Impacts of a geotextile container dune core on marine turtle nesting in Juno Beach, Florida, United States

Sarah E. Hirsch1,2, Stephanie Kedzuf1,3, Justin R. Perrault1

Hard armoring technologies (e.g. rock revetments and seawalls), which are installed to protect homes from beach erosion, can diminish the aesthetics and amenity of the beach. Over time, these structures cause beach narrowing and often prevent marine turtle access to nesting habitat altogether. An alternative armoring technology, known as geotextile dune core systems (or geocores), has been developed and implemented to protect inland infrastructure from beach erosion, yet there remains an absence of research on possible effects on marine turtles. In this study, we examined the impacts of a geocore installed on Juno Beach, Florida, United States in February 2014 on loggerhead (Caretta caretta) and green turtle (Chelonia mydas) nesting success, hatching success, and emergence success. A before-after-control-impact paired series design evaluated the difference in nesting success per week for the impact and control sites 4 years before (2010–2013) and 4 years after (2014–2017) the installation of the geocore. Neither loggerhead nor green turtle nesting success was significantly different after the installation of the geocore; however, when analyzing loggerhead crawls that came to within 5 m of the geotextile bags, nesting success decreased. Neither hatching nor emergence success was significantly different after the installation of the geocore for either species. Our results suggest that geocores may minimally affect loggerhead and green turtles and provide a suitable restoration technique for homeowners facing beach erosion.

Key words: beach erosion, geocore, green sea turtle, loggerhead sea turtle

Implications for Practice

• This is the first published study to address the impacts of geocores on marine turtles, providing a foundation for future research.
• Our results suggest that geocores minimally impact marine turtle nesting, hatching success, and emergence success and therefore could provide a more suitable armoring solution to coastal erosion in comparison to historical hard-armoring techniques such as seawalls.

Introduction

The beaches in Florida, United States, host some of the most important marine turtle nesting grounds in the Western Hemisphere (Ehrhart et al. 2014). Three marine turtle species regularly nest on Florida’s beaches: loggerhead (Caretta caretta), green (Chelonia mydas), and leatherback (Dermochelys coriacea) sea turtles. Loggerhead turtles experienced a 42% decline in their nest numbers during the early to mid-2000s, but nest numbers have increased dramatically (by 71%) since 2007 (FWC 2017). Leatherback and green turtle nesting have been exponentially increasing since systematic monitoring began in 1989 (FWC 2017). These trends are encouraging; however, marine turtles are facing a drastically changing coastline.

Unique challenges exist for Florida’s beach management. Florida’s densely populated coasts are an essential part of the state’s economy, generating over $15 billion in revenue for the state (Shivlani et al. 2003). However, these same beaches also provide critical habitat for marine turtles, shorebirds, and a host of other species, requiring beach management decisions to balance economic value with ecological implications (Shivlani et al. 2003; Martínez et al. 2007). Coastal development and sea level rise are altering natural beach dynamics, resulting in much of Florida’s coastline being classified as critically eroding habitat and leaving homes and infrastructure vulnerable during storm events (Mosier 1998; Pilkey & Cooper 2012; FDEP 2016). Large-scale beach nourishment projects occur on a regular basis to increase shoreline width, protect inland structures, and increase tourism (Rumbold et al. 2001).

Nourishment projects do not offer long-term solutions for private homeowners trying to protect smaller sections of beach in front of their homes from the encroaching shoreline. Historically, homeowners relied on hard-armoring technologies (e.g. rock revetments, seawalls, etc.) to safeguard their properties from beach erosion. Consequently, multiple forms of
hard-arming structures stabilize approximately one-quarter of Florida’s coastline (Schroeder & Mosier 2000). Seawall construction continued at an unprecedented rate on Florida’s beaches in the early 1980s with few studies evaluating the impact on marine turtles (Schmahl & Conklin 1991; Mosier 1998; Ruppert 2008). As a result, seawalls are the most common anthropogenic barrier to marine turtles accessing Florida’s southeast beaches (Schroeder & Mosier 2000; Witherington et al. 2011a). Mounting evidence has suggested that seawalls ultimately exacerbate beach erosion, causing beach narrowing or loss because the structures prevent the natural processes that allow for dune accretion (USACE 1984; Ruppert 2008; Pilkey & Cooper 2012). Thus, seawalls tend to have a detrimental effect on marine turtle nesting habitat.

Marine turtles are less likely to emerge on a beach with a seawall in comparison to a natural beach. Those turtles that do emerge near seawalls have a higher tendency to return to the water without depositing a clutch of eggs (i.e. false crawl) than those on beaches without an anthropogenic barrier (Mosier 1998), lowering overall nesting success (the ratio of nests to false crawls). Marine turtles expend tremendous amounts of energy to crawl out of the water onto the beach to nest (Mosier 1998; Burns et al. 2016). Wasting these energy reserves on unsuccessful nesting attempts could ultimately reduce the number of clutches laid or the number of eggs per clutch, diminishing overall reproductive output (Broderick et al. 2003; Katselidis et al. 2013). Furthermore, the nests that are deposited are vulnerable to tidal activity, especially during storm events (Rizkalla & Savage 2011), which can decrease hatching and emergence success or completely wash out a nest (Whitmore & Dutton 1985; Foley et al. 2006; Rizkalla & Savage 2011).

With the majority of marine turtle nesting in the United States occurring on private lands, it is imperative for coastal management to address the balance between erosion control measures and their impacts to wildlife (Fuentes et al. 2016). New alternative technologies for preventing beach erosion are constantly being developed (Pilkey & Cooper 2012). One of these technologies is a geotextile container used as a dune core (hereafter, geocore), which involves burying large sand-filled bags made from geotextile fabric at the base of the dune (Fig. 1). The reconstructed dune is typically planted with native, dune stabilizing plants with the goal of restoring a “natural” dune system (Gregory et al. 2005). Geocores are better at maintaining the aesthetics and amenity of the beach in comparison to hard armor solutions (Parab et al. 2011). If geocores can protect existing infrastructure while reestablishing a dune system suitable for marine turtles, they may provide a valuable restoration technique for coastal management.

The Florida Department of Environmental Protection (FDEP) oversees all construction activities that occur on Florida beaches, including regulating the construction of geocores (Ruppert 2008). Historically, FDEP favored permitting vertical seawalls to protect private homes because their installation impacted less of the active sandy beach compared to the sloped design of a geocore built closer to the waterline (Gregory et al. 2005). Under rule 62B-56 of the Florida Administrative Code, FDEP details the requirements for the installation of a geocore. These requirements include, but are not limited to, maintaining a minimum of one vertical meter of beach quality sand covering the geotextile bags at all times, planting dune stabilizing vegetation on the reconstructed dune, and ensuring the reconstructed dune does not cause any significant impacts to state or federalally listed threatened or endangered species. If at any time the geotextile bags are exposed (e.g. storm event, vandalism), the permittee is required to rectify the issue by either replacing the sand over the geotextile bags to the minimum one vertical meter or by removing the geotextile bags from the beach (deeming the geocore a failure).

Despite the fact that geocores have been installed on beaches throughout the state of Florida, and on beaches around the world, to our knowledge, no studies have been published on their impacts to marine turtle nesting. The objective of our study was to determine the effects of a geocore installed in February 2014 along 150.5 m of beach in Juno Beach, Florida, on loggerhead and green turtle (1) nesting success, (2) hatching success, and (3) emergence success.

Methods

Geocore Installation
The geocore was installed along 150.5 m of coastline located on the southern portion of Juno Beach, Florida (Fig. 2). Prior to installation, in February 2012, 200 cubic yards of upland-sourced beach quality sand (i.e. sand obtained from an inland sand mine) was added to the project area to protect the upland structures. In October 2012, Hurricane Sandy caused massive beach erosion resulting in an escarpment more than 4 m in height. In February 2013, the homeowners conducted an emergency sand replacement to reconstruct the dune and protect their property. In January 2014, FDEP issued a permit for the installation of the geotextile containers and construction was completed on 28 February 2014. The geocore was constructed in three segments: the south segment was 27 m long, 10.5 m wide, and 3.5 m high; the middle segment was 61.5 m long, 5 m wide, and 3.5 m high; the north segment was 62 m long, 5 m wide, and 3.5 m high. A double layer of geotextile bags placed along the length of the project area formed by a western wall of geotextile bags and an eastern wall of geotextile bags. Additionally, an upper layer of geotextile bags were placed on top of the western wall of geotextile bags. In total, the geocore consisted of approximately 250 geotextile bags. Approximately 5,500 cubic yards of upland-sourced sand covered the geotextile bags, creating a final seaward slope of 26.6° for the reconstructed dune. Native sea oats (Uniola paniculata), sea grapes (Coccoloba uvifera), and railroad vine (Ipomoea pes-caprae) were planted to stabilize the newly constructed dune. In January 2016, a high tide event exposed the geotextile bags. The following month, beach quality sand was added to the project site to cover the geotextile bags with a minimum of one vertical meter of sand and the dune replanted to comply with permit conditions. Hurricane Matthew caused a large escarpment to form at the project site in October 2016. Adding beach-compatible sand in February 2017 eliminated the
Geocores and marine turtles

Figure 1. Schematic of a geotextile container (geocore) buried at the base of a dune.

Figure 2. Location of the geocore/impact site and control site in Juno Beach, Florida, United States.

Figure 3. Location of the geocore. To avoid the compounding effects of the rocks on the northern end and the transition zone where the structure curves inland on the south end, the northern and southern portions of the project area were not included in statistical analyses.

The northern end of the project site is characterized by natural Anastasia Formation limestone rock that is exposed during marine turtle nesting season. These rocks prevent turtles from accessing that section of beach. To avoid the confounding effects of the rocks on the north end and in the transition zone where the structure curves inland on the south end, the northern and southern portions of the project area were not included in statistical analyses (Fig. 3). Consequently, the impact site for this study utilized a 106.3-m stretch of beach. A control area of the same size located 122 m to the south left a small buffer area between the two sites (Fig. 2). The control site has a similar density of crawls, beach width, and number of single-family homes in comparison to the impact site before the installation of the geocore.

Marine Turtle Monitoring

Standardized marine turtle nesting surveys have been conducted on Juno Beach, Florida, United States since 1989 in accordance with Florida Fish and Wildlife Conservation Commission’s Index Nesting Beach Program protocols (FWC 2016). Juno Beach (9.62 km) has ecological importance for three species of marine turtles. Hosting an average of 5,370 loggerhead nests, 1,680 green turtle nests, and 141...
leatherback nests annually since 2010, Juno Beach is one of the highest-density nesting beaches in the United States (LMC unpublished data).

Daily dawn nesting surveys were conducted from March through October of 2010–2017. During surveys, all crawls were identified to species and crawl type (i.e. nest or false crawl) (Table 1). In accordance with established guidelines set by FWC (2016), crawl type was determined based on visual cues left in the sand (not the confirmed presence or absence of eggs). Nests are defined as emergences that result in the successful deposition of eggs and are characterized by a mound of sprayed sand covering a portion of the incoming tracks, whereas false crawls are defined as an emergence that did not result in the deposition of eggs. Nesting success is the proportion of crawls that resulted in successful oviposition compared to the total number of crawls (i.e. nests plus false crawls). A submeter global positioning system (GPS) location was recorded at each nest site or at the furthest point inland of a false crawl using a handheld device (Trimble Pathfinder ProXH, ProXL, GeoXH, GeoXT, or Pro6T; Trimble Inc., Sunnyvale, CA, U.S.A.). A random sampling scheme established a temporally and spatially unbiased sample set for analysis of hatching and emergence success (FWC 2016). Every seventh loggerhead nest and every sixth green turtle nest documented in the project area were marked. Daily monitoring of marked nests occurred throughout incubation to document instances of overwash, predation, and hatching. Nests were excavated and the contents inventoried 72 hours postemergence, or at 70 days incubation in cases where an emergence was not noted (FWC 2016). Contents were sorted into the following categories: empty/hatched eggshells, whole/unhatched eggs, live pipped, dead pipped, live-in-nest, and dead-in-nest. Clutch size was determined by adding empty eggshells, plus unhatched eggs, plus live pipped, plus dead pipped eggs. Hatching success was calculated as the number of empty eggshells divided by the clutch size. Emergence success was calculated as the number of empty eggshells minus any live or dead hatchlings found in the chamber divided by the clutch size.

### Statistical Analyses

A standard before-after-control-impact paired series (BACIPS) approach was used (modeled after Rumbold et al. 2001) to compare the difference (delta: Δ) in nesting success by week between the control and impact sites. Positive Δ values represent an increase in nesting success in comparison to the control and vice versa. The BACIPS approach was used because it is designed to detect localized environmental impacts of an unreplicated point source disturbance. Due to the inherent lack of randomization with a project such as a geocore installation, BACIPS assumes that if there is no impact, then the control and impact sites will display similar trends across years. The design provides an approach that can cancel the effects of year-to-year variation by pairing the effects of the control to the impact site in each year (Schwarz 2015). Because marine turtle nesting is variable in space and time, a BACIPS approach was the best way to determine the impact of the geocore installation from other environmental influences.

Historical dawn nesting survey data were pooled for four seasons prior to the installation of the geocore (2010–2013; hereafter, before years). These values were compared to survey data that were pooled for four seasons after installation of the geocore (2014–2017; hereafter, after years). For loggerhead turtles, the data were not normally distributed as determined by the Shapiro–Wilk test. The data could not be transformed to fit a normal distribution; therefore, a nonparametric Mann–Whitney

### Table 1. Loggerhead (Caretta caretta) and green turtle (Chelonia mydas) nest and false crawl counts in the control area and impact (i.e. geocore) area of Juno Beach, Florida for the study period (22 April–1 September for loggerheads; 10 June–25 August for green turtles). The percentage in parentheses represents the number of nests or false crawls during our study period in comparison to total nests and false crawls during the entire nesting season (1 April–31 October).

<table>
<thead>
<tr>
<th>Year</th>
<th>Nests</th>
<th>False Crawls</th>
<th>Nests</th>
<th>False Crawls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Impact (Geocore)</td>
<td>Control</td>
<td>Impact (Geocore)</td>
</tr>
<tr>
<td>C. caretta</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>55 (100%)</td>
<td>88 (100%)</td>
<td>115 (100%)</td>
<td>130 (100%)</td>
</tr>
<tr>
<td>2011</td>
<td>81 (100%)</td>
<td>79 (100%)</td>
<td>106 (100%)</td>
<td>64 (100%)</td>
</tr>
<tr>
<td>2012</td>
<td>116 (100%)</td>
<td>60 (100%)</td>
<td>162 (100%)</td>
<td>65 (100%)</td>
</tr>
<tr>
<td>2013</td>
<td>92 (100%)</td>
<td>92 (100%)</td>
<td>84 (100%)</td>
<td>72 (100%)</td>
</tr>
<tr>
<td>2014</td>
<td>55 (100%)</td>
<td>57 (100%)</td>
<td>131 (100%)</td>
<td>74 (100%)</td>
</tr>
<tr>
<td>2015</td>
<td>60 (100%)</td>
<td>140 (100%)</td>
<td>139 (99%)</td>
<td>172 (100%)</td>
</tr>
<tr>
<td>2016</td>
<td>149 (100%)</td>
<td>88 (100%)</td>
<td>186 (100%)</td>
<td>184 (100%)</td>
</tr>
<tr>
<td>2017</td>
<td>64 (100%)</td>
<td>81 (100%)</td>
<td>157 (100%)</td>
<td>175 (100%)</td>
</tr>
<tr>
<td>C. mydas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>32 (100%)</td>
<td>46 (89%)</td>
<td>37 (95%)</td>
<td>52 (98%)</td>
</tr>
<tr>
<td>2011</td>
<td>24 (96%)</td>
<td>22 (96%)</td>
<td>32 (100%)</td>
<td>31 (100%)</td>
</tr>
<tr>
<td>2012</td>
<td>14 (93%)</td>
<td>8 (100%)</td>
<td>29 (100%)</td>
<td>16 (100%)</td>
</tr>
<tr>
<td>2013</td>
<td>56 (95%)</td>
<td>67 (93%)</td>
<td>43 (100%)</td>
<td>49 (96%)</td>
</tr>
<tr>
<td>2014</td>
<td>5 (83%)</td>
<td>5 (100%)</td>
<td>4 (100%)</td>
<td>5 (100%)</td>
</tr>
<tr>
<td>2015</td>
<td>72 (97%)</td>
<td>83 (91%)</td>
<td>63 (91%)</td>
<td>127 (94%)</td>
</tr>
<tr>
<td>2016</td>
<td>12 (100%)</td>
<td>6 (100%)</td>
<td>7 (88%)</td>
<td>9 (82%)</td>
</tr>
<tr>
<td>2017</td>
<td>44 (94%)</td>
<td>140 (97%)</td>
<td>110 (97%)</td>
<td>201 (99%)</td>
</tr>
</tbody>
</table>
U test was used to compare Δ values by week for loggerhead nesting success. For green turtles, the data were normally distributed, and a paired-samples t test was used to compare the Δ values by week. Although nesting season runs from 1 April to 31 October, only nests and false crawls documented from 22 April to 1 September for loggerheads and from 10 June to 25 August for green turtles were used in the analysis. This eliminated weeks where little (e.g. 1–2 crawls/week) to no activity was observed at the control or impact site across the 8 years of the study (2010–2017) and also normalized variation across seasons when turtles may start to nest early and linger later into the season in high nesting years compared to low nesting years. The date ranges included in the analysis still represent the majority (>95% for loggerheads and >80% for green turtles) of the marine turtle nesting activity on the study beach. Low leatherback numbers (<10 nests) at the impact site from 2010 to 2017 prevented any analyses for this species.

To further investigate any potential impacts of the geocore on marine turtle nesting, we evaluated the nesting success of crawls that came to within 1, 3, 5, and 7 m of the seaward edge of the buried geotextile bags. This allowed for the evaluation of potential impacts from the slope of the reconstructed dune. All crawls were plotted in ArcGIS 10.5.1 and the Multiple Ring Buffer tool was used to obtain the number of nests and false crawls within each distance from the geotextile bags. Data were pooled for the before years and after years. For each species, a chi-square test was run to compare overall nesting success of the entire impact site to nesting success within 1, 3, 5, and 7 m of the buried geotextile bags both before and after the installation.

Hatching success and emergence success for loggerhead and green turtles were also analyzed. We compared the pooled data from the before years to the pooled data for the after years. Due to low sample sizes, a Mann–Whitney U test was performed to compare the average hatching and emergence success before and after for each species on the impact and control sites. Nests predated or lost to erosion/washed out due to storm events were not included in the evaluation because an accurate total clutch size could not be determined. All statistical analyses were performed using IBM SPSS Statistics 24 (SPSS, Inc., Chicago, IL, U.S.A.) and p values less than 0.05 were considered significant.

Results

The number of loggerhead nests documented at the impact site varied from 57 to 140 nests per year; similar to the control site, which ranged from 55 to 149 nests per year. For green turtles, nest counts varied from 3 to 140 per year at the impact site and 5 to 72 per year at the control site (Table 1). The large variability in green turtle nest counts per year is due to the biennial nesting pattern (a year of high nesting followed by a year of suppressed nesting) that the Florida green turtle population exhibits (Weishampel et al. 2002). In years that exhibited high green turtle nest numbers, the impact site had a higher number of nests, whereas in years where green turtle nesting was lower, the control site had a higher number of nests. The BACIPS analysis controlled for both factors. Nesting success was not significantly different for loggerheads (Δ = −11.69%; U = 234; p = 0.423) or for green turtles (Δ = −3.53%; t_{10} = 0.455; p = 0.659) after construction of the geocore in comparison to the control site.

Overall nesting success for loggerhead turtles at the impact site before installation of the geocore was 49.1%. Nesting success was not significantly different for those crawls that came to within 1 (p = 0.916), 3 (p = 0.652), 5 (p = 0.404), and 7 (p = 0.481) m of the site where the geocore would be installed. From 2014 to 2017, loggerhead nesting success at the impact site was 37.7%. For those crawls that came to within 1, 3, and 5 m of the geotextile bags, nesting success significantly dropped to 11.4% (X^2 = 10.02; p = 0.002), 10.8% (X^2 = 19.17; p < 0.001), and 26.4% (X^2 = 5.88; p = 0.015), respectively. For crawls within 7 m of the geotextile bags, nesting success (39.5%) was similar to the overall nesting success (p = 0.618) after the installation of the geocore (Table S1).

For green turtles, nesting success was 50.7% for the impact site before installation of the geocore. Nesting success was not significantly different for those crawls that were within 1 (p = 0.800), 3 (p = 0.130), 5 (p = 0.128), and 7 (p = 0.165) m of the site where the geocore would be installed. In 4 years after the installation of the geocore, nesting success was 40.8% at the impact site. Nesting success was not significantly different for those green turtles that crawled within 1 (p = 0.299), 3 (p = 0.498), 5 (p = 0.292), and 7 (p = 0.146) m of the geotextile bags after installation of the geocore (Table S1).

Loggerhead hatching and emergence success were not significantly different after the installation of the geocore (Table 2). In the before years, median (interquartile ranges are reported in Table 2) loggerhead hatching success was 77.38% at the control site and 89.52% at the impact site (p = 0.191), while emergence success was 76.19% at the control site and 86.72% at the impact site (p = 0.244). Median loggerhead hatching success for the after years was 74.38% at the control site and 69.84% at the impact site (p = 0.905), while emergence success was 68.60% at the control site and 68.10% at the impact site (p = 0.905).

Similarly, green turtle hatching and emergence success were not significantly different after the installation of the geocore (Table 2). For green turtles, median hatching success in the before years was 89.88% at the control site and 84.13% at the impact site (p = 0.404), while emergence success was 89.88% at the control site and 81.19% at the impact site (p = 0.487). For the after years, median green turtle hatching success was 93.52% at the control site and 84.11% at the impact site (p = 0.220), while emergence success was 92.59% at the control site and 82.46% at the impact site (p = 0.220).

Discussion

Before armoring the coastline with geocores, studies on their effectiveness for erosion control and their suitability for wildlife
should be examined (Pilkey & Cooper 2012). In the current study, we evaluated the effects of a geocore on marine turtle nesting success retrospectively. Neither loggerhead nor green turtle nesting success was significantly different after the installation of the geocore. It is worth noting that nesting success did decrease in the after years for both species at both the control site and the impact site. Because the decrease in nesting success was also seen at the control site, the decline is likely due to other environmental factors. For instance, when the sand is dry, marine turtles have a difficult time constructing an egg chamber due to collapse of the egg chamber (Mortimer 1990). In the after years, Juno Beach saw some of the hottest and driest conditions on record (NOAA 2018), which could lead to an increase in the number of false crawls if the turtles cannot build an egg chamber, thereby lowering nesting success. The BACIPS design nullified these environmental influences by comparing the change at the control site with the change at the impact site.

To determine if the turtles were responding to the reconstructed dune, we also compared the nesting success at increasing distances from the buried geotextile bags. In the before years, overall loggerhead nesting success was similar to the nesting success of loggerheads that came within 1–7 m of the upland barrier/vegetation line where the geocore would be placed. In contrast, after the installation of the geocore, loggerhead nesting success was significantly lower for crawls that came within 5 m of the buried geotextile bags when compared to the overall nesting success at the impact site. For green turtles, prior to the installation of the geocore, overall nesting success was not significantly different than the nesting success of those crawls that came within 1–7 m of the upland barrier. Similarly, after the installation of the geocore, overall green turtle nesting success was not significantly different from the nesting success of green turtles that came within 1–7 m of the buried geotextile bags.

It appears that loggerheads and green turtles may be reacting to the geocore differently. Because loggerhead turtles that crawled to within 5 m of the buried geotextile bags had a significantly lower nesting success, it is likely that the loggerheads are responding to the change in the slope of the reconstructed dune. It is curious that overall loggerhead nesting success was not significantly different after the installation of the geocore. This warrants further investigation. Studies have suggested that dune features may be a leading factor in loggerhead nest site selection (Camhi 1993; Salmon et al. 1995; Witherington et al. 2011b; Hays 2012). Physically measuring the slope at nest and false crawl sites could provide critical information in determining if slope is a deciding factor for loggerhead nest site selection. Maurer and Johnson (2017) did measure slope, distance crawled from the mean high tide line, and elevation for loggerheads nesting on a Mississippi barrier island. They concluded that loggerheads crawl shorter distances on steeper slopes and that nest sites had a longer crawl distance with a flatter slope than false crawls; however, their sample size was extremely limited (Maurer & Johnson 2017). Hays (2012) looked at the finer scale of beach slope and found that loggerheads false crawled more frequently at an abruptly steeper beach slope during the final quarter of the turtle’s crawl. Short steep slopes deterred loggerhead nesting while gradual slopes were more favorable for loggerhead nesting (Hays 2012). It is plausible that in the current study, the slope of the reconstructed dune (26.6°) was steep enough to deter loggerheads from nesting when they crawled to within 5 m of the buried geotextile bags. When Witherington et al. (2011b) presented loggerhead turtles with a portable wall mid-beach that served to emulate a seawall, the turtles were equally as likely to lay a nest when compared to turtles with access to the entire sandy beach. However, turtles presented with the wall were more likely to deposit their eggs closer to the waterline even though the majority of the turtles did not physically encounter the wall. The turtles scattered their nests across the available beach, treating the area as a narrow beach instead of clustering their nests at the base of the wall, suggesting that the wall acted as a visual cue similar to a dune feature (Witherington et al. 2011b). The slope of the reconstructed dune in the current study may be providing a similar visual cue for loggerhead turtles. This would support our findings of a similar overall nesting success even though nesting success was lower when turtles crawled closer to the geotextile bags.

On the other hand, green turtle nesting success was not significantly different for those turtles that crawled to within

<table>
<thead>
<tr>
<th>Year</th>
<th>Control</th>
<th>Impact</th>
<th>N</th>
<th>U</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010–2013 HS</td>
<td>77.38% (60.38–91.30%)</td>
<td>89.52% (84.87–92.86%)</td>
<td>17</td>
<td>11</td>
<td>0.191</td>
</tr>
<tr>
<td>2010–2013 ES</td>
<td>76.19% (60.38–90.43%)</td>
<td>86.72% (81.34–91.67%)</td>
<td>17</td>
<td>11</td>
<td>0.244</td>
</tr>
<tr>
<td>2014–2017 HS</td>
<td>74.38% (45.29–85.39%)</td>
<td>69.84% (55.76–86.19%)</td>
<td>39</td>
<td>141</td>
<td>0.005</td>
</tr>
<tr>
<td>2014–2017 ES</td>
<td>68.60% (41.85–84.41%)</td>
<td>68.10% (54.91–85.36%)</td>
<td>39</td>
<td>141</td>
<td>0.005</td>
</tr>
<tr>
<td>2010–2013 HS</td>
<td>89.88% (83.12–97.39%)</td>
<td>84.13% (80.25–93.75%)</td>
<td>11</td>
<td>17</td>
<td>0.404</td>
</tr>
<tr>
<td>2010–2013 ES</td>
<td>89.88% (81.14–95.95%)</td>
<td>81.19% (76.19–93.75%)</td>
<td>11</td>
<td>17</td>
<td>0.487</td>
</tr>
<tr>
<td>2014–2017 HS</td>
<td>93.52% (88.37–95.68%)</td>
<td>84.11% (65.47–94.12%)</td>
<td>33</td>
<td>27</td>
<td>0.220</td>
</tr>
<tr>
<td>2014–2017 ES</td>
<td>92.59% (87.56–94.86%)</td>
<td>82.46% (63.79–92.63%)</td>
<td>33</td>
<td>27</td>
<td>0.220</td>
</tr>
</tbody>
</table>
7 m of the buried geotextile bags. Studies have suggested that vegetation and elevation could play a role in green turtle nest site selection (Hays et al. 1995; Zavaleta-Lizárraga & Morales-Mávil 2013). If green turtles prefer to nest at higher elevations and closer to vegetation, this could explain our results. The reconstructed dune provides a slope that allows for an increase in elevation. Additionally, the planting of native vegetation could encourage green turtles to nest as they approach the geocore.

Microhabitat cues such as slope and sand characteristics (e.g., grain size, moisture content, compaction, composition) are often cited as potential factors that impact marine turtle nesting on nourished beaches (Ackerman 1997; Wood & Bjorndal 2000; Brock et al. 2009). Because installation of geocores results in reconstructed dunes, alterations in natural beach slope and sand characteristics occur. These factors certainly play a role in the measured effects of geocores on marine turtles. For instance, Cisneros et al. (2017) found that sand with a large grain size and higher carbonate content resulted in a lower nesting success (leatherback, loggerhead, and green turtle crawls were combined for the analysis). Similarly, Yalçin-Özdilek et al. (2007) found that uniformly sorted sand with a smaller grain size (350 μm) was favorable for green turtle nesting. Loggerheads were also shown to false crawl more frequently on beaches with more shells and to nest more frequently on less shelly beaches (Garvemestani et al. 2000). Our understanding of nest site selection is crucial for our ability to restore proper nesting habitat for marine turtles. Since the current study did not directly address the factors that potentially influence marine turtle nest site selection, it is imperative that these factors be a focus of future research.

In the current study, we were not able to detect any differences in hatching and emergence success for either species. However, our sample sizes were generally small for this aspect of this study and we did not distinguish between nests incubating in natural beach sand and sand used for the dune reconstruction. In 4 years after the installation of the geocore, only two nests (one loggerhead and one green turtle) laid directly over the geocore were excavated and inventoried for hatching and emergence success. Therefore, we cannot draw conclusions on the quality of sand placed during the dune reconstruction. Other dune restoration projects that used upland-sourced sand reported low carbonate content in comparison to natural beach sand and offshore sourced sand (Cisneros et al. 2017). However, carbonate content is just one of the many factors that influence marine turtle hatching success. Mota (2009) demonstrated how sand parameters including grain size, carbonate content, and water content are interconnected and warned that biologists need to study these relationships to understand how these characteristics influence hatching success. It remains unclear exactly how physical sand characteristics impact clutch viability (Steinitz et al. 1998); therefore, sand quality should be a focus of future research. Furthermore, in the case of geocores, some scientists speculate that the geotextile bags could leach toxic plasticizers, with potential detrimental effects on hatching success (Gregory et al. 2005). Evaluating hatching success, emergence success, and hatching fitness for nests laid near and directly above the geotextile bags is another worthwhile endeavor for future studies. An additional limitation of this study was the inability to address the implications of tidal activity resulting in the complete wash out of nests, which would lower overall hatching production. Evaluating how geocores respond during extensive erosion events and the implication for incubating marine turtle nests, especially if nest placement is altered, should be investigated. As storms continue to intensify and increase in frequency (Emanuel 2005; Webster et al. 2005) more challenging erosion events may test the integrity of the geocore.

It is important to note that with many geocore projects, as is the case with this study, emergency sand additions often occur before the installation of the geocore to protect homes while the lengthy permitting process is undertaken. As a result, conclusions drawn from before and after comparisons can be challenging to interpret because of beach alterations made before the installment of the geocore. Additionally, multiple additions of sand to cover the geotextile bags after installation could alter the microhabitat each year, leading to seasonal differences in sand quality. Geocores are typically installed to protect a few adjacent homes, meaning the scale and sample sizes are generally limited. Because each geocore installation varies in design and is subject to different wave energies (e.g., Florida’s east coast is subject to higher wave energy resulting in greater erosional forces in comparison to Florida’s west coast beaches; Mota 2009), it can be challenging to compare one project to another. Moreover, the detrimental impacts of seawalls were not realized immediately (Scheroder & Mosier 2000); therefore, studies on the suitability of geocores need to consider the long-term impacts.

The results presented here are the first of their kind. The current study suggests that geocores, in relation to their impacts on marine turtle nesting, may be an improved coastal armoring method compared to seawalls. This is an encouraging finding that requires further exploration so that management strategies can be appropriately adjusted. The recovery of these imperiled species depends on our ability to understand the required habitat for successful marine turtle nesting, hatching success, and emergence success so that proper management techniques can be implemented.

Acknowledgments

We gratefully acknowledge all Loggerhead Marinelife Center staff, seasonal technicians, and interns for their countless hours in the field collecting data. Sincere thanks to Dr. C. Manire for his thoughtful comments and review of the manuscript prior to submission. All field work was conducted under FWC Marine Turtle Permits MTP-060 and MTP-154. This study was funded in part by a grant award from the Sea Turtle Grants Program (grant no. 17-002C). Data during the 2010–2013 seasons were collected under contract with Palm Beach County Department of Environmental Resources Management. To fulfill permit requirements (FDEP permit PB-1108 GT), the homeowners who installed the geotextile
containers contracted Loggerhead Marinelife Center to conduct sea turtle monitoring during the 2014–2017 seasons. The funders had no role in study conception, design, data collection and analysis, decision to publish, or preparation of the manuscript.

LITERATURE CITED


Cisneros JA, Briggs TR, Martin K (2017) Placed sediment characteristics compared to sea turtle nesting and hatching patterns: a case study from Palm Beach County, FL. Shore & Beach 85:35–40


Hays AW (2012) Determining the impacts of beach restoration on loggerhead (Caretta caretta) and green turtle (Chelonia mydas) nesting patterns and reproductive success along Florida’s Atlantic Coast. MS thesis. University of Central Florida, Orlando


Mortimer JA (1990) The influence of beach sand characteristics on the nesting behavior and clutch survival of green turtles (Chelonia mydas). Copeia 1990:802–817


Supporting Information
The following information may be found in the online version of this article:

Table S1. Overall loggerhead (Caretta caretta) and green turtle (Chelonia mydas) nesting success compared to those crawls that came to within 1, 3, 5, and 7 m of the geocore sand bags before (2010–2013) and after (2014–2017) installation.

Received: 16 January, 2018; First decision: 28 March, 2018; Revised: 17 August, 2018; Accepted: 19 August, 2018; First published online: 11 September, 2018