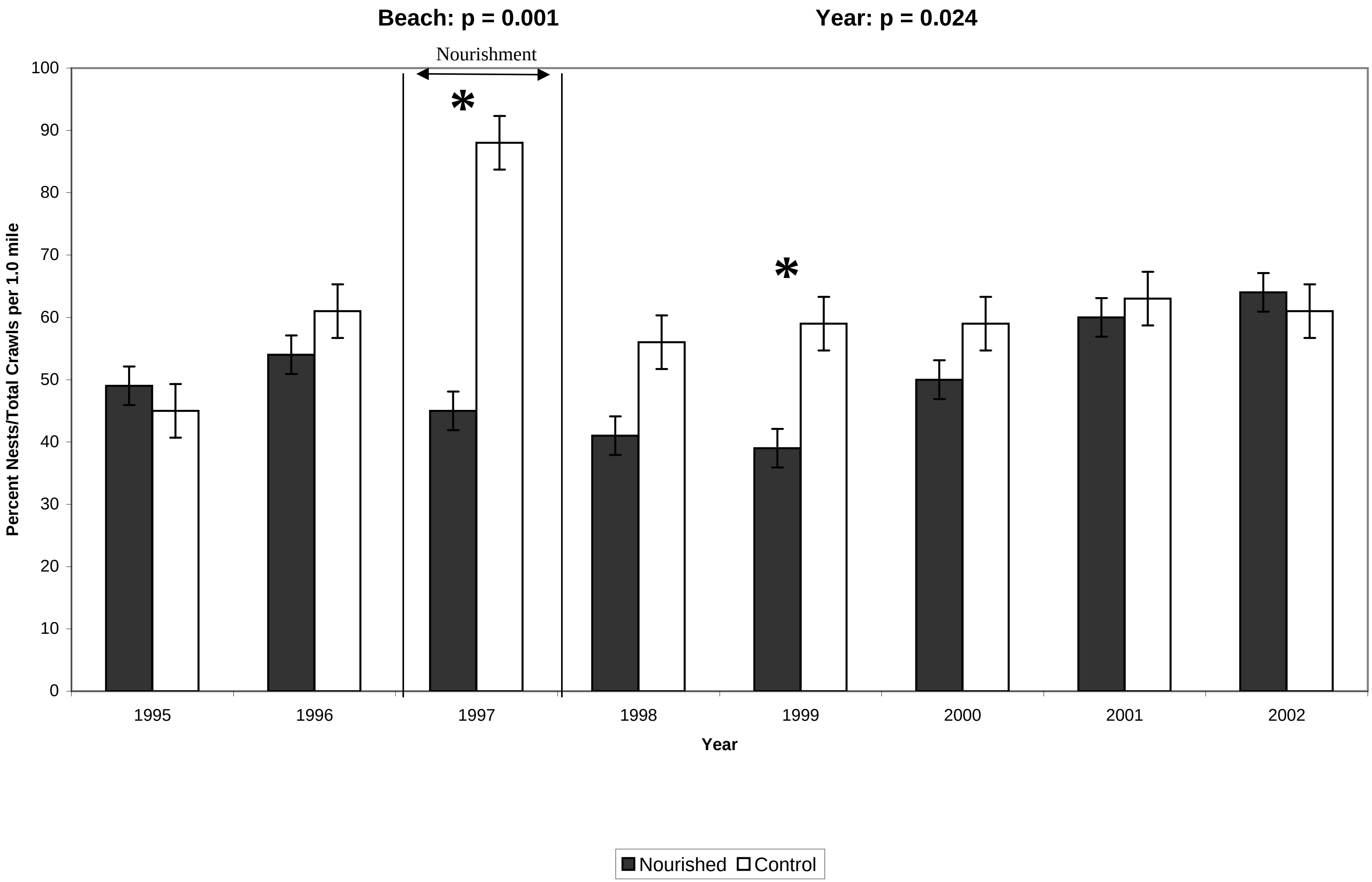
Year: p = 0.008
Nourishment
False Crawls/1.0 mile
Year
0
5
10
15
20
25
1995
1996
1997
1998
1999
2000
2001
2002
A
A
A
A
B
A
A
A

Figure 17. Nest to total crawl ratio on Hilton Head Island's nourished beach and Kiawah Island (control) from 1995 – 2002. Asterisks indicate significant differences between nourished and control nest to total crawl ratios between years.



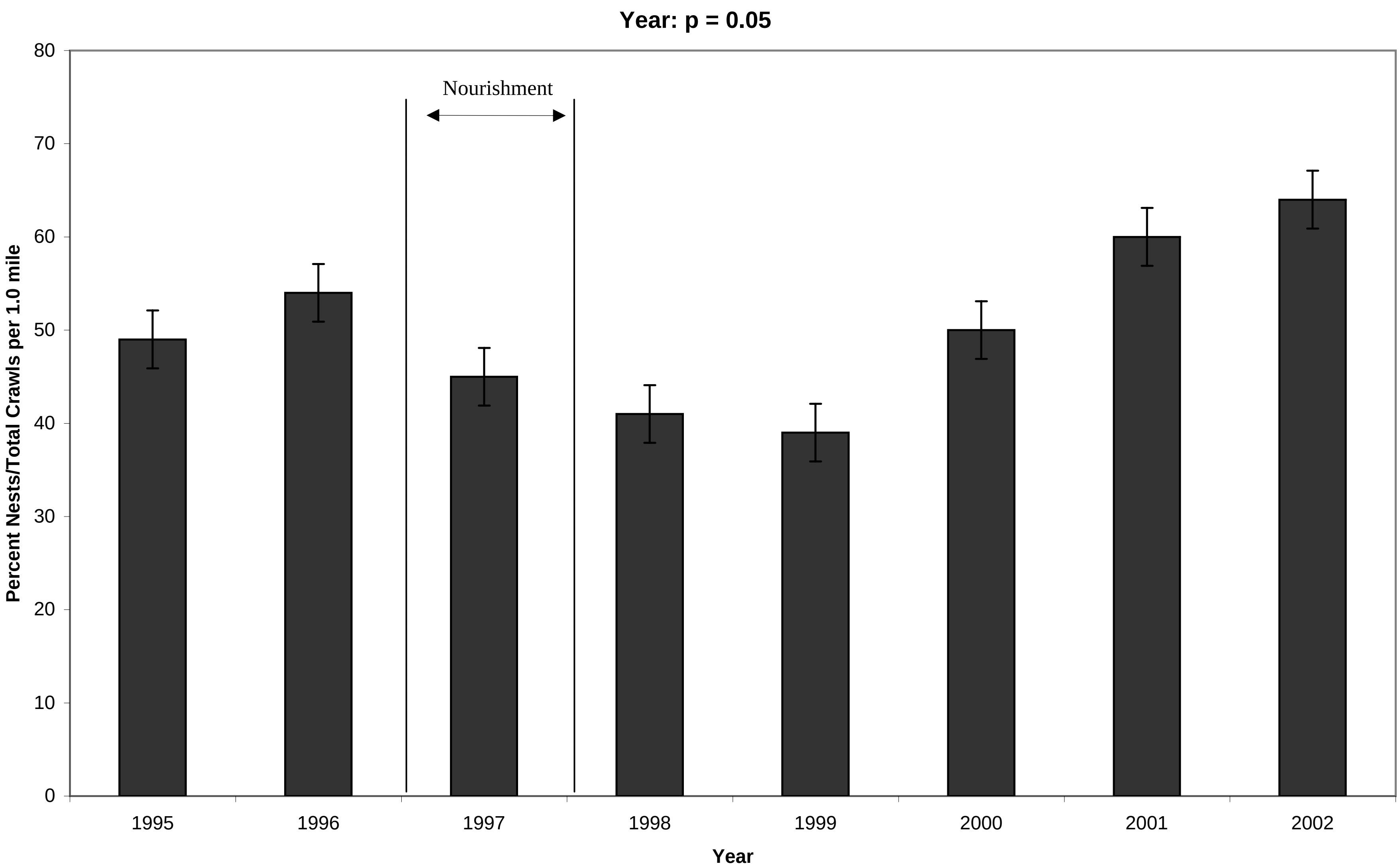
Beach: p < 0.001
Year: p = 0.066
Nourishment
*
*
*
80
70
60
50
40
30
20
10
0
-10
Percent Nests/Total Crawls per 1.0 mile
1995
1996
1997
1998
1999
2000
2001
2002
Year
Hilton Head Nourished
Kiawah

Figure 18. Nest to total crawl ratio on Hilton Head Island's nourished versus control beaches from 1995 – 2002. Asterisks indicate significant differences between pairwise comparisons.



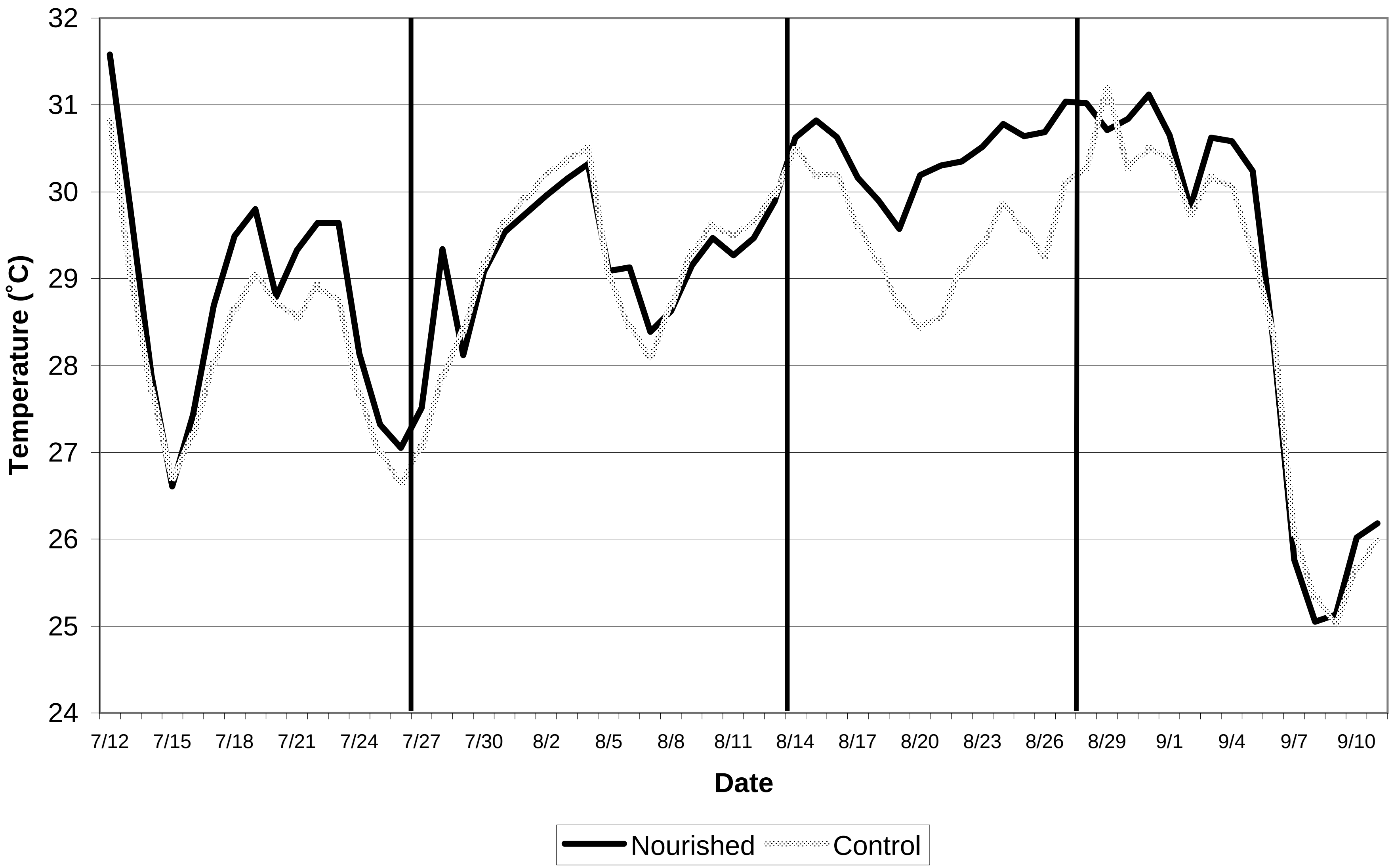
Beach: p = 0.001
Year: p = 0.024
Nourishment
Percent Nests/Total Crawls per 1.0 mile
0
10
20
30
40
50
60
70
80
90
100
1995
1996
1997
1998
1999
2000
2001
2002
Year
Nourished
Control

Figure 19. Nest to total crawl ratios on Hilton Head Island's nourished area pre- versus post- nourishment from 1995 – 2002.



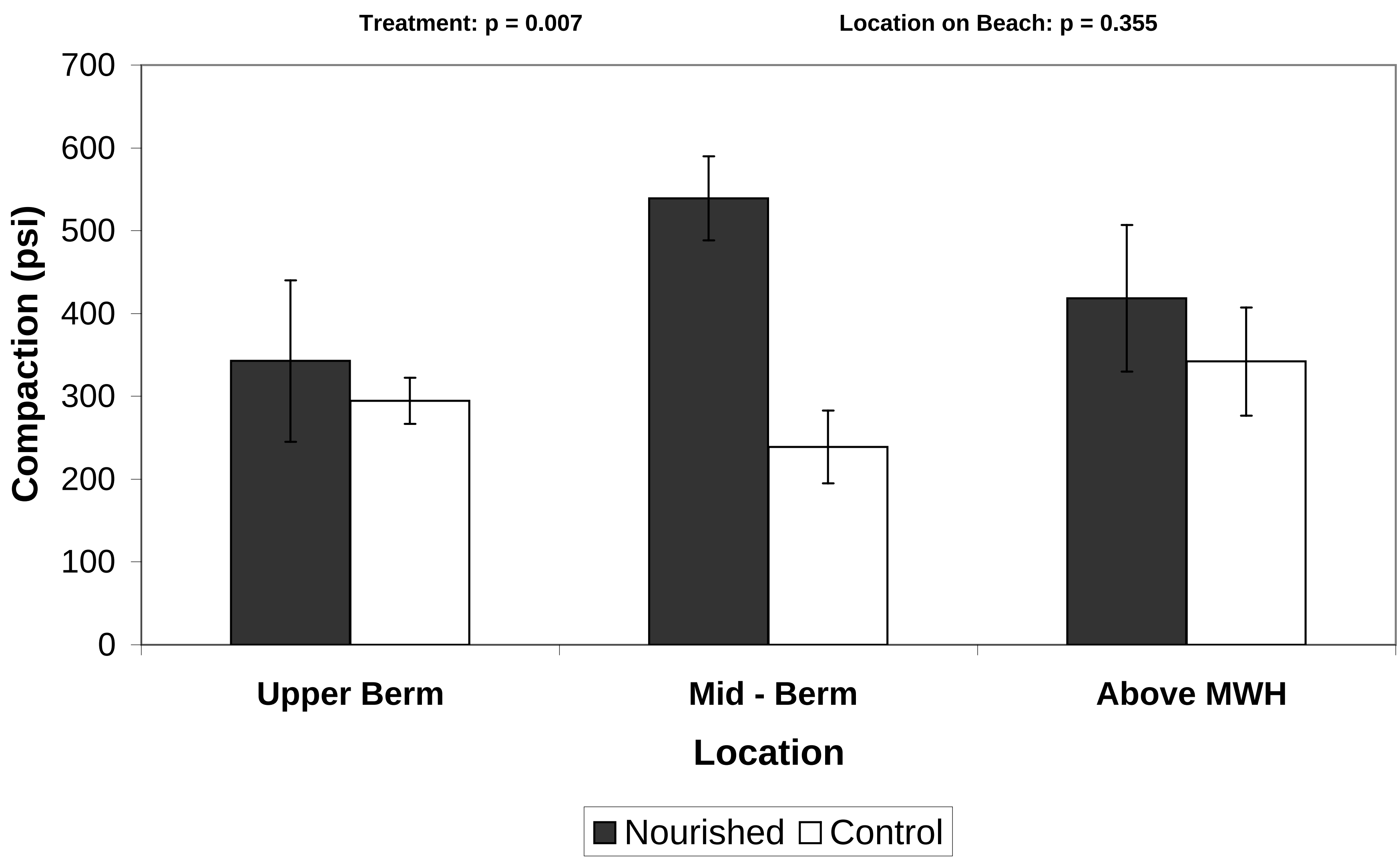
Year: p = 0.05
Nourishment
Percent Nests/Total Crawls per 1.0 mile
0
10
20
30
40
50
60
70
80
1995
1996
1997
1998
1999
2000
2001
2002
Year

Figure 20. Comparison of temperature on Hunting Island's nourished and control beaches.



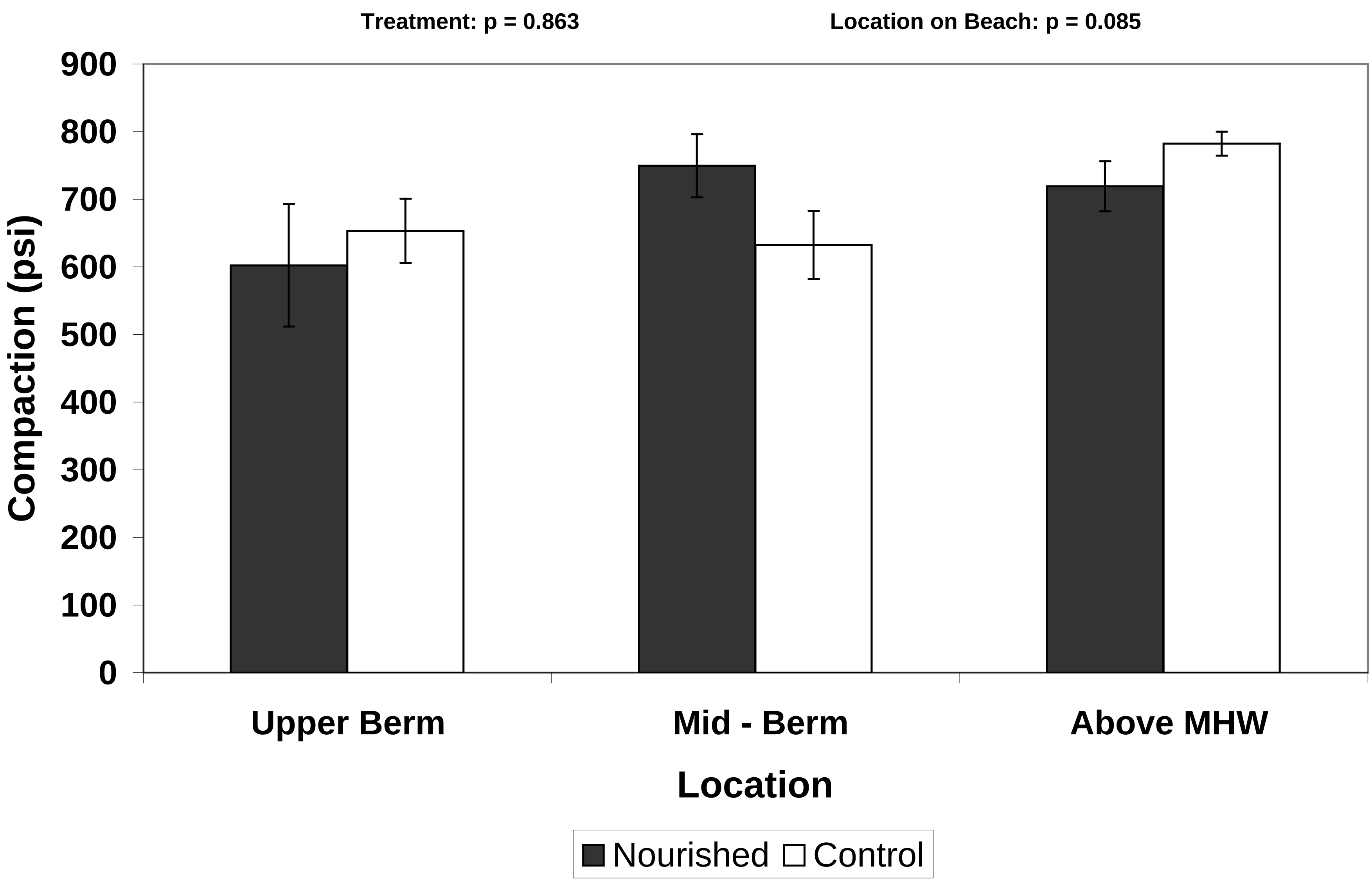
Temperature (˚C)
32
31
30
29
28
27
26
25
24
7/12
7/15
7/18
7/21
7/24
7/27
7/30
8/2
8/5
8/8
8/11
8/14
8/17
8/20
8/23
8/26
8/29
9/1
9/4
9/7
9/10
Date
Nourished
Control

Figure 21. Comparison of compaction on Hunting Island's nourished and control beaches at 15 cm sand depth in 2003. The nourished beach was significantly more compact.



Treatment: p = 0.007
Location on Beach: p = 0.355
Compaction (psi)
700
600
500
400
300
200
100
0
Upper Berm
Mid - Berm
Above MWH
Location
Nourished
Control

Figure 22. Comparison of compaction on Hunting Island's nourished and control beaches at 30 cm sand depth in 2003.



Treatment: p = 0.863
Location on Beach: p = 0.085
900
800
700
600
500
400
300
200
100
0
Compaction (psi)
Upper Berm
Mid - Berm
Above MHW
Location
Nourished
Control

Figure 23. Comparison of compaction on Hunting Island's nourished and control beaches at 45 cm sand depth in 2003.

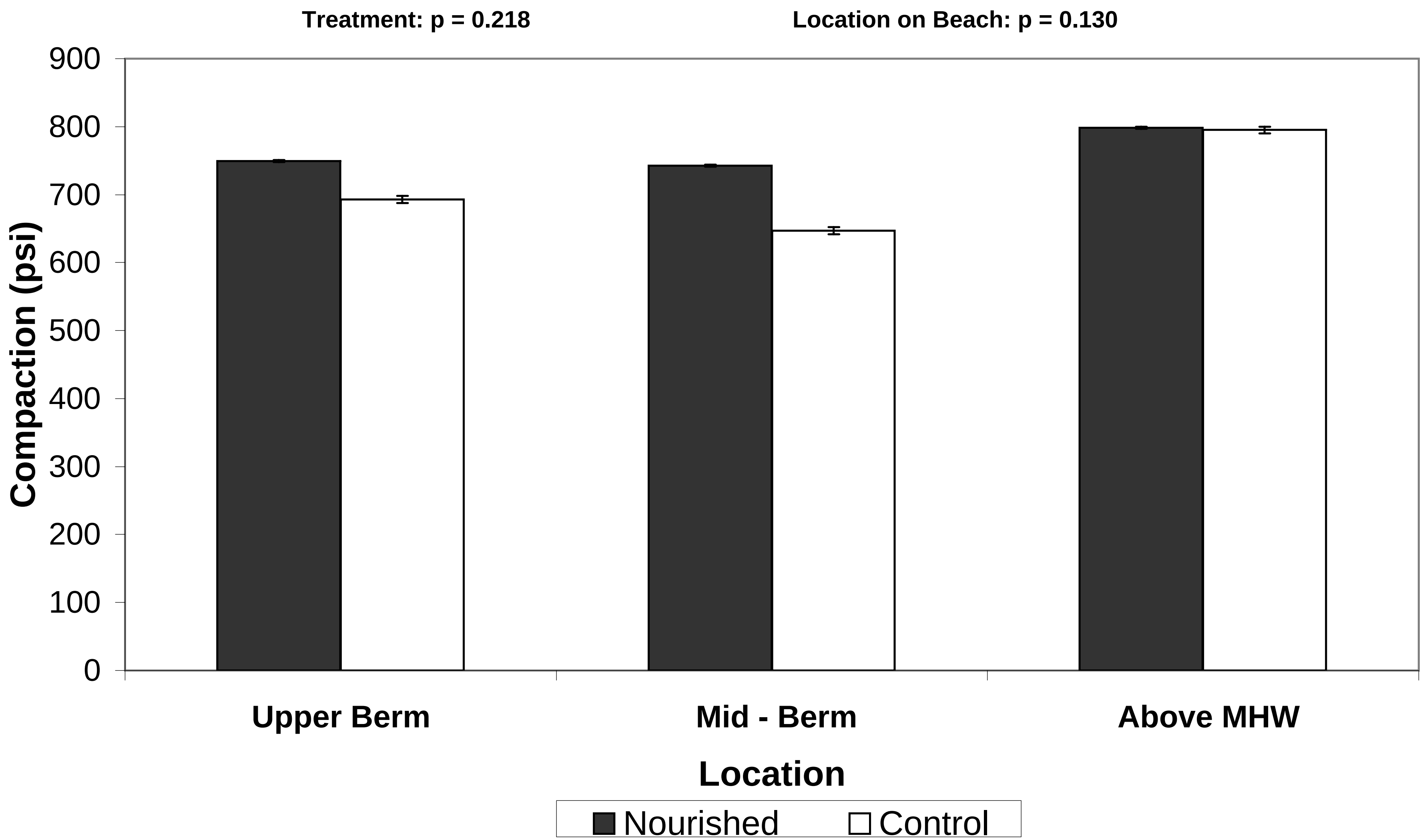
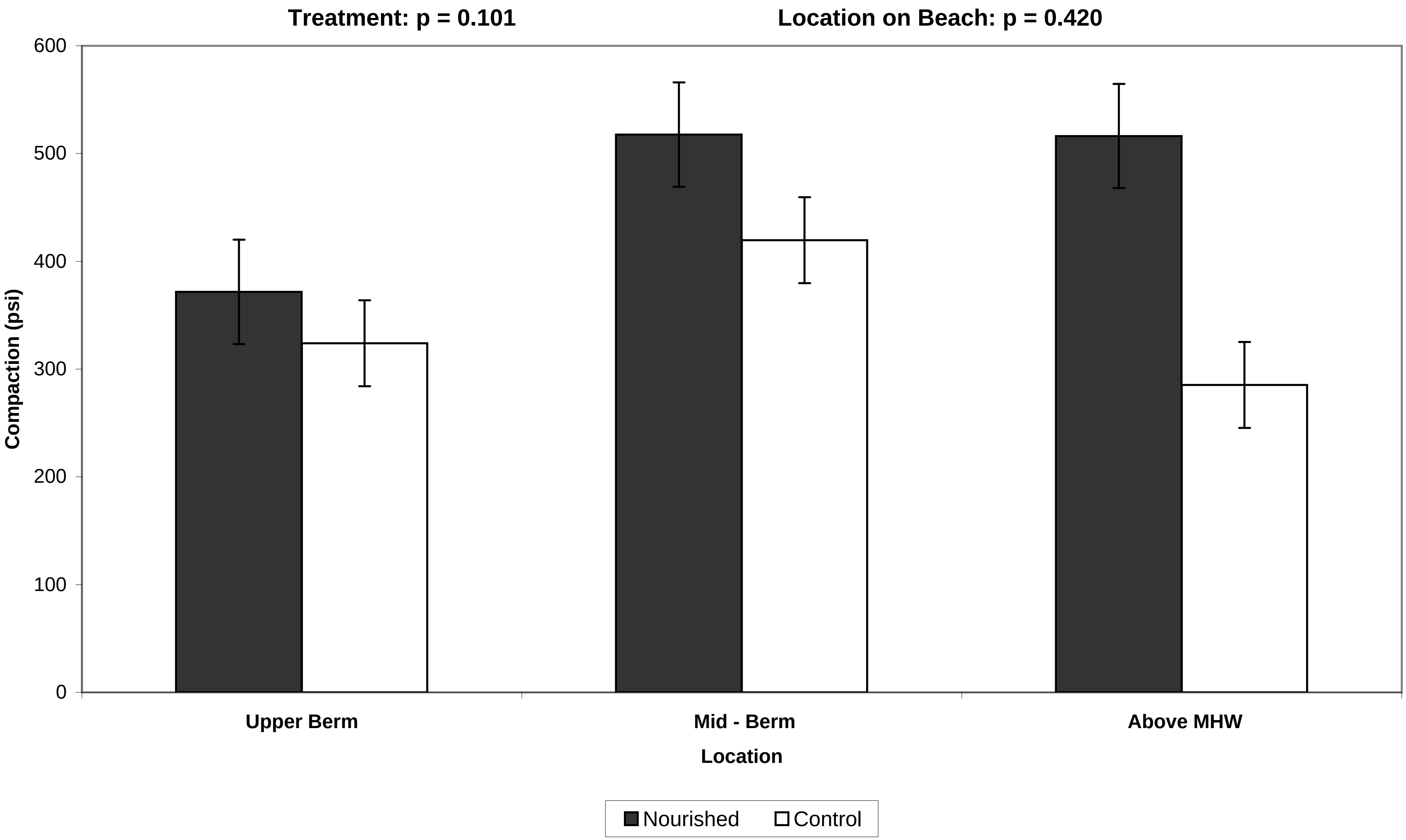

Treatment: p = 0.218
Location on Beach: p = 0.130
900
800
700
600
500
400
300
200
100
0
Compaction (psi)
Upper Berm
Mid - Berm
Above MHW
Location
Nourished
Control

Figure 24. Comparison of compaction on Hunting Island’s nourished and control beaches at 15 cm sand depth in 2004.



Treatment: p = 0.101
Location on Beach: p = 0.420
600
500
400
300
200
100
0
Compaction (psi)
Upper Berm
Mid - Berm
Above MHW
Location
Nourished
Control

Figure 25. Comparison of compaction on Hunting Island’s nourished and control beaches at 30 cm sand depth in 2004.

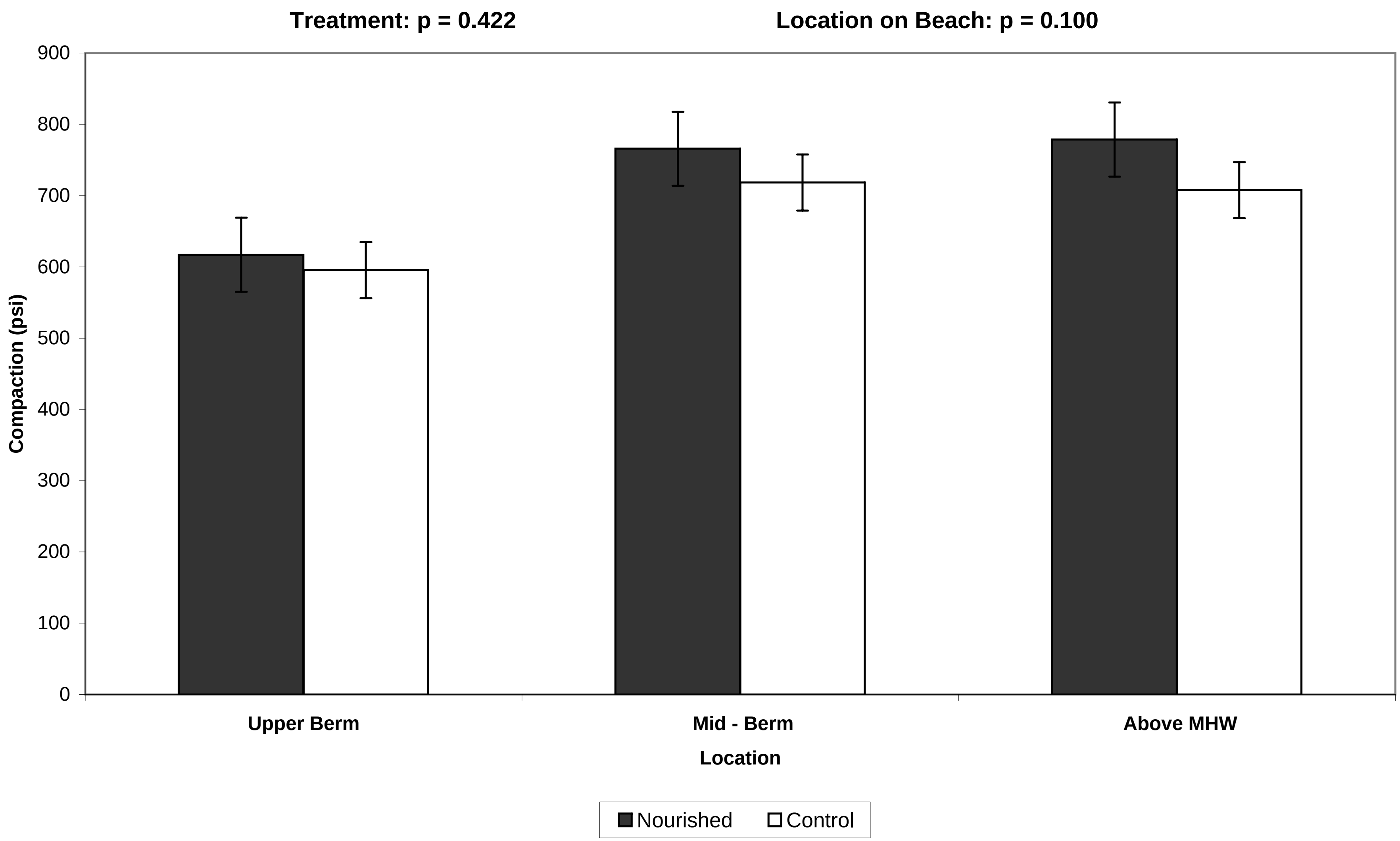
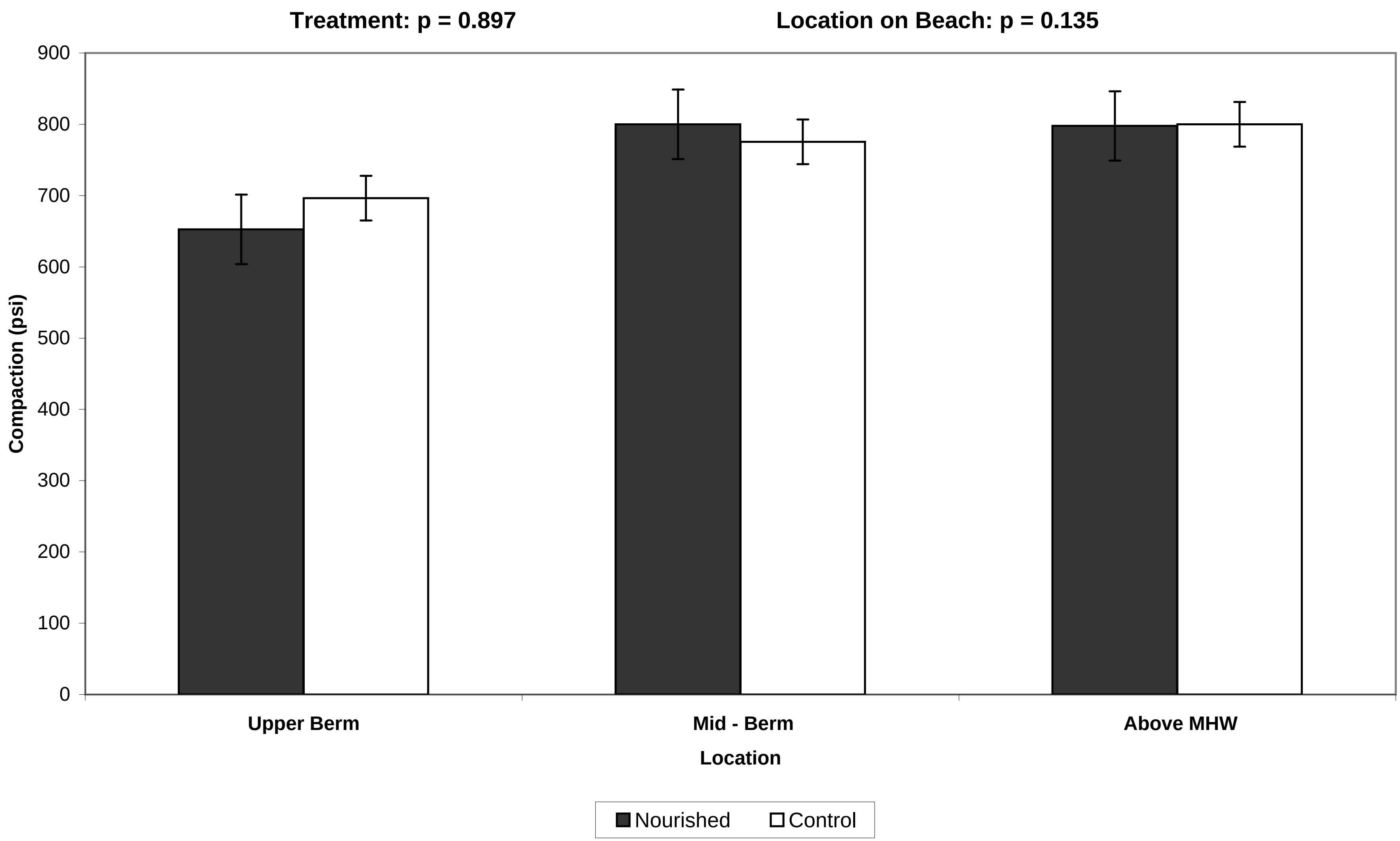

Treatment: p = 0.422
Location on Beach: p = 0.100
900
800
700
600
500
400
300
200
100
0
Compaction (psi)
Upper Berm
Mid - Berm
Above MHW
Location
Nourished
Control

Figure 26. Comparison of compaction on Hunting Island's nourished and control beaches at 45 cm sand depth in 2004.



Treatment: p = 0.897
Location on Beach: p = 0.135
Compaction (psi)
900
800
700
600
500
400
300
200
100
0
Upper Berm
Mid - Berm
Above MHW
Location
Nourished
Control

Figure 27. Box plot comparisons of mean grain size on Hunting Island's nourished and control beaches. The middle line on the box indicates the median, the top and bottom of the box indicate the 25th and 75th quartile, and the lines outside of the box indicate the 5th and 95th quartile. Grain size on the nourished beach was significantly coarser than the reference beach.

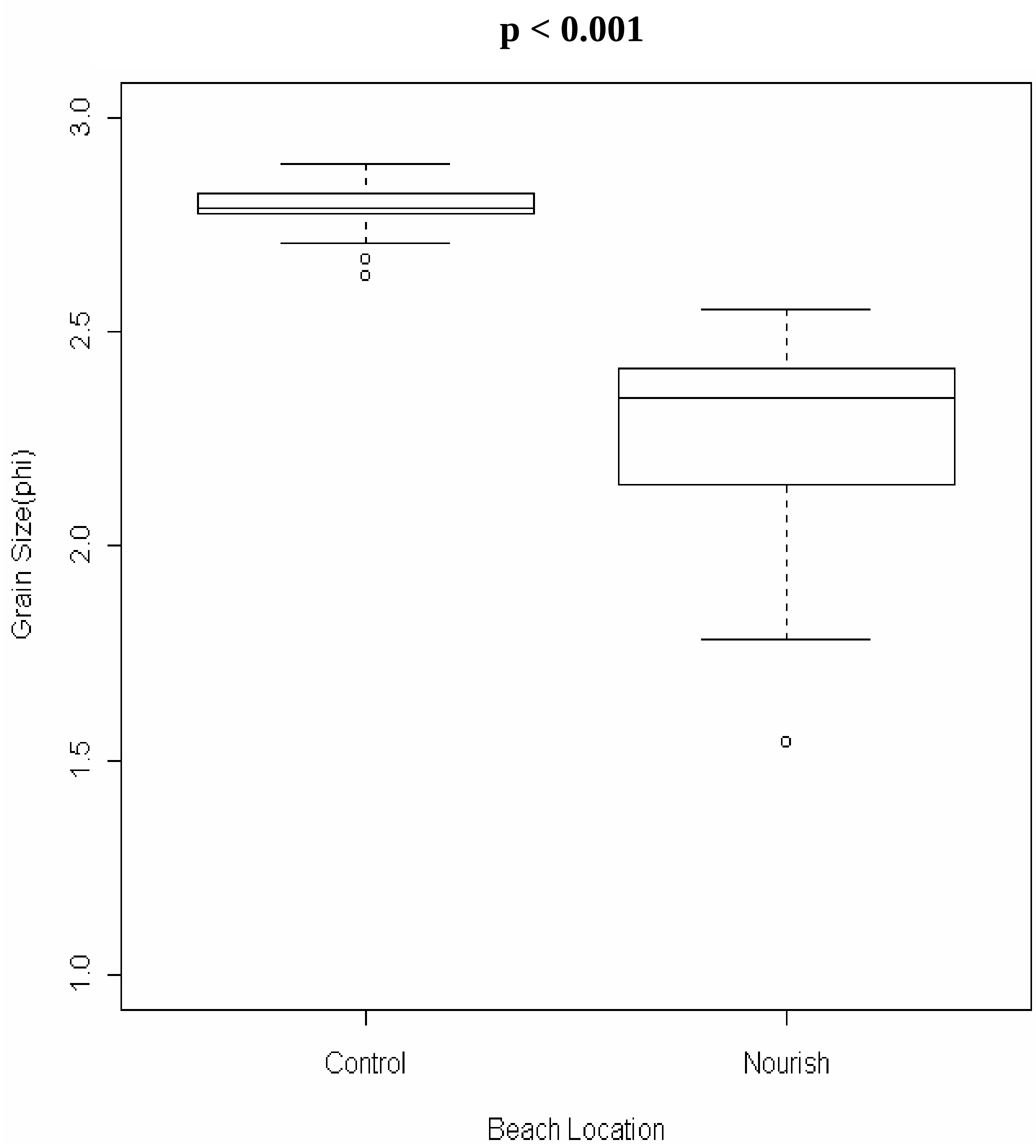
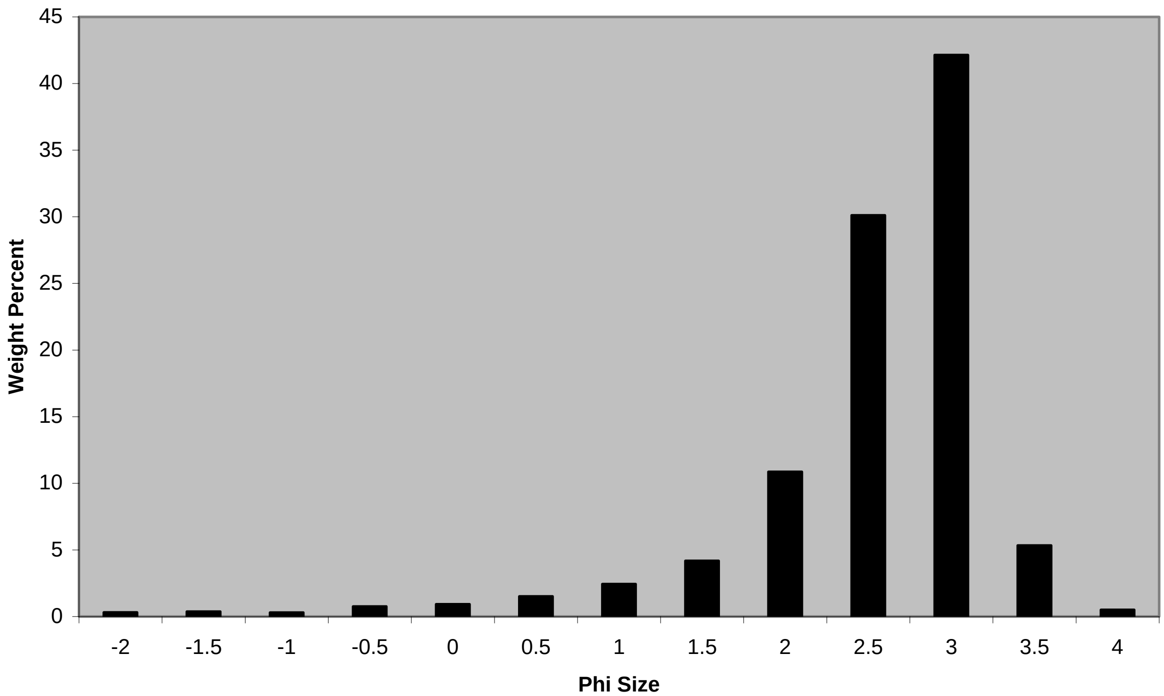

p < 0.001
Grain Size(phi)
3.0
2.5
2.0
1.5
1.0
Control
Nourish
Beach Location

Figure 28. Cumulative grain size frequency distribution for the entire populations on Hunting Island's nourished and control beaches. The upper graph is the nourished beach. The lower graph is the control beach. The nourished beach had a significantly wider grain size distribution.

Nourished Beach



p = 0.013

Control Beach

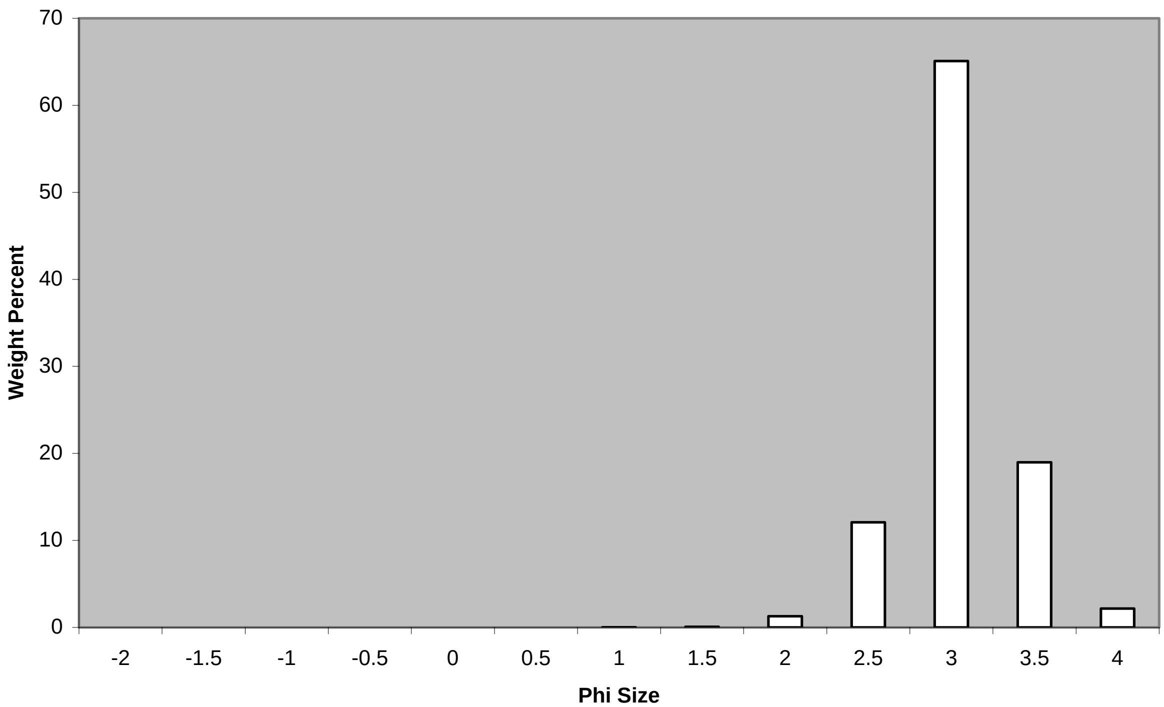
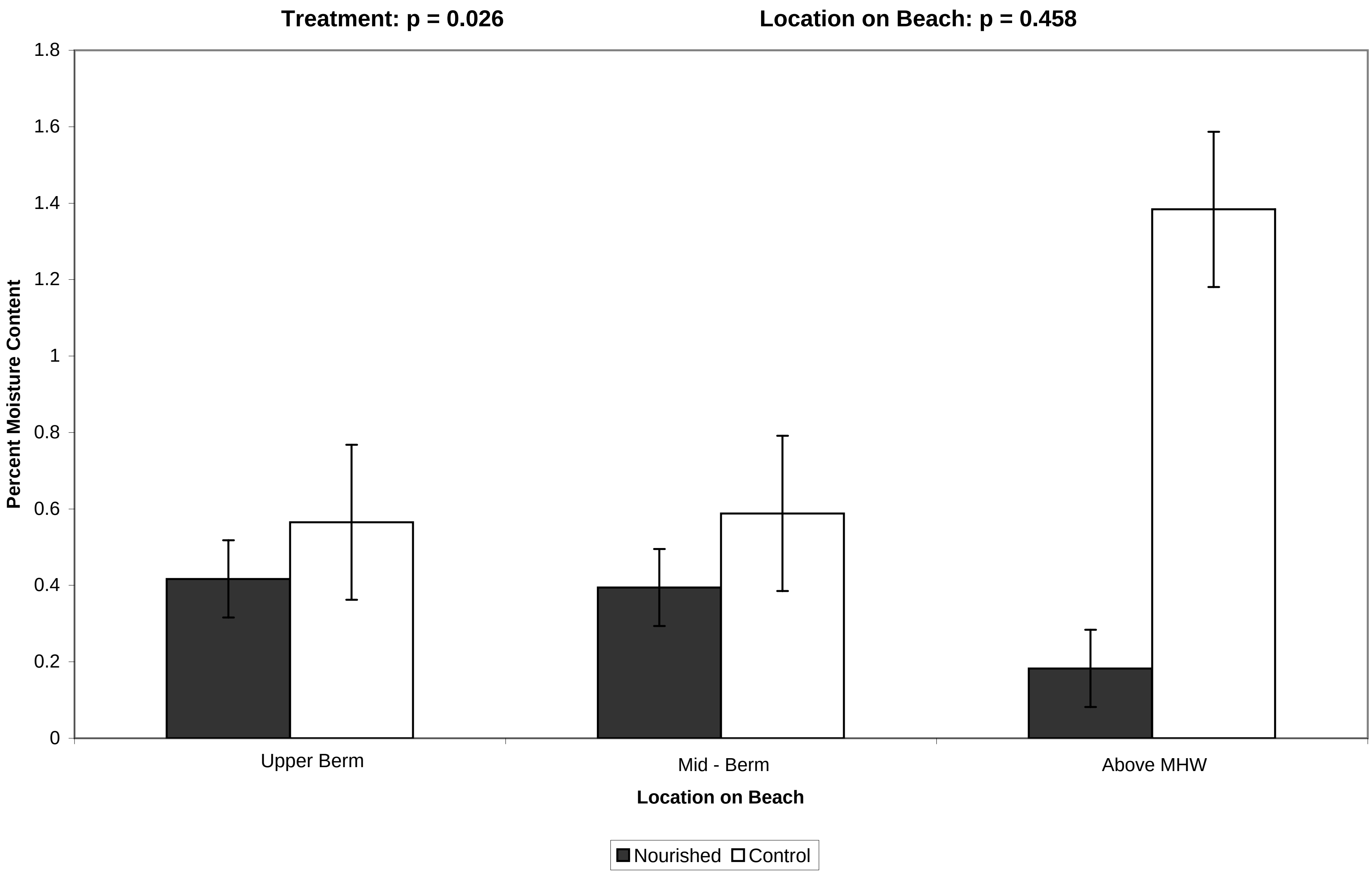
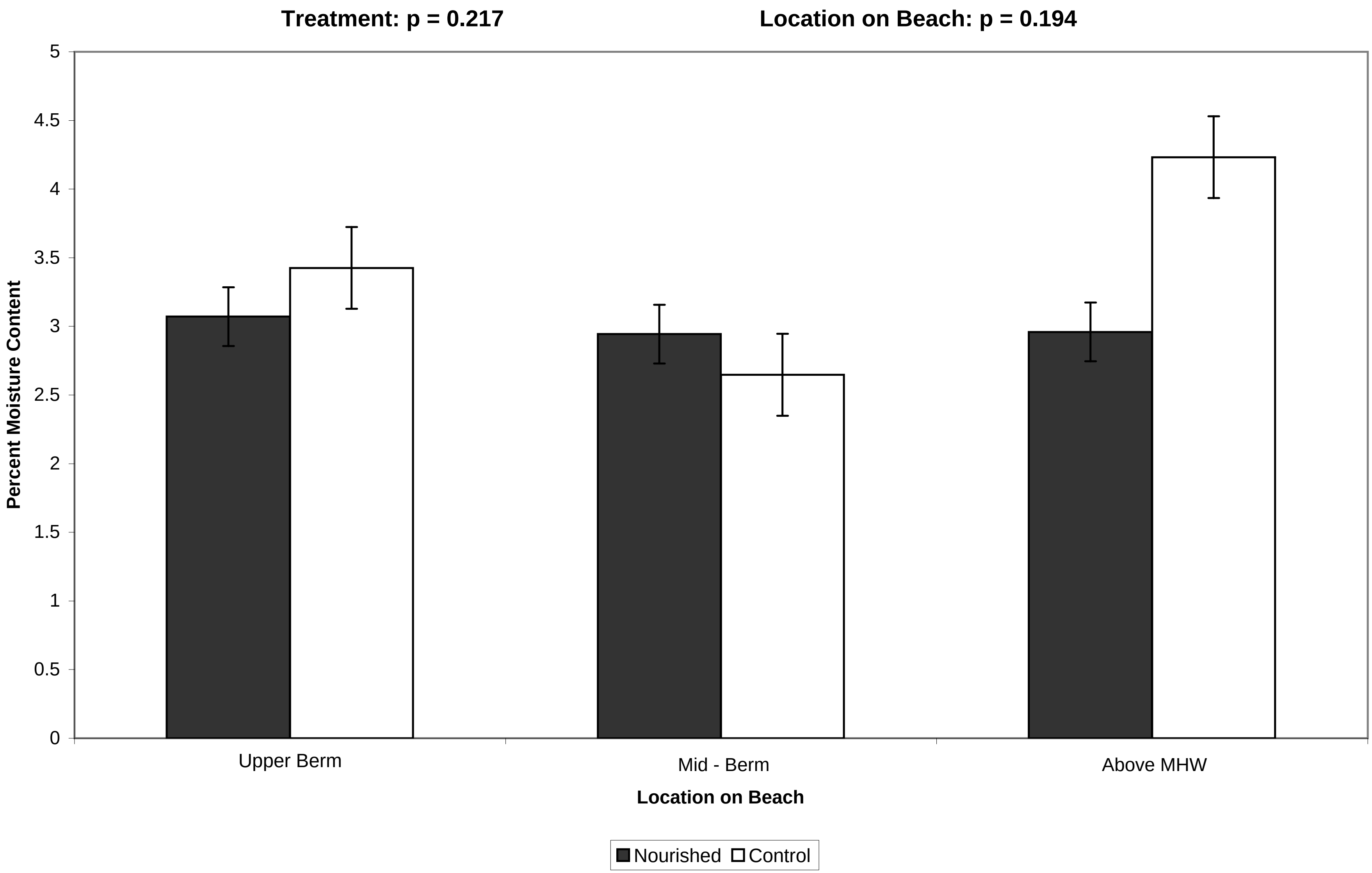


Figure 29. Comparison of moisture content on Hunting Island's nourished and control beaches at 15 cm sand depth. The control beach had significantly higher moisture content.



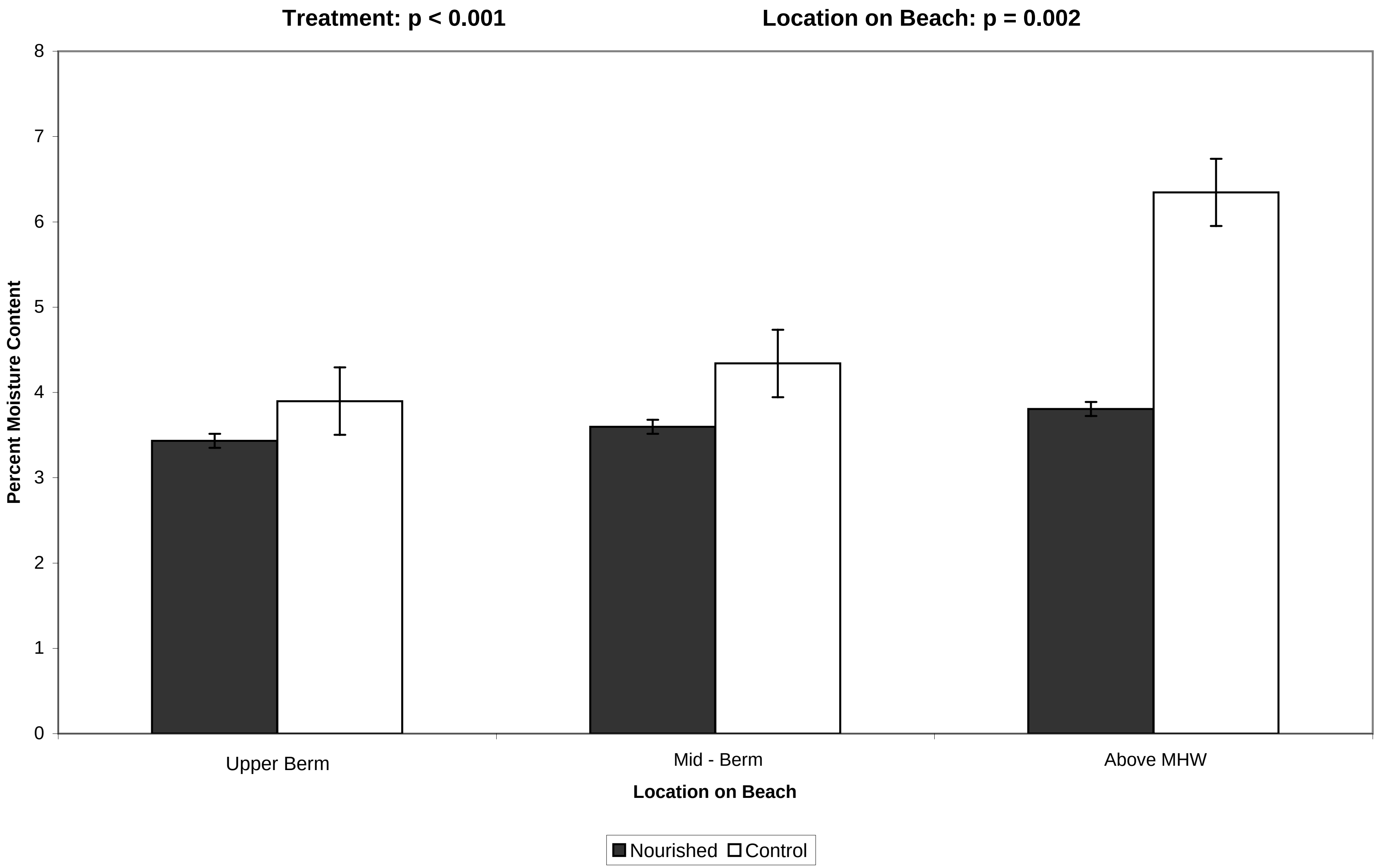
Treatment: p = 0.026
Location on Beach: p = 0.458
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Percent Moisture Content
Upper Berm
Mid - Berm
Above MHW
Location on Beach
Nourished
Control

Figure 30. Comparison of moisture content on Hunting Island's nourished and control beaches at 30 cm sand depth.



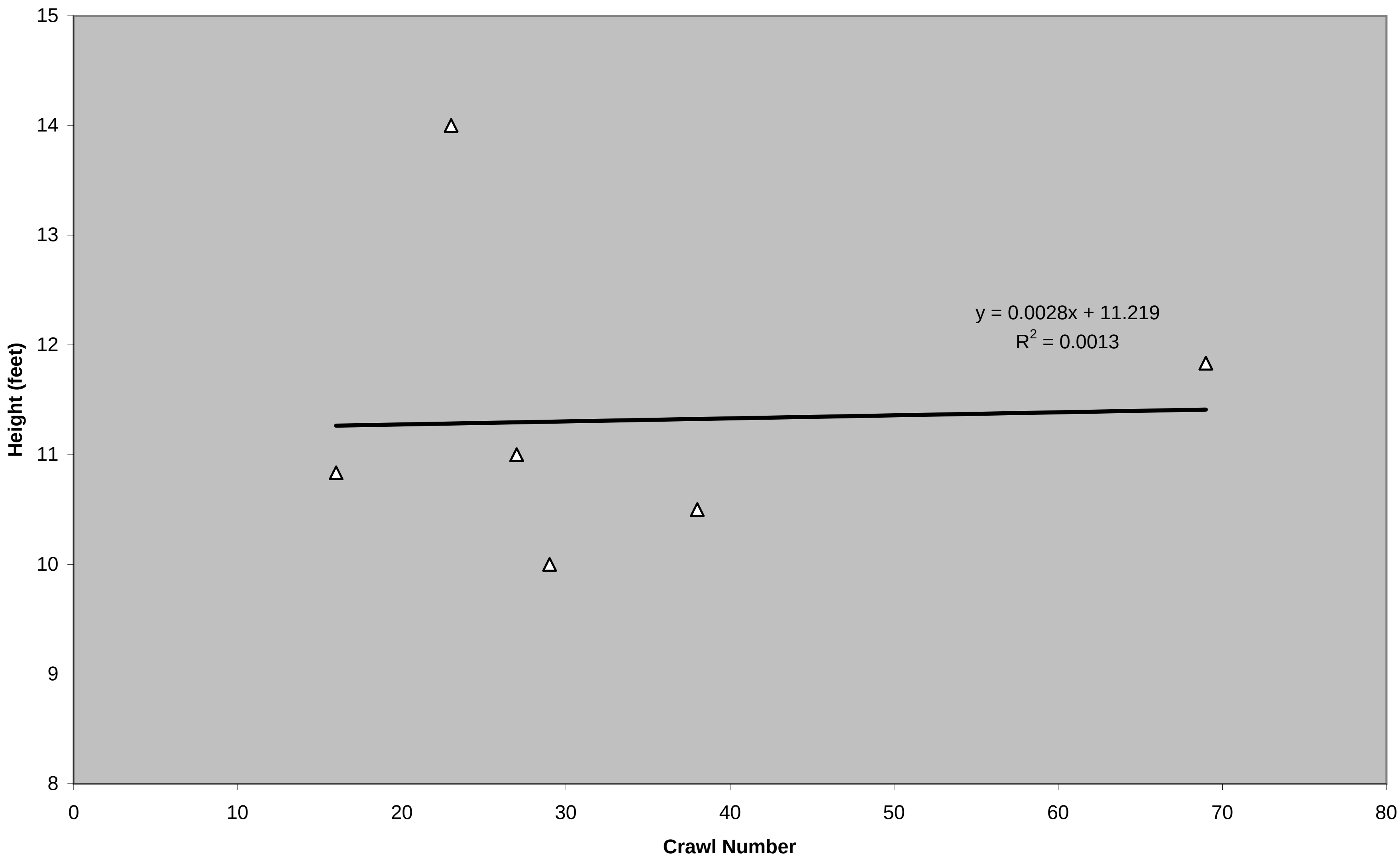
Treatment: p = 0.217
Location on Beach: p = 0.194
Percent Moisture Content
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Upper Berm
Mid - Berm
Above MHW
Location on Beach
Nourished
Control

Figure 31. Comparison of moisture content on Hunting Island's nourished and control beaches at 45 cm sand depth. The control beach and the above mean high water zone had significantly higher moisture contents.



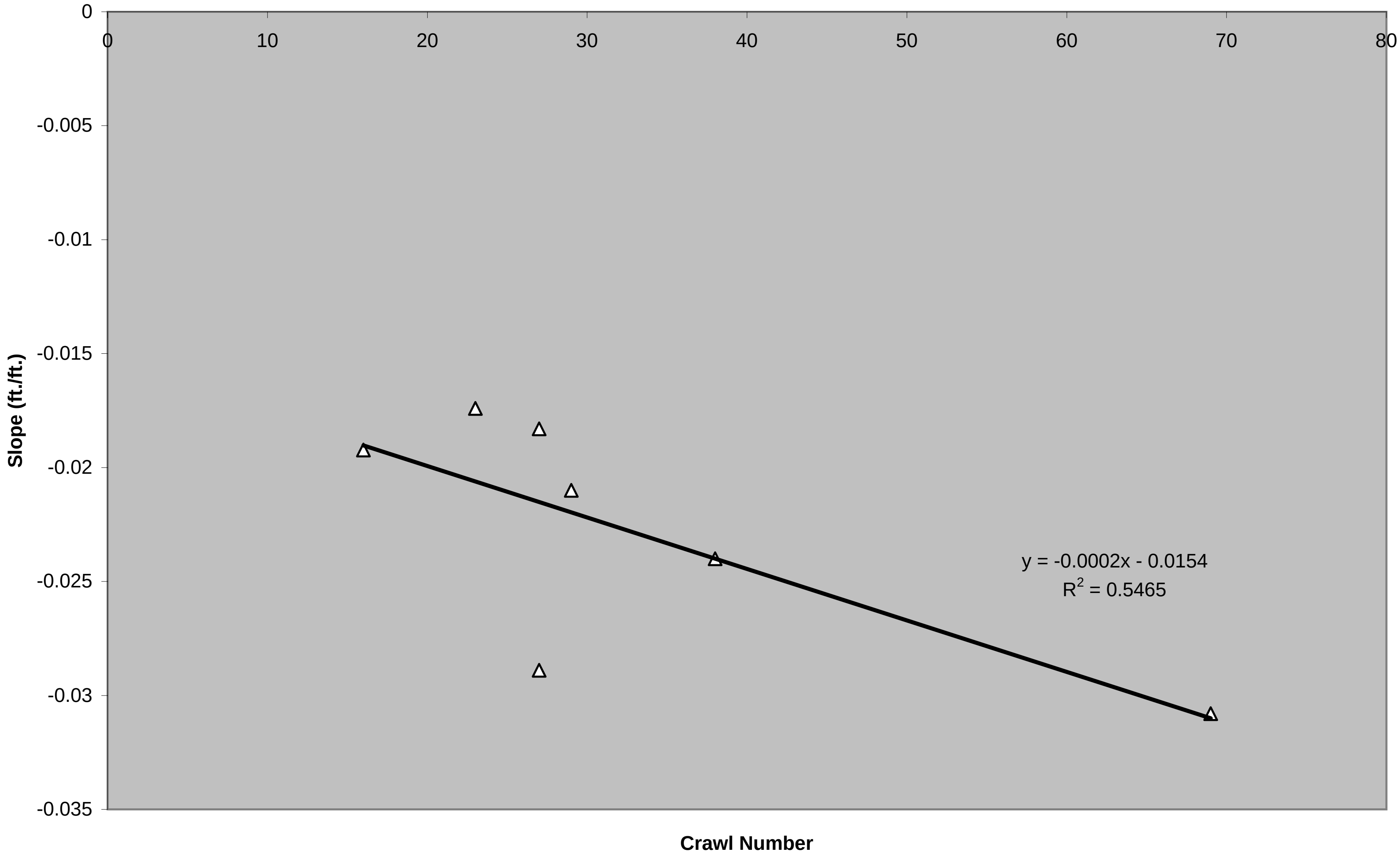
Treatment: p < 0.001
Location on Beach: p = 0.002
Percent Moisture Content
8
7
6
5
4
3
2
1
0
Upper Berm
Mid - Berm
Above MHW
Location on Beach
Nourished
Control

Figure 32. Relationship of maximum height and crawl number on Hilton Head Island in 1999.



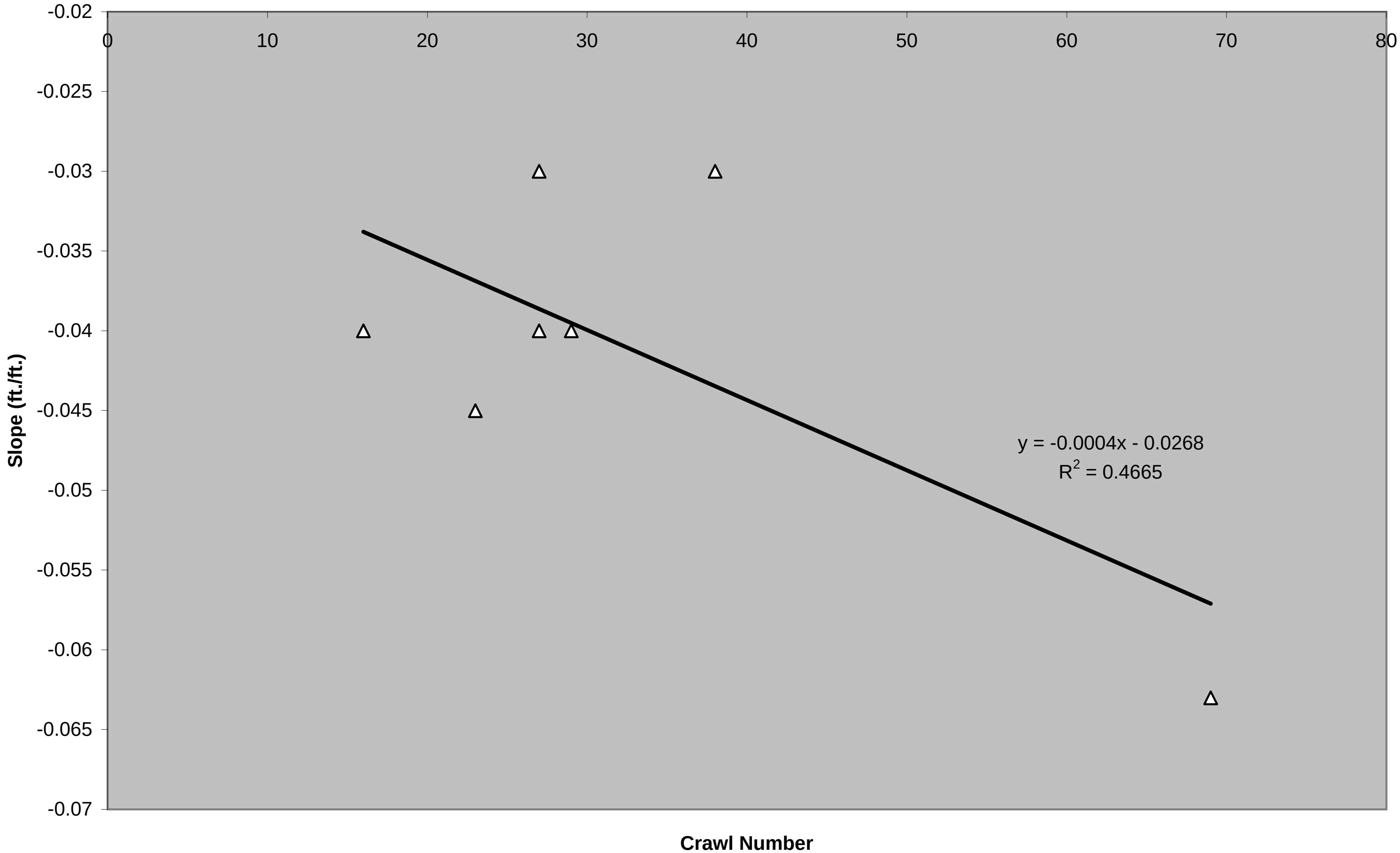
15
14
13
12
11
10
9
8
Height (feet)
y = 0.0028x + 11.219
R2 = 0.0013
0
10
20
30
40
50
60
70
80
Crawl Number

Figure 33. Relationship of mean slope from MHW to MLW and crawl number on Hilton Head Island in 1999.



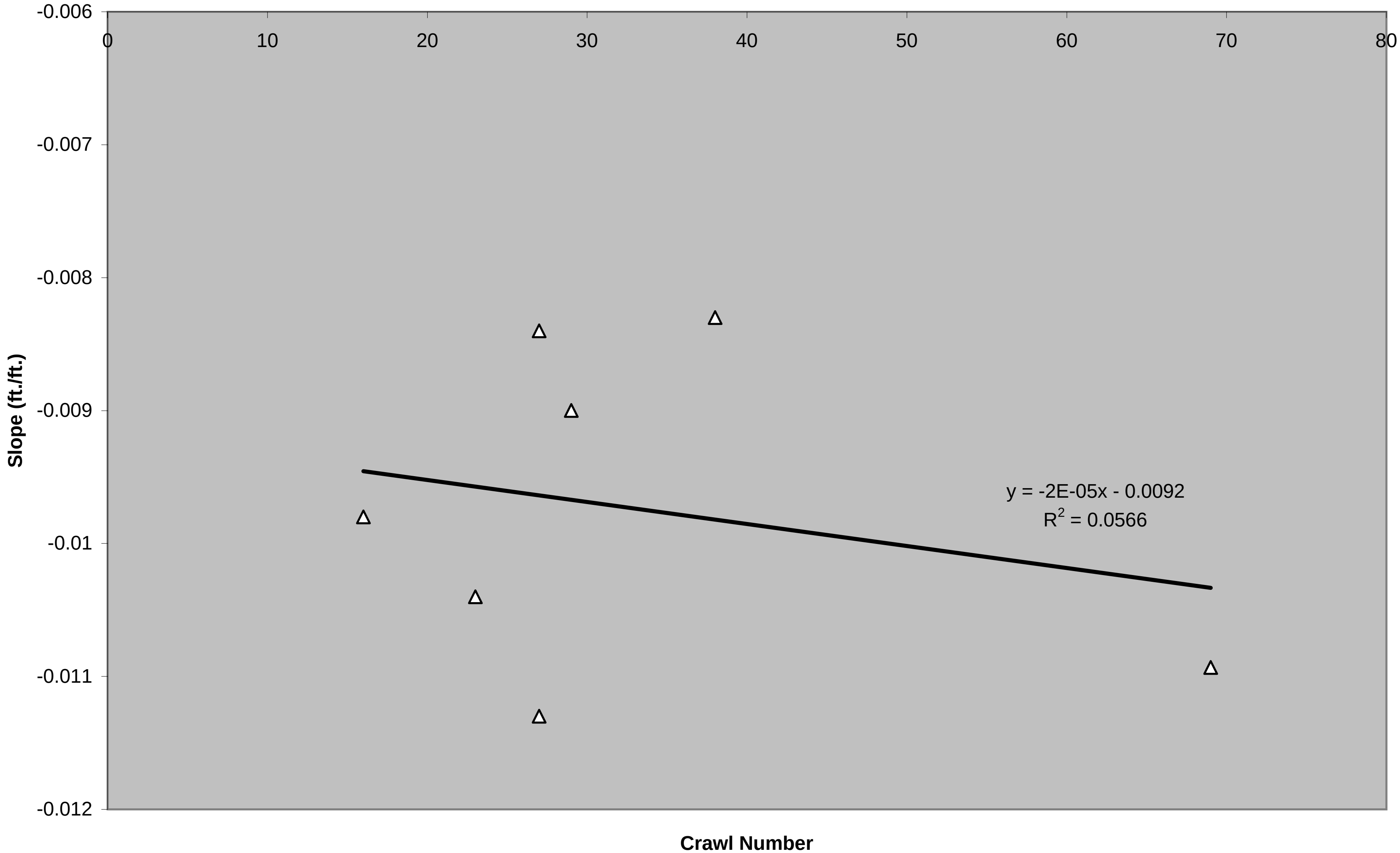
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
0
10
20
30
40
50
60
70
80
Slope (ft./ft.)
y = -0.0002x - 0.0154
R2 = 0.5465
Crawl Number

Figure 34. Relationship of maximum slope from MHW to MLW and crawl number on Hilton Head Island in 1999.



-0.02
-0.025
-0.03
-0.035
-0.04
-0.045
-0.05
-0.055
-0.06
-0.065
-0.07
0
10
20
30
40
50
60
70
80
Slope (ft./ft.)
y = -0.0004x - 0.0268
R2 = 0.4665
Crawl Number

Figure 35. Relationship of mean subtidal slope crawl number on Hilton Head Island in 1999.



-0.006
-0.007
-0.008
-0.009
-0.01
-0.011
-0.012
0
10
20
30
40
50
60
70
80
Slope (ft./ft.)
y = -2E-05x - 0.0092
R2 = 0.0566
Crawl Number

Figure 36. Relationship of maximum height and crawl number on Kiawah Island in 1999.

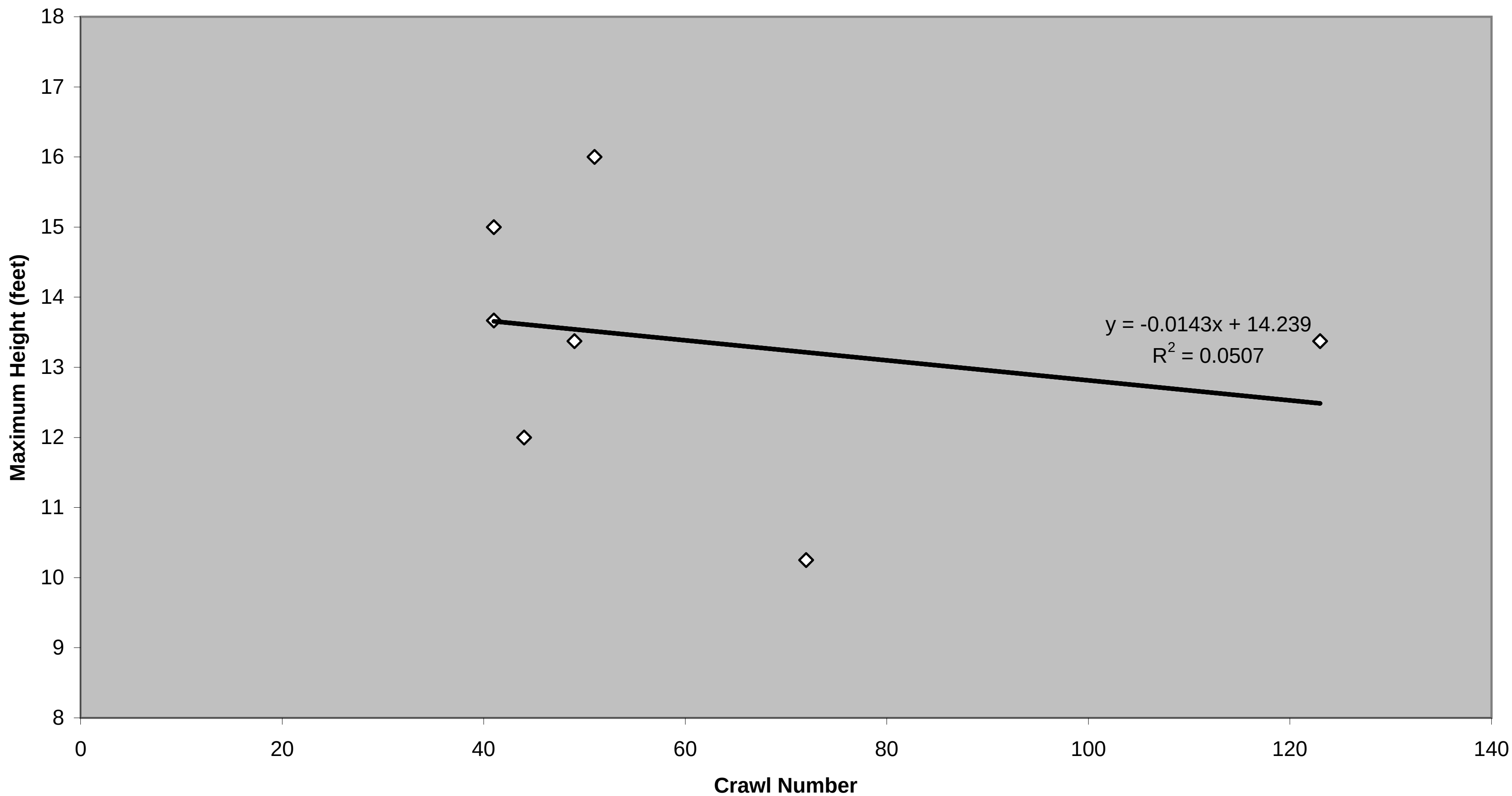
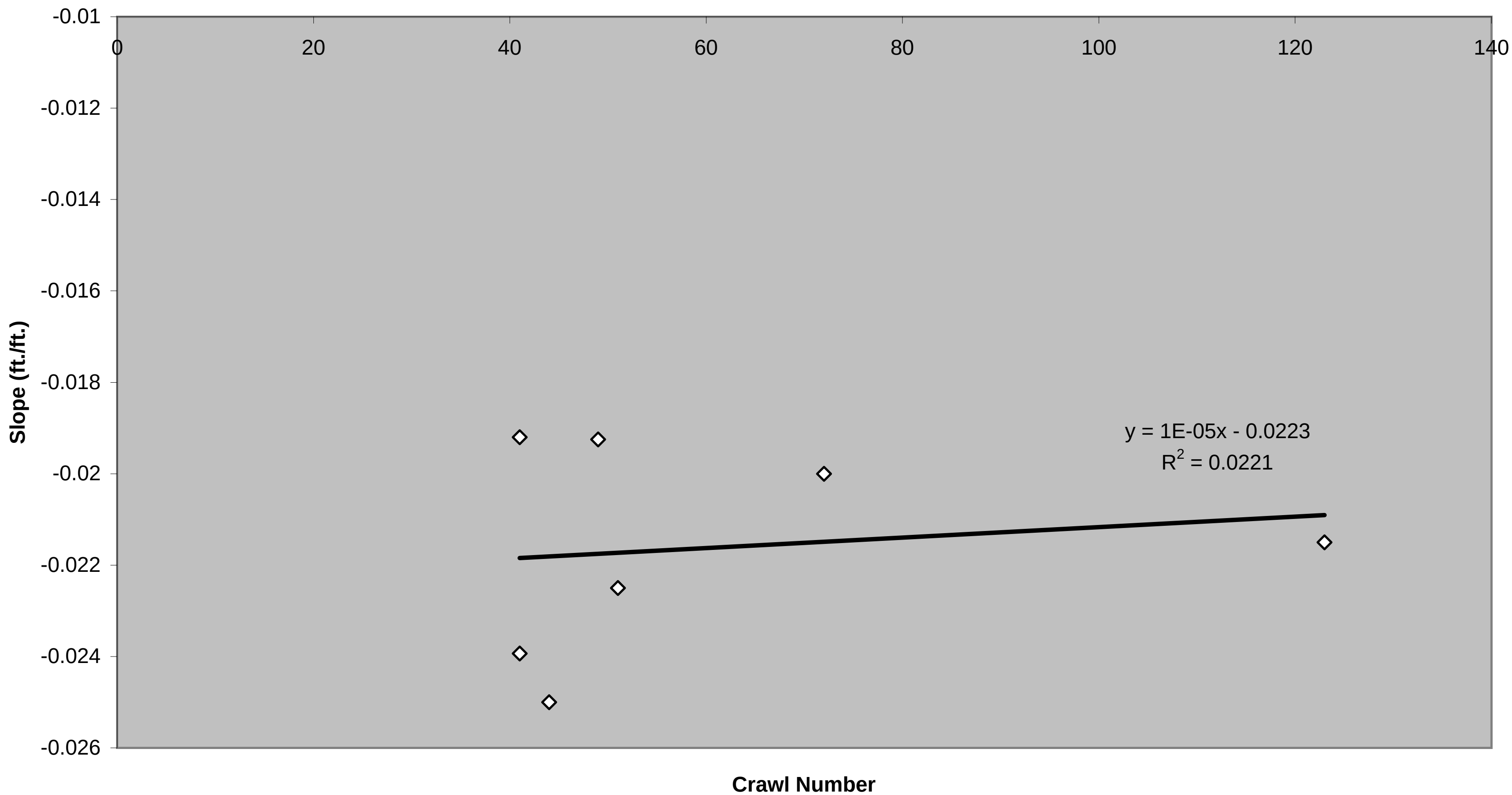
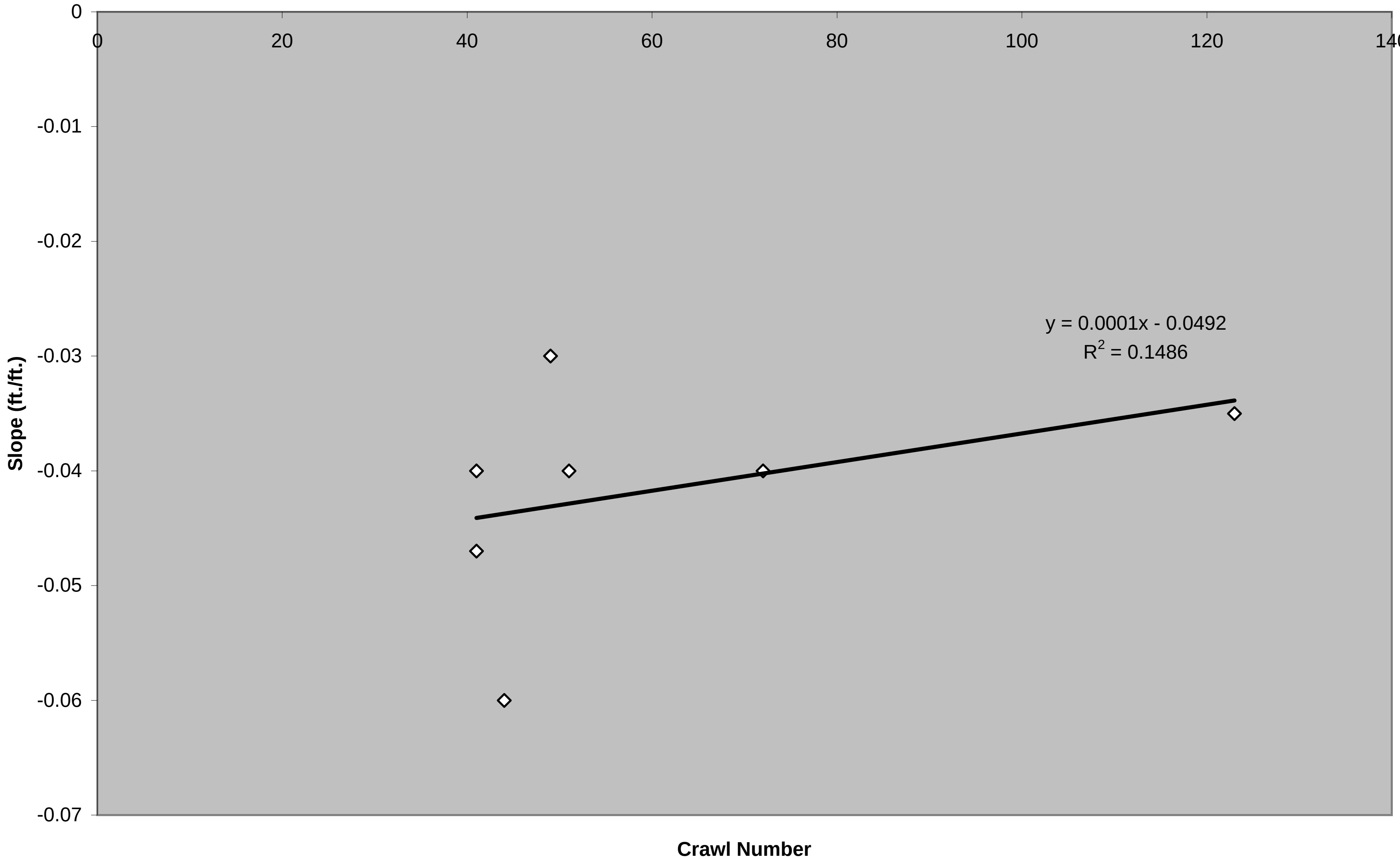

18
17
16
15
14
13
12
11
10
9
8
Maximum Height (feet)
y = -0.0143x + 14.239
R2 = 0.0507
0
20
40
60
80
100
120
140
Crawl Number

Figure 37. Relationship of mean slope from MHW to MLW and crawl number on Kiawah Island in 1999.



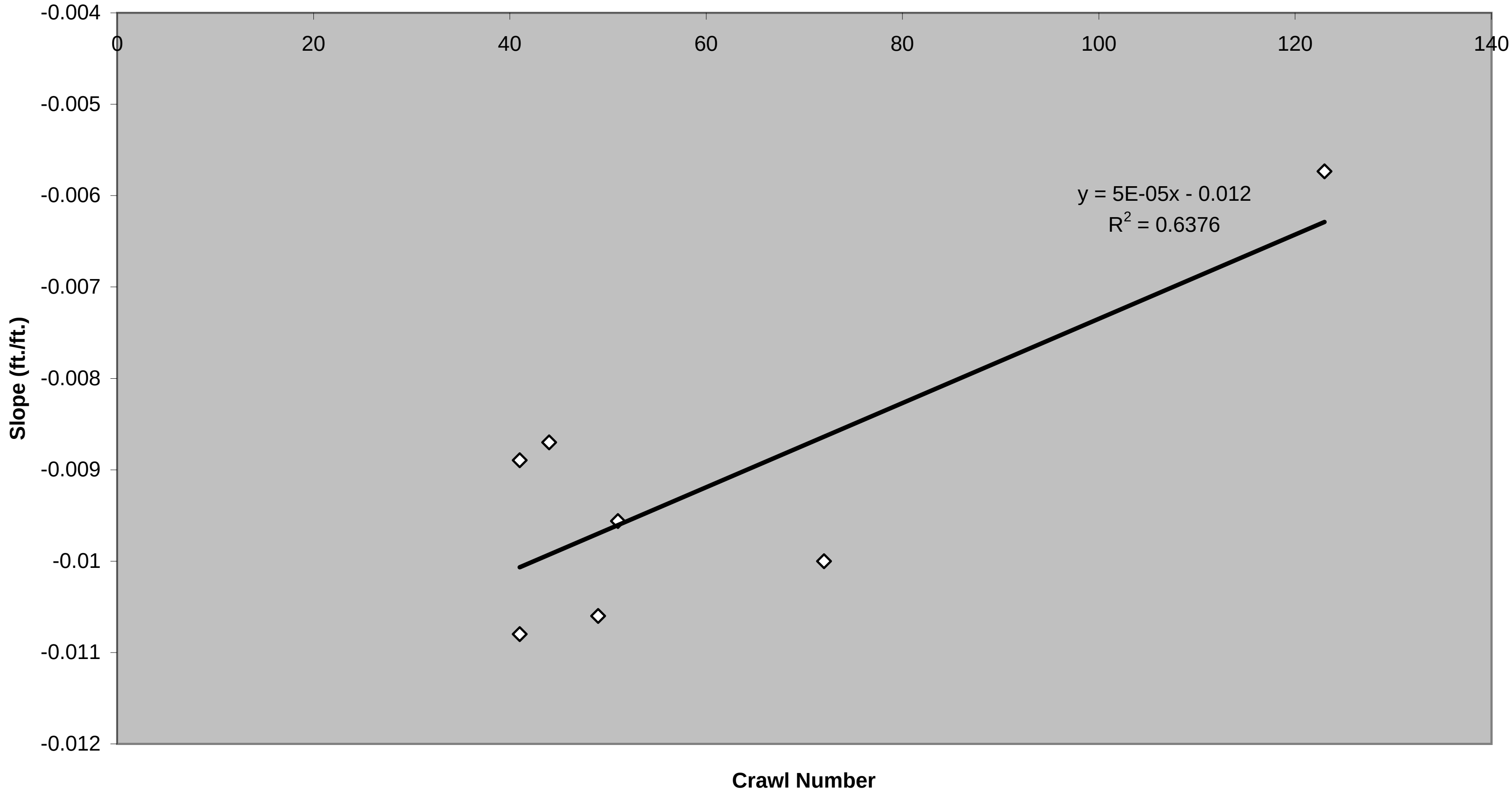
-0.01
-0.012
-0.014
-0.016
-0.018
-0.02
-0.022
-0.024
-0.026
0
20
40
60
80
100
120
140
Slope (ft./ft.)
y = 1E-05x - 0.0223
R2 = 0.0221
Crawl Number

Figure 38. Relationship of maximum slope from MHW to MLW and crawl number on Kiawah Island in 1999.



0
20
40
60
80
100
120
140
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
Slope (ft./ft.)
y = 0.0001x - 0.0492
R^2 = 0.1486
Crawl Number

Figure 39. Relationship of mean subtidal slope and crawl number on Kiawah Island in 1999. Significant relationships were found with more gradual slopes having higher crawl numbers.



-0.004
-0.005
-0.006
-0.007
-0.008
-0.009
-0.01
-0.011
-0.012
0
20
40
60
80
100
120
140
y = 5E-05x - 0.012
R2 = 0.6376
Slope (ft./ft.)
Crawl Number

Table 1. Comparison of mean temperatures, differences between temperatures, and significant differences on Hunting Island's nourished and control beaches between the four two-week periods and for the overall eight-week period.

Period	**Nourished (˚C)**	**Reference (˚C)**	**Difference (˚C)**	**Significance**
1	28.7	28.2	0.51	**P<0.001**
2	29.4	29.4	0.00	P=0.26
3	30.5	29.5	1.01	**P<0.001**
4	28.6	28.4	0.21	P=0.076
All	29.3	28.9	0.42	**P<0.001**

Table 2. Comparison of mean grain size and sorting of Hunting Island’s nourished and control beaches.

Treatment	Mean Grain Size	Mean Sorting
Nourished n = 45	2.79 Fine sand	0.333 Very well sorted
Reference n = 45	2.27 Fine sand	0.738 Moderately sorted

APPENDIX

Station*	Mean Grain Size	Size Class	Standard Deviation	Description
C 0ft. 1 (15)	2.789	F	0.352	W
C 0ft. 1 (30)	2.838	F	0.358	W
C 0ft. 1 (45)	2.879	F	0.358	W
C 0ft. 2 (15)	2.836	F	0.317	VW
C 0ft. 2 (30)	2.875	F	0.371	W
C 0ft. 2 (45)	2.838	F	0.316	VW
C 0ft. 3 (15)	2.74	F	0.338	VW
C 0ft. 3 (30)	2.81	F	0.325	VW
C 0ft. 3 (45)	2.872	F	0.295	VW
C 500ft. 1 (15)	2.788	F	0.344	VW
C 500ft. 1 (30)	2.784	F	0.358	W
C 500ft. 1 (45)	2.824	F	0.325	VW
C 500ft. 2 (15)	2.794	F	0.354	W
C 500ft. 2 (30)	2.805	F	0.331	VW
C 500ft. 2 (45)	2.788	F	0.308	VW
C 500ft. 3 (15)	2.842	F	0.331	VW
C 500ft. 3 (30)	2.786	F	0.29	VW
C 500ft. 3 (45)	2.71	F	0.375	W
C 1000ft. 1 (15)	2.774	F	0.327	VW
C 1000ft. 1 (30)	2.807	F	0.326	VW
C 1000ft. 1 (45)	2.782	F	0.36	W
C 1000ft. 2 (15)	2.707	F	0.357	W
C 1000ft. 2 (30)	2.819	F	0.283	VW
C 1000ft. 2 (45)	2.628	F	0.385	W
C 1000ft. 3 (15)	2.762	F	0.425	W
C 1000ft. 3 (30)	2.716	F	0.337	VW
C 1000ft. 3 (45)	2.714	F	0.358	W
C 1500ft. 1 (15)	2.782	F	0.348	VW
C 1500ft. 1 (30)	2.774	F	0.346	VW
C 1500ft. 1 (45)	2.667	F	0.293	VW
C 1500ft. 2 (15)	2.832	F	0.333	VW
C 1500ft. 2 (30)	2.814	F	0.277	VW
C 1500ft. 2 (45)	2.829	F	0.322	VW
C 1500ft. 3 (15)	2.754	F	0.359	W
C 1500ft. 3 (30)	2.733	F	0.354	W
C 1500ft. 3 (45)	2.768	F	0.355	W
C 2000ft. 1 (15)	2.793	F	0.316	VW
C 2000ft. 1 (30)	2.894	F	0.306	VW
C 2000ft. 1 (45)	2.877	F	0.285	VW
C 2000ft. 2 (15)	2.789	F	0.327	VW
C 2000ft. 2 (30)	2.781	F	0.317	VW
C 2000ft. 2 (45)	2.794	F	0.346	VW
C 2000ft. 3 (15)	2.811	F	0.305	VW
C 2000ft. 3 (30)	2.787	F	0.326	VW
C 2000ft. 3 (45)	2.823	F	0.283	VW
Mean	**2.791311111**		**0.333377778**	

* Station codes are as follow: control beach, transect (0 - 2000 ft.), beach location (1 = upper berm, 2 = mid-berm, 3 = above mean high water), depth (15, 30, and 45 cm).

Station*	Mean Grain Size	Size Class	Standard Deviation	Description
N 0ft. 1 (15)	2.352	F	0.701	MW
N 0ft. 1 (30)	2.381	F	0.631	MW
N 0ft. 1 (45)	2.363	F	0.619	MW
N 0ft. 2 (15)	2.355	F	0.668	MW
N 0ft. 2 (30)	2.381	F	0.607	MW
N 0ft. 2 (45)	2.392	F	0.632	MW
N 0ft. 3 (15)	1.954	M	0.504	MW
N 0ft. 3 (30)	2.381	F	0.564	MW
N 0ft. 3 (45)	2.218	F	0.949	M
N 500ft. 1 (15)	2.17	F	1.021	P
N 500ft. 1 (30)	1.54	M	1.407	P
N 500ft. 1 (45)	2.138	F	0.845	M
N 500ft. 2 (15)	2.479	F	0.674	MW
N 500ft. 2 (30)	2.346	F	0.698	MW
N 500ft. 2 (45)	2.259	F	0.813	M
N 500ft. 3 (15)	2.072	F	1.007	P
N 500ft. 3 (30)	2.095	F	0.882	M
N 500ft. 3 (45)	2.099	F	0.731	M
N 1000ft. 1 (15)	2.413	F	0.43	W
N 1000ft. 1 (30)	2.496	F	0.42	W
N 1000ft. 1 (45)	2.538	F	0.408	W
N 1000ft. 2 (15)	2.405	F	0.646	MW
N 1000ft. 2 (30)	2.332	F	0.691	MW
N 1000ft. 2 (45)	2.258	F	0.761	M
N 1000ft. 3 (15)	2.187	F	0.939	M
N 1000ft. 3 (30)	2.179	F	0.937	M
N 1000ft. 3 (45)	2.145	F	1.003	P
N 1500ft. 1 (15)	2.144	F	0.839	M
N 1500ft. 1 (30)	2.278	F	0.805	M
N 1500ft. 1 (45)	2.299	F	0.775	M
N 1500ft. 2 (15)	2.432	F	0.715	M
N 1500ft. 2 (30)	2.281	F	0.603	MW
N 1500ft. 2 (45)	2.005	F	0.939	M
N 1500ft. 3 (15)	2.482	F	0.48	W
N 1500ft. 3 (30)	2.453	F	0.459	W
N 1500ft. 3 (45)	2.447	F	0.495	W
N 2000ft. 1 (15)	2.52	F	0.466	W
N 2000ft. 1 (30)	2.553	F	0.463	W
N 2000ft. 1 (45)	2.512	F	0.442	W
N 2000ft. 2 (15)	2.118	F	0.95	M
N 2000ft. 2 (30)	2.384	F	0.711	M
N 2000ft. 2 (45)	2.432	F	0.692	MW
N 2000ft. 3 (15)	2.361	F	0.75	M
N 2000ft. 3 (30)	1.906	M	1.185	P
N 2000ft. 3 (45)	1.783	M	1.253	P
Mean	**2.273733333**		**0.738**	

* Station codes are as follow: nourished beach, transect (0 - 2000 ft.), beach location (1 = upper berm, 2 = mid-berm, 3 = above mean high water), depth (15, 30, and 45 cm).

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