The Effects of Artificial Beach Nourishment on Marine Turtles: Differences between Loggerhead and Green Turtles

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Abstract

Marine turtle reproductive success is correlated with the stability and quality of the nesting environment. Female marine turtles show fidelity to nesting beaches, making artificial beach nourishment practices directly relevant to their recovery. We evaluated the impacts of artificial beach nourishment on Loggerhead (*Caretta caretta*) and Green turtles (*Chelonia mydas*) between artificially nourished and nonnourished beaches. We observed reduced nesting success (ratio of nesting emergences to emergences not resulting in nest deposition) for both species. This negative effect lasted for one season in Loggerheads and for at least one season in Green turtles. Physical attributes of the fill sand did not impede nesting attempts. We argue that the decrease in nesting success resulted from an altered beach profile not favorable for nest deposition, which subsequently improved in later seasons as the beach equilibrated to a more natural slope. We observed a 52.2% decrease in reproductive output (hatchlings km^{-1} yr^{-1}) for Loggerheads one year postnourishment, with a 44.1% increase observed the two seasons postnourishment. In Green turtles, a 0.8% reduction was observed the first season postnourishment, despite a 13% increase in the nonnourished area. The reduction in reproductive output in both cases was primarily a consequence of decreased nesting success, lowering nest numbers. These results reveal stronger negative effects of beach nourishment on Loggerheads compared to Green turtles and the importance of minimizing excessive nonnesting emergences associated with artificial beach nourishment. Nourished areas also experienced more than 600% increase in the number of Loggerhead hatchlings disoriented by artificial lighting over two years postnourishment.

Key words: **beach nourishment, compaction, disorientation, Green turtle, hatching success, Loggerhead, marine turtles, nest placement, reproductive success, shoreline restoration.**

Introduction

For oviparous species, the habitat in which eggs are deposited strongly influences offspring survival and may have important consequences for adult reproductive success (Martin 1988; Hays & Speakman 1993). Marine turtles have an oviparous reproductive strategy and thus depend on suitable terrestrial nesting environments (Miller 1997; Pritchard 1997). Gravid marine turtles typically exhibit nest site fidelity to beaches with characteristics conducive to successful nesting over evolutionary time (Carr 1986; Witherington 1986; Bowen et al. 1992; Bowen 1995; Weishampel et al. 2003). Coastal ecosystem management at nesting beaches directly affects future generations of marine turtles and is essential for the recovery of these endangered species.

Coastal ecosystems are dynamic and experience erosional and accrectional fluctuations from sedimentary exchange between dune, beach, and offshore sand sources. Global climate change and sea level rise lead to enhanced coastal erosion (Walton 1978; Nicholls & Klein 2004), and vulnerability of a particular beach varies with adjacent land use (Fish et al. 2005). Anthropogenic components can obstruct or accelerate coastal processes (Southwick 1996). Artificial navigational inlets prevent the littoral transport of sands and result in chronic erosion on downdrift beaches (Douglas 2002; Kriebel et al. 2003). Conversely, shoreline recession is impeded by urban coastal development and armoring (i.e., seawalls, bulkheads, or rock revetments; Olsen & Bodge 1991; Pilkey 1991) in that a fixed landward boundary is established that prevents or disrupts sedimentary exchanges. These pressures, collectively termed coastal squeeze (Doody 2001), lead to the reduction of dry beaches and, consequently, nesting habitat for marine turtles.

Loggerheads (*Caretta caretta*) and Green turtles (*Chelonia mydas*) typically favor steeply sloped, moderate- to high-energy beaches, with gradually sloped offshore approaches where a deep nest cavity can be dug above the high water line (Provancha & Ehrhart 1987; Hays et al.

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1995). This often results in Green turtles nesting further from the water because their larger size allows for a deeper nest cavity relative to Loggerheads. Nesting habitats frequently overlap between the two species. In the United States, Loggerhead nests greatly outnumber Green turtle nests, but Green turtles still nest in significant numbers. Green turtle nest production in the United States has exhibited a high/low biennial pattern since at least 1989. Even-numbered years (e.g., 2000, 2002) have experienced a high number of nests, whereas nest production decreases during odd-numbered years (e.g., 1999, 2001). From 1989 to 2003, the estimated annual number of Loggerhead nests in the United States has fluctuated without a conspicuous trend (Weishampel et al. 2004).

The Atlantic beaches of east central Florida, U.S.A., along the Archie Carr National Wildlife Refuge (included in this study), have provided nest sites for 18% of the Atlantic basin Loggerhead population and for at least 30% of the Florida Atlantic Green turtle population (NMFS & USFWS 1991; Ehrhart et al. 2003). These beaches are critically eroded and subject to instability, accelerated rates of erosion (Bruun 1962), loss of habitat to coastal development, and chronic erosion caused by an updrift navigational inlet known as Port Canaveral Inlet (Kriebel et al. 2003). These conditions have led to the development of a long-term management plan calling for the "restoration and maintenance" of these beaches. Due to the economic value of developed coastal property (Douglas 2002), the attrition over many decades required for inland retreat, and the detrimental effects of coastal armoring, artificial beach nourishment is currently the accepted engineering solution for shoreline protection (Lucas & Parkinson 2002). This is particularly relevant in the light of global climate change and rising sea levels (Fish et al. 2005).

Artificial beach nourishment, commonly referred to as beach nourishment or restoration, is the mechanical placement of sand on a beach to advance the shoreline seaward or to build up a dune (Dean 2002). This process results in an engineered beach that may or may not restore natural processes. Artificial beach nourishment projects modify ecosystem components (sand grain size, shape and color, silt–clay and moisture content, beach hardness, mineral content, water potential, and porosity/gas diffusion) and potentially cause detrimental changes to the biota in the area (Dean 2002). Nourishment projects also modify marine turtle nesting beaches, potentially influencing nesting and reproductive success. However, properly implemented nourishment projects can mitigate the loss of marine turtle nesting beaches when the alternative is chronically eroded or nonexistent beaches (i.e., low-quality nesting habitat).

The effect on total reproductive output for marine turtles is a crucial component for determining the success of nourishment projects. These projects affect nesting marine turtles in several ways (Crain et al. 1995), and thus, impact assessment must integrate responses in terms of both nesting behavior and reproductive success.

Previous studies and generalizations concerning nourishment projects have focused on the negative impacts on Loggerhead turtles (Crain et al. 1995; Trindell et al. 1998). Previously documented effects on Green turtles have not been reported using statistically significant sample sizes ($n < 20$; Ehrhart & Herren 1998; Ehrhart & Holloway-Adkins 2000; Palm Beach County Department of Environmental Resources Management 2001). We describe the effects of a nourishment project on populations of two species of marine turtles: the Loggerhead and the Green turtle. Using pre- and postnourishment comparisons to adjacent nonnourished (natural) beaches, we were able to distinguish direct effects of the nourishment project from naturally fluctuating patterns in both species.

Our objectives included a comparative evaluation for Loggerhead and Green turtles of standard parameters such as assessing total nesting, nesting success, nest placement, and overall reproductive success and accounting for effects on postemergence hatchlings. By incorporating these parameters, we test the hypothesis that a single beach nourishment project will have no effect on Loggerhead or Green turtles.

Methods

Study Sites

This study was conducted on a 40.5-km beach located on the central east coast of Florida, U.S.A., including the Archie Carr National Wildlife Refuge. A centrally located 5-km portion was artificially nourished from February through April 2002, prior to the 2002 marine turtle nesting season (officially 1 May to 31 October). The northernmost reach of the project was near the Town of Indialantic (lat 28.09033134N, long 80.56484286W) and extended southward to Melbourne Beach (lat 28.05308977N, long 80.54984894W).

Approximately 917,000 m^3 of sand obtained from offshore sources was pumped onto the beach using a hydraulic pipeline dredge. Bulldozers manipulated the sand to construct a berm extending 34.5 m, on average, from the natural berm and to advance the mean high water line (MHWL) seaward an average of 37.1 m. The new profile was elevated 3.1–3.3 m above the mean low water line with no constructed slope. Along the landward portion of the berm, a dune feature was constructed and the seaward edge of the berm constructed to have a 1:15 slope. With the exception of coarse grain size fraction (>1 mm) being 5–10% higher (Olsen Associates, Inc. 2003), the geotechnical characteristics of the sand was comparable to those of the native sand as described by grain size sieve analyses, visual estimates of shell content, and high-temperature carbonate burn tests. The substrate was mechanically tilled to reduce shear resistance (beach hardness) to less than 35.2 kg/cm^2, as recommended for turtle nesting beaches by the U.S. Fish and Wildlife Service and the Florida Department of Environmental Protection (FDEP).

Since 1990, systematic marine turtle nesting surveys that established baseline nesting and reproductive information were conducted throughout the study area. As a result, we have been able to assess pre- and postnourishment comparisons to adjacent nonnourished (natural) beaches and take into account annual fluctuations and patterns when determining the effects of beach nourishment on Loggerheads and Green turtles. The physical attributes of the adjacent nonnourished beaches and those of the nourished beach prenourishment (1990–2001) included a 5- to 25-m wide sloped berm with characteristics of a barrier island high-energy beach. Prior studies established that there was little to no average differences in reproductive or nesting success (Osegovic 2001; Weishampel et al. 2003). Comparisons of nesting activity and reproductive success on the 5-km nourished beach were made with those of turtles nesting on adjacent sections of nonnourished beach (13.5 km north and 22.0 km south of the nourished beach).

Nesting Activity and Placement

Nesting typically occurs at night but can be most easily enumerated and evaluated during the early morning. Evidence of nightly nesting activity was recorded daily from 1 May to 31 August during morning surveys using an all-terrain vehicle. To eliminate variation caused by tidal fluctuations, only tracks that were above the most recent high tide were used. Tracks were differentiated as a nesting or a nonnesting emergence based on track patterns and identified to species using characteristics outlined in Pritchard and Mortimer (1999) and Schroeder and Murphy (1999). Nesting success was defined as the number of emergences that resulted in nests divided by the total number of emergences. The nourished beach was divided into sections parallel to the long axis of the beach and nests, and nonnesting emergences were placed into the section where a clutch was deposited or the tracks reached an apex. The sections of beach were defined as (1) dune, naturally elevated westward portion including vegetation; (2) foredune, constructed mound at base of dune; (3) berm, flat area comprising the largest portion of the beach; (4) gradient, sloping portion seaward of the berm; or (5) scarp, escarpment formed intermittently by erosion along the seaward edge of the berm.

For all nests to be evaluated for reproductive success (described below) and two arbitrarily chosen nonnesting emergences per day, straight-line distances were measured from the clutch or the apex eastward to the most recent MHWL and westward to the upper margin of the berm at the base of the dune. A seawall or a building may have indicated the dune base. The combined measurements of distance to dune base and to MHWL were used to calculate the width of beach available to the female upon emergence. For all nonnesting emergences, the stage to which nesting activity progressed was categorized as (1) emergence, no attempt to excavate sand; (2) preliminary body pit, no indication of an egg chamber; or (3) an open egg chamber abandoned before oviposition occurred.

Reproductive Success

Three measures of reproductive success described aspects of survivorship and productivity: (1) hatching success (HS) (the percentage of eggs that hatched); (2) emerging success (the number of hatchlings that reached the surface of the sand); and (3) reproductive output (the total number of nests multiplied by the mean emerging success and mean clutch size of sampled nests). Nests used to evaluate reproductive success were selected to represent nests spatially and temporally throughout the study sites. In addition, nests in the nourished area were selected to achieve a minimum of 150 marked nests as required by federal and state permit conditions of the nourishment project. Nests were marked the morning following oviposition according to Osegovic (2001) and monitored throughout incubation periods for disturbances by erosion. Nests washed out by erosion were included in reproductive success measures as 0% hatching and emerging success. Nests were excavated 72 hours after hatchling tracks were observed or 65 days after oviposition. Nest contents were exhumed and evaluated for reproductive success using techniques outlined by Miller (1999) and Osegovic (2001). Reproductive output was expressed as production density (hatchlings km^{-1} yr^{-1}) and was calculated as the estimated number of hatchlings entering the ocean and did not include hatchling mortality postemergence.

Postemergence Hatchlings

Artificially lighted beaches disrupt hatchling orientation to the water upon emerging from the nest. When evidenced by tracks found during surveys, the modal direction of emerging hatchlings was noted. Nests were considered disturbed by artificial lights (disoriented) if the collective angular direction of travel for emerging hatchlings varied from a "V" formation and were circular in nature or if tracks were mostly in a "V" formation but the direction of travel was away from the ocean (Miller 1999; Witherington & Martin 2000). Postemergence nests with disoriented hatchlings were enumerated. To calculate the percentage of disoriented nests, we divided the number of disoriented nests by the total number of nests deposited. This does not take into account nests with 0% emerging success or hatchling tracks that were obliterated by rain or wind before surveys; therefore, reported proportions are a minimum value.

Data Analyses

Data collected during the 2002 and 2003 Loggerhead nesting seasons were analyzed for differences between the nourished and the nonnourished study sites. In addition, these data were compared to the historical average

(1990–2001), one year prior to nourishment (2001), and two seasons postnourishment (2002 and 2003). Data collected during the 2002 Green turtle reproductive season were analyzed for differences between the nourished and the nonnourished study sites. In addition, these data were compared to the historical biennial average (1990–2000, even years only) and one year postnourishment (2002). Differences between species were analyzed using the 2002 data and historical averages recorded during the even years when Green turtles nested in significant numbers. Nonparametric statistical tests were used in most analyses due to nonnormality of the data. A probability of 0.05 or less was considered significant unless otherwise stated. To compare variations in nest and apex locations among the measured beach width and the straight-line distance from the MHWL within each species and within the nourished and nonnourished areas, we used the nonparametric Spearman's correlation coefficient.

Results

Nesting Activity and Placement

Loggerhead nesting in the nourished areas decreased 53.2% from 2001 to 2002 ($n = 1{,}828$ and 972 nests, respectively) and increased 54.1% during 2003 ($n = 1{,}798$ nests), whereas nesting in the nonnourished area decreased 11.9% from 2001 to 2002 ($n = 17{,}051$ and 15,014 nests, respectively) and 10% from 2002 to 2003 ($n = 13{,}546$ nests). Compared to the nonnourished area, nesting success was significantly lower in the nourishment area during the two seasons postnourishment. In both areas, a significant decrease occurred during 2002 relative to 2001 (nourished: $\chi^2 = 523.66$, $p < 0.0001$ and nonnourished: $\chi^2 = 1{,}134.8$, $p < 0.001$). Although decreases in nest production were observed in both areas, the decrease in nourished areas (48.4%) was more than twice that observed in nonnourished areas (22.3%; Fig. 1). During the third season postnourishment (2003), nesting success increased significantly in the nourished ($\chi^2 = 334.17$, $p < 0.0001$) and nonnourished ($\chi^2 = 449.04$, $p < 0.0001$) areas, and the increase was more dramatic in the nourished area than in the nonnourished area (42.6 and 15.6%, respectively; Fig. 1).

The 2002 season (an even year) was a high Green turtle nesting season; nesting increased 11% in the nonnourished area from 2000 to 2002 (2,661 and 2,998 nests, respectively) but decreased 36.5% in the nourished area (312 and 198 nests, respectively). For the historical mean and the even-numbered season prior to the nourishment (2000), nesting success rates were significantly higher in the nourishment area compared to the nonnourished areas, whereas during the first season postnourishment (2002), the nourished area had significantly lower nesting success rates. However, nesting success in both areas was significantly lower in 2002 than in 2000 ($\chi^2 = 143.23$, $p < 0.0001$), decreasing 7.3 and 54.7% in the nonnourished and nourished areas, respectively (Fig. 2). From 2000 to 2002, Loggerhead and Green turtle nesting success decreased approximately 50 and 10% in the nourished and the nonnourished areas, respectively.

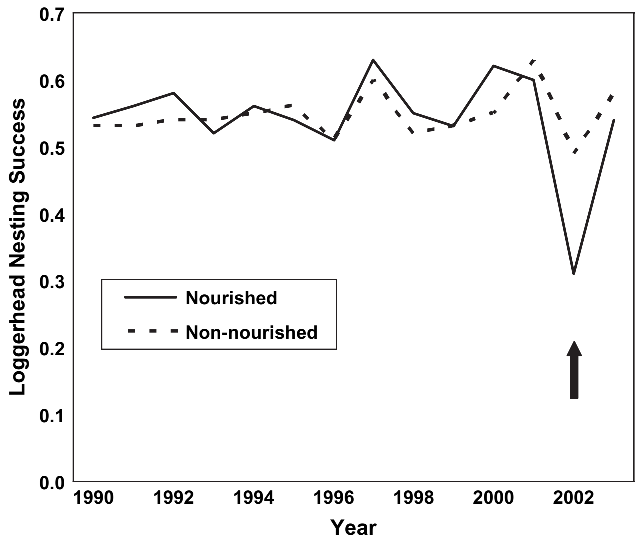

Figure 1. Comparison of Loggerhead nesting success between the nourished and the nonnourished areas. The arrow indicates the first nesting season immediately following the nourishment project.

Of the nonnesting emergences observed after nourishment during 2002 and 2003, more emergences were aborted with no attempt to dig than at any other stage. In 2002, Loggerhead nonnesting emergences comprised 34 (1.6%) abandoned egg chambers (AEC), 403 (18.7%) preliminary body pits, and 1,717 (79.7%) emergences with no attempt to dig. Green turtle nesting activity resulted in

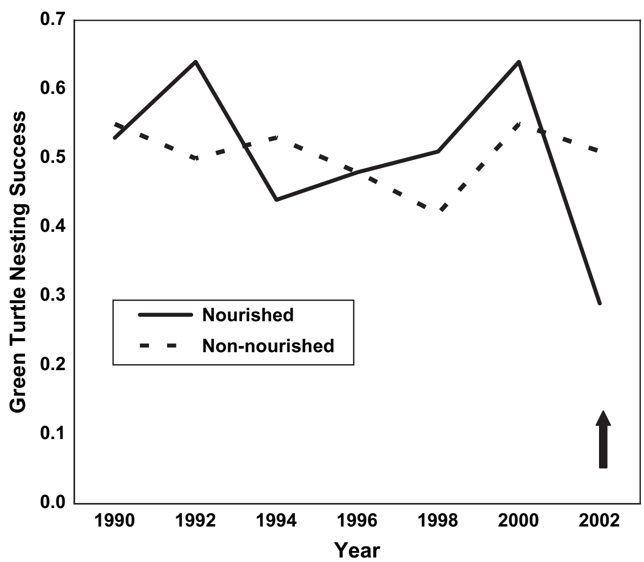

Figure 2. Comparison of Green turtle nesting success between the nourished and the nonnourished areas. The arrow indicates the first nesting season immediately following the nourishment project.

Table 1. Distribution of nests and apexes in regard to the nourished beach profile.

			Loggerhead			
	Green Turtle, 2002		2002		2003	
Section	*Nest*	*Apex*	*Nest*	*Apex*	*Nest*	*Apex*
Total emergences	198	496	972	2,154	1,798	1,556
Emergences in different sections (%)						
Scarp	0.0	0.4	0.1	0.3	0.1	38.7
Gradient	0.5	10.3	12.1	8.7	51.3	0.1
Berm	7.0	61.5	55.9	71.4	40.4	50.6
Foredune	91.4	27.0	31.5	18.5	8.1	10.2
Dune	1.1	0.8	0.4	1.0	0.2	0.4

16 (3.2%) AEC, 90 (18.1%) preliminary body pits, and 390 (78.6%) emergences with no attempt to dig. Loggerhead nonnesting emergences during 2003 resulted in 116 (7.5%) AEC, 443 (28.5%) preliminary body pits, and 997 (64.1%) emergences with no digging.

Distributions of nests and apexes in regard to the section of the nourished beach profile are indicated in Table 1. Green turtles nested on the constructed foredune most often. During 2002, more than half of the Loggerhead crawls were deposited on the berm. However, in 2003, significant decreases in the distance from high tide ($H = 59.17$, $p < 0.001$) and increases from distance to dune ($H = 87.19$, $p < 0.001$) were documented for nesting crawls for Loggerheads. This altered the distribution of nest placement such that more nests were placed on the gradient in 2003 than in previous years (Table 1).

Correlations among the measured beach width and the straight-line distance from the MHWL to nests or the apexes (Table 2) indicate that crawl length was strongly correlated with beach width in the nonnourished area for both species. In the nonnourished area, Green turtles did not crawl significantly further up the beach than did Loggerheads. Both species crawled significantly farther from the MHWL in the nourished area than in the nonnourished area before nesting or aborting a nesting attempt. A significant correlation between crawl length and beach width in the nourished area was exhibited by Green turtles but did not exist for Loggerheads. On the nourished beach, Green turtles crawled significantly farther than Loggerheads (Table 2). For both areas, the crawl lengths of nesting and nonnesting attempts were not significantly different, with the exception of Green turtle nests being significantly longer than nonnesting attempts on the nourished beach (Table 2).

Reproductive Success

Loggerhead reproductive success rates did not differ significantly between beaches in 2001, 2002, or 2003 (Table 3). Loggerhead mean hatching and emerging success on the nourished and nonnourished beaches increased each year (2001–2003); however, success rates did not increase significantly relative to the previous year (Table 3). Green turtle reproductive success rates did not differ significantly between beaches in 2000 or 2002 (Table 4). A significant increase in HS ($H = 25.9$, $p < 0.001$) and emerging success ($H = 22.4$, $p < 0.001$) occurred for both areas from 2000 to 2002 (Table 4).

Loggerhead and Green turtle hatching and emerging success in 2002 did not differ significantly ($H = 7.5$ and 7.0, respectively) between areas or between species in the same area. HS, excluding washed out nests, was significantly higher in the nourished area than in the nonnourished area for Loggerheads in 2002 and 2003, but Green turtle HS in 2002 was not significantly different in either of the areas (Appendix). During 2002, comparisons between Loggerhead and Green turtle HS did not differ significantly between species in the same area (Appendix).

Estimated Loggerhead reproductive output for the nonnourished area increased 8.0% from 2001 to 2002 and by 16.3% from 2002 to 2003 (Fig. 3). The nourished area produced 52.2% fewer hatchlings/km in 2002 than in 2001 and 44.1% more hatchlings/km in 2003 than in 2002 for

Table 2. Spearman's Rho correlation coefficients between the measured beach width and the straight-line distances from the MHWL ± SE of the mean to the nest sites or the apexes.

Variable	r_s	*p*	*n*	*Distance From MHWL (m)*	*Beach Width (m)*
Nourished					
Loggerhead nest	0.08	n.s.	246	19.36 ± 0.97	44.63
Loggerhead apex	0.15	0.02	251	18.58 ± 0.82	43.87
Green turtle nest	0.67	<0.0001	107	36.24 ± 1.43	41.27
Green turtle apex	0.22	0.03	108	24.43 ± 1.42	45.05
Nonnourished					
Loggerhead nest	0.74	<0.0001	232	9.66 ± 0.34	15.29
Loggerhead apex	0.62	<0.0001	209	9.91 ± 0.35	14.01
Green turtle nest	0.86	<0.0001	164	12.69 ± 0.51	14.90
Green turtle apex	0.91	<0.0001	17	9.93 ± 1.25	11.30

A Kruskal–Wallis analysis of variance ($H = 289.0$, $p < 0.0001$) indicated significant differences. Dunn's multiple comparisons found that all nourished area nests and apex distances from MHWL were significantly greater than those in the nonnourished areas. Values for Loggerheads represent 2002 and 2003 combined and those for Green turtles represent 2002. n.s., not significant.

Table 3. Loggerhead turtle mean hatching and emerging success ± SE of the mean during years prior to and postnourishment compared during the same year for each beach.

		HS (%)		Emerging Success (%)	
Year	*Nourishment Status*	*Nourished*	*Nonnourished*	*Nourished*	*Nonnourished*
2001	Prenourish	46.7 ± 8.8 (18)	47.6 ± 3.2 (143)	46.4 ± 8.8 (18)	45.5 ± 3.2 (143)
2002	Postnourish	59.9 ± 3.2 (152)	56.8 ± 2.8 (177)	58.9 ± 3.3 (151)	55.2 ± 2.8 (177)
2003	Postnourish	69.2 ± 3.3 (106)	67.2 ± 2.2 (186)	66.9 ± 3.4 (106)	65.9 ± 2.2 (186)

A Kruskal–Wallis analysis of variance indicated that the values were not significantly different. Numbers in parentheses are the numbers of nests compared.

Table 4. Green turtle mean hatching and emerging success ± SE of the mean during years prior to and postnourishment compared during the same years for each beach.

		HS (%)		Emerging Success (%)	
Year	*Nourishment Status*	*Nourished*	*Nonnourished*	*Nourished*	*Nonnourished*
2000	Prenourish	51.3 ± 5.2 (7)	46.8 ± 5.3 (41)	50.1 ± 5.1 (7)	46.6 ± 5.2 (41)
2002	Postnourish	73.4 ± 2.0 (136)	64.0 ± 2.5 (141)	71.0 ± 2.1 (136)	62.9 ± 2.5 (141)

A Kruskal–Wallis analysis of variance indicated that the values were not significantly different. Numbers in parentheses are the numbers of nests compared.

a 14.9% increase from 2001 to 2003 (Fig. 3). Estimated Green turtle reproductive output for the nonnourished area increased 48.1% in 2002 relative to 2000 and in the nourished area it decreased 0.8% from 2000 to 2002 (Fig. 4).

Postemergence Hatchlings

A significant increase in disorientation frequency was recorded for each season postnourishment (Fig. 5). There were significantly more disorientations during 2002 ($n = 24$ nests) than in 2001 ($n = 4$ nests; $\chi^2 = 27.270$, $p < 0.0001$), and in 2003, incidents ($n = 158$ nests) were significantly more numerous than in 2002 ($\chi^2 = 38.347$, $p < 0.0001$). The mean number of disorientations in the years from 1995 to 2001 (prenourishment) was 1.7 nests, with a maximum of four nests observed in one year. In the nonnourished area, one clutch was disoriented in 2002 and three during 2003. None of the observed disoriented hatchlings were Green turtle nests.

Discussion

Comparative data from this study established that the 2002 Brevard County nourishment project, one season postnourishment, has statistically similar negative effects

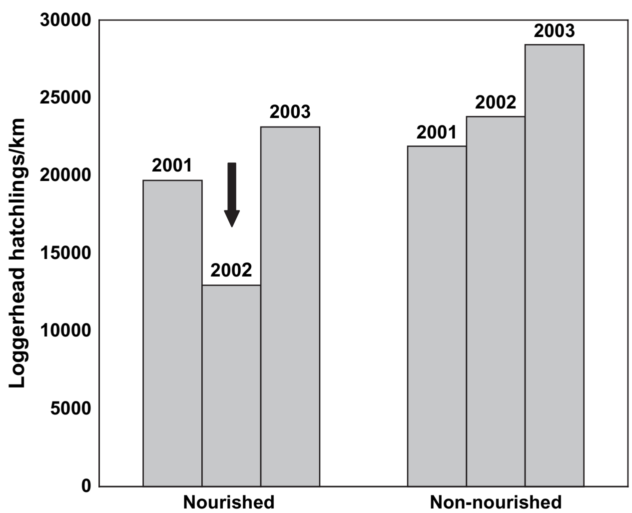

Figure 3. Comparison of Loggerhead reproductive output (number of hatchlings km^{-1} yr^{-1}) between the nourished and the nonnourished areas. The arrow indicates the first nesting season immediately following the nourishment project.

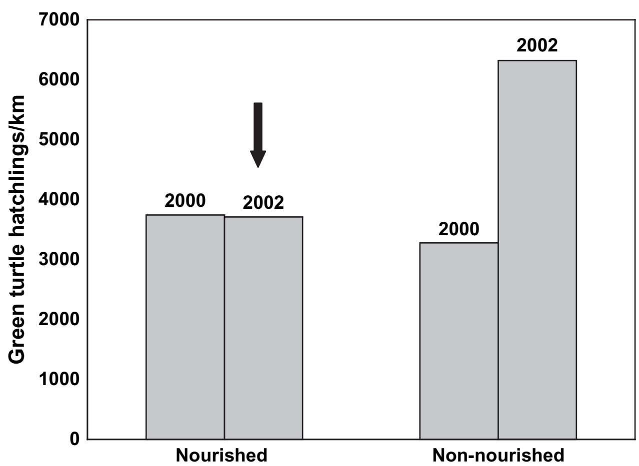

Figure 4. Comparison of Green turtle reproductive output (number of hatchlings km^{-1} yr^{-1}) between the nourished and the nonnourished areas. The arrow indicates the first nesting season immediately following the nourishment project.

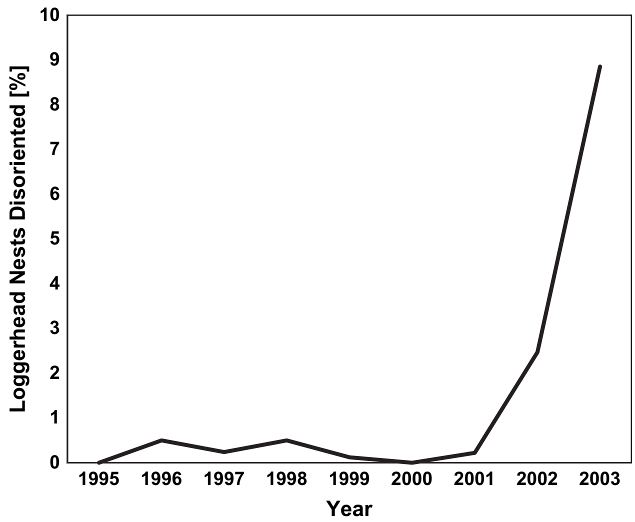

Figure 5. Percentage of Loggerhead nests in which hatchling disorientations were observed for the nourished area 1995–2003. The first season postnourishment is 2002.

on Loggerhead and Green turtle nesting success and no significant differences on reproductive success when compared to the nonnourished area or between species.

Nesting Activity and Placement

Numerous studies have described the effects of beach nourishment on the Loggerhead (Crain et al. 1995; Steinitz et al. 1998; Rumbold et al. 2001), concluding that nesting success, and therefore nest density, decreases during the year following nourishment. Low Loggerhead nest production in the nourished area was partly the result of fewer nests produced in the area and statewide. However, low Green turtle nest production in the nourished area appears to be directly related to the nourishment, as marked growth continued in the nonnourished area and statewide (Florida Fish and Wildlife Research Institute, Index Nesting Beach Survey database). To understand how females respond to the altered profile and substrate, it is necessary to compare the efforts (nesting success) of females in their attempts to nest.

Historically (1990–2001), nesting success for the 40.5-km beach has been roughly 0.50, with 50% of all emergences resulting in nests (Weishampel et al. 2003). The low nesting success rates for Loggerheads and Green turtles observed in the nourished area one season postnourishment (0.31 and 0.29, respectively) indicated that females attempted to nest on the nourished beach but were unsuccessful in proportionately more attempts than in previous years on the same beach or in the nonnourished areas under the same annual conditions. This would imply that of the number of females emerging, fewer were receiving the appropriate cue(s) to nest. As a result of low Green turtle nest production during 2003, conclusions concerning long-term nesting success rates for Green turtles (two to three nesting seasons postnourishment) cannot be made due to low sample size. The return of Loggerhead nesting success to equivalent rates similar to those on the adjacent nonnourished beach and historical rates two seasons postnourishment was observed during this study.

In previous studies, the reduction in nesting success during the first year postnourishment for Loggerheads has been attributed to escarpments obstructing accessibility and increased sand compaction that impeded egg chamber construction (Crain et al. 1995; Steinitz et al. 1998; Herren 1999; Rumbold et al. 2001). In this study, escarpments did not obstruct beach accessibility. If shear resistance (i.e., compaction) of the nourished substrate prevented females from digging a nest chamber, thus decreasing nesting success, a large portion of AEC would be expected (Raymond 1984). In our study, however, the numbers of AEC recorded for Loggerheads and Green turtles in the nourished area were minimal.

Typically, first season postnourishment Loggerhead nesting success is significantly below average, followed by a return to average levels during the second or third seasons. Steinitz et al. (1998) found that nesting success on nourished and natural beaches became more similar as the physical characteristics of the beaches became similar. The nourishment project reported here was completed one week before Loggerhead nesting began. Storm and wave activity had not equilibrated the new profile of the nourished beach before Loggerheads attempted to nest. During 2002, the nourished beach was characterized as wide and relatively level or flat with a steeply sloped gradient at the seaward edge, unlike the adjacent natural beaches with a relatively continuous slope from dune to surf. The profile remained the same during 2003, with the exception of the equilibration along the seaward portion of the beach above high tide line. The change in distribution of Loggerhead nests from the berm to the gradient, with a corresponding significant decrease in crawl distance during 2003, supports the hypothesis that the equilibrated seaward face of the beach (the gradient) became more attractive to Loggerheads over time. This timing suggests that the unequilibrated beach profile was a major contributor to the decrease in nesting success during 2002 and that the increase in Loggerhead nesting success during 2003 occurred because the profile had equilibrated. Green turtles typically deposit clutches more distant from the surf line than do Loggerheads; as a result, Loggerheads may experience a decline in nesting success until that portion of the beach profile becomes more suitable.

The wider nourished beach did not alter Green turtle nest placement; females increased crawl lengths inland, traversing the entire nourished profile (mean beach width = 41.3 m) to nest on the constructed foredune and dune. The nonnesting crawl lengths were significantly shorter than the nesting attempts in the nourished area but not significantly different on the narrow nonnourished beach. This indicates the early termination of a nesting attempt before reaching the dune on the nourished beach. Turtles that crawled farther and reached the foredune area nested more often than those that did not. This supports the idea that variables associated with the presence of a dune feature initiated nesting on the nourished beach.

Loggerheads and Green turtles maintain levels of fidelity to nesting beaches that vary over short timescales in response to beach dynamics (Godley et al. 2001). This suggests that when nourished beaches are unfavorable for nesting, marine turtles are capable of reemerging on adjacent beaches that are favorable. Thus, a mosaic of nourished and nonnourished beach sections or adjacent nourished beach sections applied during different years would have a smaller impact on nesting than would long, contiguous stretches of nourished beach applied in a single application.

Reproductive Success

Sediment characteristics are integral to reproductive success (Bustard 1973; McGehee 1979; Packard & Packard 1988). Nourished beaches have had positive effects (Broadwell 1991; Ehrhart & Holloway-Adkins 2000; Ehrhart & Roberts 2001), negative effects (Ehrhart 1995; Ecological Associates, Inc. 1998), or no apparent effect (Raymond 1984; Nelson et al. 1987; Broadwell 1991; Ryder 1993; Steinitz et al. 1998; Herren 1999) on HS. These inconsistent results are attributed to different physical attributes of the nourished beaches and the extent of erosion on preexisting beaches. Studies demonstrating negative results reported that differences were difficult to explain or hampered by low sample sizes (Ehrhart 1995; Ecological Associates, Inc. 1998).

The nourished beach in this study did not significantly affect reproductive success as measured by hatching and emerging success for Loggerheads or Green turtles. These rates were nearly equal and not significantly different from those for the nonnourished area. This indicates that hatchlings did not encounter difficulties extricating themselves from the nourished substrate. Our results indicate that the nourished beach provided an incubation microhabitat for Loggerhead and Green turtle reproduction similar to that of adjacent nonnourished areas. However, when washed out nests were excluded, Loggerhead HS rates in the nourished area were significantly higher than in the nonnourished area. This suggests that the substrate and/or nest location was more conducive to the proper development of Loggerhead eggs but that washed out nests along the equilibrated face of the berm reduced the calculated success rate for Loggerhead nests. The same pattern is not observed in Green turtles because a majority of their nests were placed on the foredune and were unsusceptible to washout.

Postemergence Hatchlings

Hatchlings often become disoriented by artificial beachfront lighting (Witherington & Martin 2000). Loggerhead hatchling disorientations increased significantly postnourishment, whereas no Green turtle disorientations were observed. Green turtle hatchling disorientations may have been more logistically difficult to record due to the close proximity of nests to the foredune and the expansive profile that was traversed during surveys.

A clear cause and effect relationship explains the increase in hatchling disorientations in the nourished area. An increase in elevation of the nourished beach combined with an easterly expansion allowed light sources not previously visible to be seen by hatchlings. Evening lighting surveys of this area conducted prior to the nourishment project (February 2002) and after project completion (April 2002) noted that potential lighting problems nearly tripled. Despite the greater nesting density in the nonnourished areas, only four disorientation incidents were recorded during 2002 and 2003. The increase in events reported in the nourished area for 2003 relative to that in 2002 indicates an increase beyond that caused by increased nest densities.

Conclusions

The findings in this study reject our null hypothesis that beach nourishment, as described in this project, has no effects on Loggerheads or Green turtles. Rather, the effects on the number of nests produced are negative (as a result of decreased nest-to-nonnesting emergence ratios) for both species, though the effect is ephemeral in Loggerheads (one season postnourishment). Reproductive success is not altered by the nourishment process for either species. Total reproductive output, as a measure of the number of hatchlings produced, is a better estimate of positive project effects to marine turtles. In our study, the total number of Loggerhead hatchlings produced decreased during the first year postnourishment and returned to nonnourished levels during the nesting season two years postnourishment. In Green turtles, the negative effects on nesting success slightly decreased overall reproductive output the first year postnourishment. Despite similarities between Loggerhead and Green turtle nesting and reproductive success, our results demonstrate that beach nourishment can have differential effects on the two species. The differences in preferential nest placement and the tendency of Loggerheads to nest closer to the water (making nests more susceptible to erosion during beach equilibration) should be considered.

Implications for Practice

- Loggerhead preference for steeply sloped beaches on the Atlantic coast and the return to more typical nesting success rates after beach equilibration implicate the initial constructed beach profile as a causal factor in decreased nesting success.

- Equilibrated profiles of nourished beaches should mirror adjacent, nonimpacted beaches. Regional differences in natural beach profiles mean that no universal template will work for all nourishment projects.
- Increased time (months or weeks) between the completion of the nourishment project and the onset of the next nesting season will allow for equilibration of the beach prior to the nesting season.
- Limiting the contiguous spatial extent of single application nourishment projects will provide marine turtles an alternative of nesting on adjacent nonnourished areas or in nourished areas that have equilibrated to a more natural profile.

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Appendix. Mean HS ± SE of the mean, calculated to exclude washed out nests on the nourished beach compared to those on the nonnourished beach during the same years and compared between species for each beach of the same year.

	Washouts (n)	*Marked Nests (%)*	*HS (%)*	*n*
Green turtle, 2002				
Nourished	7	5.10	77.4 ± 1.5a	129
Nonnourished	6	4.30	66.9 ± 2.4a	135
Loggerhead, 2002				
Nourished	27	17.80	73.4 ± 2.8b	124
Nonnourished	27	15.30	67.0 ± 2.5c	150
Loggerhead, 2003				
Nourished	14	13.20	79.7 ± 2.4d	92
Nonnourished	9	4.80	70.7 ± 2.0e	177

Significant H values indicated that values were different ($H = 32.1$ and 33.1). Dunn's multiple comparisons indicated that there were significantly more washouts on the nourished beach than on the nonnourished beach for 2002 and 2003 but found no significant differences for Green turtle values in 2002. Significant differences using Dunn's comparison. Different letters (a–e) denote significantly different HS values. Loggerhead 2002: nourished > nonnourished; Loggerhead 2003: nourished > nonnourished.