Using unmanned aerial vehicle (UAV) surveys and traditional methods to examine influences on loggerhead sea turtle (*Caretta caretta*) nest site selection

By

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Abstract

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This study examined the environmental and anthropogenic factors that may influence loggerhead sea turtle nest site selection and how these factors vary between successful nesting attempts and false crawls on a high-density sea turtle nesting beach in Boca Raton, Florida. Beach morphology, sand texture, and nests' proximity to artificial structures were measured using a combination of drone-based photogrammetry, traditional surveys with Real Time Kinematic Global Positioning System (RTK GPS), and sediment granulometry. Proximity to dune crossover stairs was significantly different between nests and false crawls, and the probability of a false crawl occurring decreased as proximity to dune crossover stairs increased. The results of this study will provide researchers with a new tool for nest monitoring and a better understanding of the microhabitat cues that may influence loggerhead sea turtle nest site selection and aid in guiding beach and sea turtle management decisions.

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Introduction

Florida beaches are a critical nesting area for loggerhead sea turtles, accounting for ninety percent of loggerhead sea turtle nests in the Southeastern United States (Ceriani & Meylan, 2015). The International Union for Conservation of Nature and Natural Resources (IUCN) Red List lists loggerhead sea turtles as internationally vulnerable, meaning their populations are currently in decline (Casale & Tucker, 2017). Climate change, sea level rise, and other anthropogenic impacts pose a severe risk to beach nesting habitat, altering the limited range of environmental conditions that marine turtles rely on to identify a suitable nesting site. Furthermore, a beach's geomorphological and sedimentary characteristics are thought to influence the nest site selection process, with turtles using micro-habitat cues to select the most successful site for their eggs (Hays et al., 1995), which may also be affected by natural and anthropogenic impacts.

Sea turtle nesting habitat monitoring efforts can include topographic surveys to identify morphologic changes in nesting habitat. Unmanned Aerial Vehicle (UAV) or drone-based photogrammetry has become increasingly common for routine beach topography surveys, as UAVs are relatively low-cost and provide imagery with a high spatial resolution capable of producing highly accurate Digital Surface Models (DSMs) and Digital Elevation Models (DEMs) (Reshetyuk, Y., & Mårtensson, 2016). The remote data acquisition by UAVs for studying morphology change could also provide opportunities for application to other monitoring efforts, such as determining sea turtle nesting patterns and identifying crawl tracks. Documenting the spatial distribution of nest locations and false crawl events in relation to geomorphological variables would allow for investigation into the possible microhabitat cues that influence nest site selection without manipulating the environment or behavior of nesting turtles in any way.

This project employed a novel combination of drone-based photogrammetry, traditional surveys with Real Time Kinematic Global Positioning System (RTK GPS), and sediment granulometry to monitor changes in beach geomorphology on a high-density loggerhead sea turtle nesting beach in Boca Raton, Florida. The data collected from this study will contribute to similar studies that used UAV-derived data to assess the relationships between beach morphology and sea turtle nest placement (Long et al., 2011; Yamamoto et al., 2015; Dunkin et al., 2016). These data were used to determine if environmental conditions correlate with nest placement based on spatial analyses using nesting data provided by Gumbo Limbo Nature Center. The results of this study will provide researchers and environmental planners with a new tool for nest monitoring and a better understanding of the ecological variables that may influence where a loggerhead sea turtle selects a nest site and aid in guiding beach and sea turtle management decisions.

Sea Turtle Nesting in Florida

Florida beaches, specifically those in Palm Beach County, are some of the highest-density nesting sites for loggerhead sea turtles in the United States. Selecting a nest site is a balance between the energetic cost of searching for a site and the benefits that a suitable nest site provides for the successful incubation of eggs (Wood & Bjorndal, 2000). Additionally, the location in which a turtle lays their nest is crucial as it directly affects its offspring's hatching success, hatchling emergence success, sex ratios, fitness, and vulnerability to predators (Miller et al., 2003). Nest site selection varies due to various spatial and temporal changes and environmental factors that drive nest placement either inland or seaward towards the shoreline (Wood & Bjorndal, 2000). Beach elevation, slope, width, sand texture, and sand temperature have been identified as potential cues that turtles use to nest in a particular area (Wood & Bjorndal, 2000; Mazaris et al., 2006). Identifying areas with statistically significant high or low nesting densities is critical to identifying the environmental characteristics of desirable nesting habitat. These can be further examined to determine morphological characteristics and environmental factors influencing nest site selection.

Nesting Process

Loggerhead sea turtles spend most of their lives in the ocean and emerge from the sea during adulthood to lay nests in the general region of their natal beaches. The official nesting season for loggerhead sea turtles is from March 1 through October 31. However, some incubating nests will remain on the beach well after October 31 (Ceriani & Meylan, 2015). The nesting process consists of several steps; the first involves the female turtle selecting a beach on which to lay her eggs (Miller et al., 2003). She will then emerge from the ocean and ascend the beach face to select a nest site. Once a nest site has been chosen, the turtle will use her front and rear flippers to form a body pit, then begin digging an egg chamber, alternating the hind flippers to scoop sand until they can no longer reach any further into the chamber (Miller, 2017). After the eggs are deposited, the turtle will fill the egg chamber with sand and camouflage the nest to disguise where the eggs are buried and prevent predation. She will then return to the sea and rest until it is time to nest again (Hays et al., 1995).

In some cases, a nesting female will abandon the nesting attempt in what is termed a false crawl. This occurs when the female turtle emerges from the water and returns without nesting (Miller, 2017). She may also begin to dig a body pit or an egg chamber and then abandon it and return to the sea. The exact reasons why a nesting attempt is aborted are unknown; however, it is possible that lighting, movement, or unfavorable environmental conditions disturb the turtle and cause it to abandon the nesting attempt (Silva et al., 2017).

Nest Site Selection and Beach Morphology

The morphological features of the beach, such as elevation, width, and slope, may be essential factors in determining loggerhead sea turtle nest site preferences (Hays et al., 1995; Wood & Bjorndal, 2000; Yamamoto et al., 2012). Loggerhead sea turtle nesting beaches are typically wide, sandy, unobstructed beaches backed by low-lying dunes with vegetation and gently sloping with a flat sandy approach from the sea (Miller et al., 2003). A potential nesting beach must be easily accessible from the ocean, have a high enough elevation to avoid frequent inundation, and have sand that is moist and fine enough to be conducive to the construction of the egg chamber and egg development (Mortimer, 1990). Nests that are laid closer to the ocean have greater chances of inundation and eggs being lost due to erosion; however, nests laid further up the beach face increase the distance that hatchlings must crawl to reach the sea and thus face greater chances of being predated upon (Whitmore & Dutton, 1985; Camhi, 1994; Miller et al., 2003).

Several studies have investigated the possible environmental cues that drive nest site selection and found that beach slope may be an essential factor in sea turtle nest site selection (Wood & Bjorndal, 2000; Siqueira-Silva et al., 2020; Maurer & Johnson, 2017; Dunkin et al., 2016). The beach-face slope can be defined as the hypotenuse of a right-angle triangle pinned by the highest point of the sub-aerial beach and the low water mark, represented by a single value (Reis & Gama, 2010; Laporte-Fauret et al., 2019). Wood & Bjorndal (2000) found that out of four environmental factors (slope, moisture, temperature, and salinity), slope appeared to have the greatest influence on nest site selection, with a significant increase in slope found at nest locations. This could be due to the slope of the beach reflecting an elevation change, with the turtles cueing into a perceived change in elevation that would decrease the likelihood of inundation and thus increase the success of the nest (Wood & Bjorndal, 2000). Likewise, Siqueira-Silva et al. (2020) found that median beach slope played a critical role in nest site selection, with a higher nesting density found on beaches with steeper slopes of approximately 7-9 degrees elevation grade. Similar patterns have been observed on Cape Canaveral beaches in Florida, with nest density positively correlated with beach slope (Provancha & Ehrhart, 1987). The median beach slope at the time of nesting plays an important role in the nesting process, as the beach must be flat enough for the sea turtle to ascend the beach face successfully yet have a high enough elevation to protect the nest from the tide (Siqueria-Silva et al., 2020). In a study on loggerhead sea turtle nesting behavior in the barrier islands off the Gulf of Mexico, Maurer & Johnson (2017) found that crawl length decreases as the beach slope increases, and when comparing false crawls versus successful nest crawls, beach slope and crawl length appeared to differ between the crawl types, but elevation remained the same. Loggerheads crawled longer distances on flatter slopes, compared to shorter distances on steep slopes, suggesting that the nesting turtle may cue into beach slope until a certain elevation is perceived to initiate the nest-digging process. Dunkin et al. (2016) created a remote sensing-based model to predict loggerhead nesting habitat suitability in Florida, using beach elevation, slope, width, and dune peak as predictors. The model results suggested that elevation has the most influence on nest site selection, which is consistent with the findings of the several aforementioned studies.

Beach width has been identified as another possible cue for nest site selection. In a study carried out on the beaches of Florida's Ten Thousand Islands, Garmestani et al. (2000) found that the number of loggerhead sea turtle nests increased dramatically as beach width increased and that the nesting to false crawl ratio was higher on beaches that were wider and had finer sand. Similarly, Mazaris et al. (2006) identified beach width as the most critical habitat variable affecting nest site selection for loggerheads on Zakynthos Island, Greece, with more expansive beaches having greater nesting densities and providing nesting females with more potential nesting sites. While these studies suggest that beach elevation, slope, and width are all critical factors in nest site selection, there may be other environmental variables, such as sediment texture, that factor into the process of where a sea turtle decides to lay eggs.

Nest Site Selection and Sand Characteristics

The sediment characteristics on beaches where loggerhead sea turtles nest varies considerably. Many studies have been carried out to determine the effects that sediment characteristics have on nest temperature and hatchling emergence success (Lolavar & Wyneken, 2020; Saito, 2019, Milton et al., 1997); however, there are currently few studies that examine the relationship between sediment texture and adult loggerhead sea turtle nest site selection. Loggerhead and green sea turtles have been observed thrusting their heads into the sand as they ascend the beach to begin the nesting process, perhaps to assess the microhabitat characteristics of the sediment around them and determine a suitable nesting site (Hendrickson, 1958; Carr & Ogren, 1960; Stoneburner & Richardson, 1981). The turtle may be evaluating sand characteristics such as temperature, moisture, and overall sediment composition (Morjan & Valenzuela, 2001).

The physical properties of the sand directly influence the composition of the nest environment and can lead to either greater or lower hatching and emergence success rates (Milton et al., 1997). Sand texture and composition impact how much heat, water vapor, oxygen, and carbon dioxide can diffuse through the sand and, thus, the nesting environment. A study by Milton et al. (1997) found that sand composition can impact the temperature of the nest, where nests buried in aragonite sand were significantly cooler than those buried in silicate sand, which has implications for hatchling sex ratios. The grain size distribution on a beach can also affect nesting success, as sand grain size influences gas and water exchange (Milton et al., 1997). Karavas et al. (2005) found higher nesting densities on beaches with well-sorted sand grains where the sand is not coarse. Well-sorted sand allows the eggs to be sufficiently aerated and for water to be drained from the nest while also preventing the egg chamber from collapsing. Beaches with extremely coarse sand are not conducive to sea turtle nesting as it is more difficult to excavate the egg chamber in sand that is very coarse or shelly (Karavas et al., 2005; Mortimer 1990). Green sea turtles have been found to prefer to nest on beaches with finer sand grains (Salleh et al., 2021); however, it is important to note that this preference may vary among species.

Wave energy influences morphology and grain size, which also can influence one another, in a feedback loop called morphodynamics (Masselink & Gehrels, 2015). Typically, the finer the sand, the flatter the slope of the beach (Bascom, 1951). The beach-face slope is also inversely related to beach width: wider beaches have flatter slopes, and narrower beaches have steeper slopes (Bujan & Masselink, 2019). In understanding the relationship that exists between beach width, grain size, and slope, it becomes evident that previous studies investigating sea turtle nest site selection may have contradictory results. There is a high probability that the nest site selection process of nesting females involves interactions of various geomorphological factors, thus, a multivariate analysis approach is best to study the impact and interaction between each feature (Kikukawa et al., 1999). Understanding how the sedimentary characteristics of beaches relate to slope and nest placement is critical to better beach management and nourishment practices, which directly impact the nesting habitat of sea turtles.

Anthropogenic Influences

Anthropogenic pressures associated with coastal development reduce the availability of optimal nesting habitat for sea turtles (Weishampel et al., 2016; Ware & Fuentes, 2020). During a nesting attempt, sea turtles may encounter physical barriers, which can modify nesting behavior and potentially impact overall nesting success. Examples of barriers include sea walls, dune crossovers, lifeguard towers, abandoned beach equipment, sand fences, and other forms of coastal development. In Palm Beach County, it is considered an obstructed nesting attempt (ONA) when a nesting female comes into direct physical contact with a manmade obstruction on the beach, regardless of whether the attempt results in a nest or a false crawl (FWC, 2021). Examining the distance between successful nests, false crawls, and man-made structures on the beach may provide insight into the consequences of different obstructions and reveal patterns in nest site selection based on proximity to these structures.

UAV Surveys and Photogrammetry

Due to the high morphodynamic activity exhibited by beaches, low-cost and high-frequency topographic surveys are necessary to characterize beach environments. The use of UAV-based photogrammetry has become increasingly common for routine beach topography surveys, as UAVs are relatively low-cost and provide imagery with a high spatial resolution (Casella et al., 2020; Briggs & Gammack-Clark, 2019). Previous studies have utilized LiDAR for topographic surveys, which has proven to be an effective yet costly survey method and is less accurate when applied to smaller-scale studies. UAVs are also more readily available and require far less training than LiDAR. The specialist training required to operate most survey-grade UAVs is comparable to that of operating professional hand-held real-time kinematic (RTK) GPS equipment (Turner et al., 2016). However, most commercial-grade UAVs require an FAA Part 107 license to be obtained before flying. In the past, surveying Ground Control Points (GCP) using RTK GPS was necessary for post-deployment data processing of aerial imagery. Many survey-grade UAVs, such as the Delair UX11, now incorporate RTK positioning, which eliminates the need for additional GCP surveys. The high spatial resolution provided by UAV imagery allows for centimeter accuracy of beach topography and is comparable to that of traditional RTK GPS beach survey methods (Turner et al., 2016). Aerial data acquired by UAVs can be processed into digital terrain models (DTM) and digital surface models (DSM), which are useful for the 3D modeling of environments.

Geomorphological characteristics such as beach elevation, slope, and width can be extracted from the DSM surface raster. These attributes can then be compared with nest and false crawl coordinates to assess trends in nesting patterns in relation to beach slope, elevation, rugosity, and width (Culver et al., 2020). A study by Long et al. (2011) used LiDAR-derived measures to characterize the topographic dynamics of a critical sea turtle nesting beach in Florida before and after an active hurricane season. The DSMs produced before and after the season allowed for the surface area and volume lost on the beach to be quantified and thus assess habitat loss. Similar studies (Yamamoto et al., 2015) have been done using LiDAR data to assess morphological changes over time to sea turtle nesting beaches. Varela et al. (2019) used UAVs and photogrammetry to create digital elevation models of a nesting beach, and then modeled various sea level rise scenarios to determine the percentage of nests that would be lost to inundation. These studies highlight the potential of UAV surveys and photogrammetry to characterize the morphological features of sea turtle nesting beaches.

Objectives and Hypotheses

The purpose of this study was to develop a relatively low-cost, easily accessible methodology for monitoring beach geomorphology and sea turtle nesting patterns. Relationships between nesting preferences and multiple morphological and anthropogenic characteristics were examined, as well as general spatial trends of nesting patterns such as nest elevation and distance from the mean high-water line. Additionally, the feasibility of using UAV-based photogrammetry to identify turtle crawl tracks and nests were explored. The objectives of this study were as follows:

1. **To determine if there is a correlation between beach slope and nest site selection.**

Hypothesis 1.1: Nesting density will be positively correlated with slope. Sections of the beach with steeper slopes will have higher nesting densities.

HO1.1: There will be no correlation between the slope of the beach and nest placement.

HO1.1a: Nesting density will be negatively correlated with slope. Sections of the beach with steeper slopes will have lower nesting densities.

Hypothesis 1.2: False crawl events will be negatively correlated with slope. Sections of the beach with flatter slopes will have higher numbers of false crawl events.

HO1.2: There will be no correlation between the slope of the beach and false crawl events.

HO1.2a: False crawl events will be positively correlated with slope. Sections of the beach with steeper slopes will have higher numbers of false crawl events.

2. **To determine if there is a correlation between beach width and nest site selection.**

Hypothesis 2.1: Nest density will be negatively correlated with beach width. Wider sections of the beach will have lower nesting densities than narrow beaches.

HO2.1: There will be no correlation between beach width and nesting density.

HO2.1a: Nesting density will be positively correlated with beach width.

Hypothesis 2.2: False crawl events will be positively correlated with beach width. Wider beaches will have higher numbers of false crawl events.

HO2.2: There will be no correlation between beach width and false crawl events.

HO2.2a: False crawl events will be negatively correlated with beach width.

3. **To determine if there is a correlation between sand texture and nest site selection.**

Hypothesis 3.1: Sand grain size and sorting will be negatively correlated with nesting density. Areas of the beach with smaller grain sizes and well-sorted sand will have higher nesting densities.

HO3.1: There will be no correlation between sand grain size and sorting and nest density.

HO3.1a: Sand grain size and sorting will be positively correlated with nesting density.

Hypothesis 3.2: Sand grain size and sorting will be positively correlated with false crawl events. Areas of the beach with larger grain sizes and poorer sorting values will have higher numbers of false crawls.

HO3.2: There will be no correlation between sand grain size and sorting and false crawl events.

HO3.2a: Sand grain size and sorting will be negatively correlated with false crawl events.

4. **To determine if there is a correlation between nest site selection and proximity to manmade obstructions on the beach (i.e., dune crossovers and lifeguard towers).**

Hypothesis 4.1: Nest density will be positively correlated with distance from manmade obstructions. There will be higher nesting densities further away from beach obstructions.

HO4.1: There will be no correlation between nesting density and distance from obstructions.

HO4.1a: Nesting density will be negatively correlated with distance from obstructions.

Hypothesis 4.2: False crawl events will be negatively correlated with distance from obstructions. There will be a greater number of false crawl events closer to obstructions.

HO4.2: There will be no correlation between false crawl events and distance from obstructions.

HO4.2a: False crawl events will be positively correlated with distance from obstructions.

Materials and Methods

Study Site Selection

Spatial analyses were conducted to identify high-density nesting areas in Boca Raton. The Optimized Hot Spot Analysis tool in ArcGIS was used to identify statistically significant clusters of high and low nesting densities using sea turtle nesting data from the 2021 nesting season provided by Gumbo Limbo Nature Center (Figure 1). This tool uses the Getis-Ord Gi* statistic to aggregate incident data and create a map of statistically significant hot and cold spots. The results of this analysis indicated there was one cold spot in northern Boca Raton beaches and two hot spots. One hot spot was found at a location called Red Reef Park, and the other was located approximately 1.5 kilometers south of the Red Reef Park hot spot. The central location at Red Reef Park was selected as the study area for this research due to its ease of access and limited exposure to beachfront condos and artificial lighting.

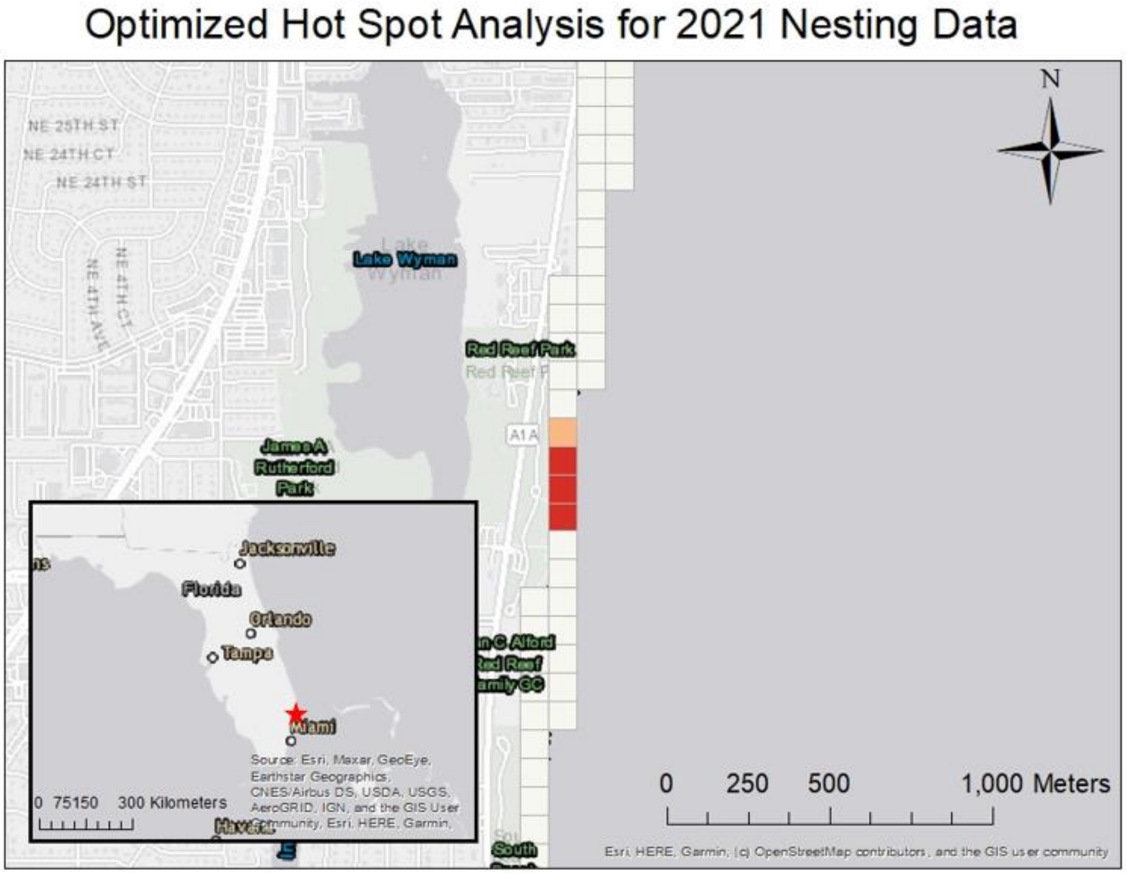
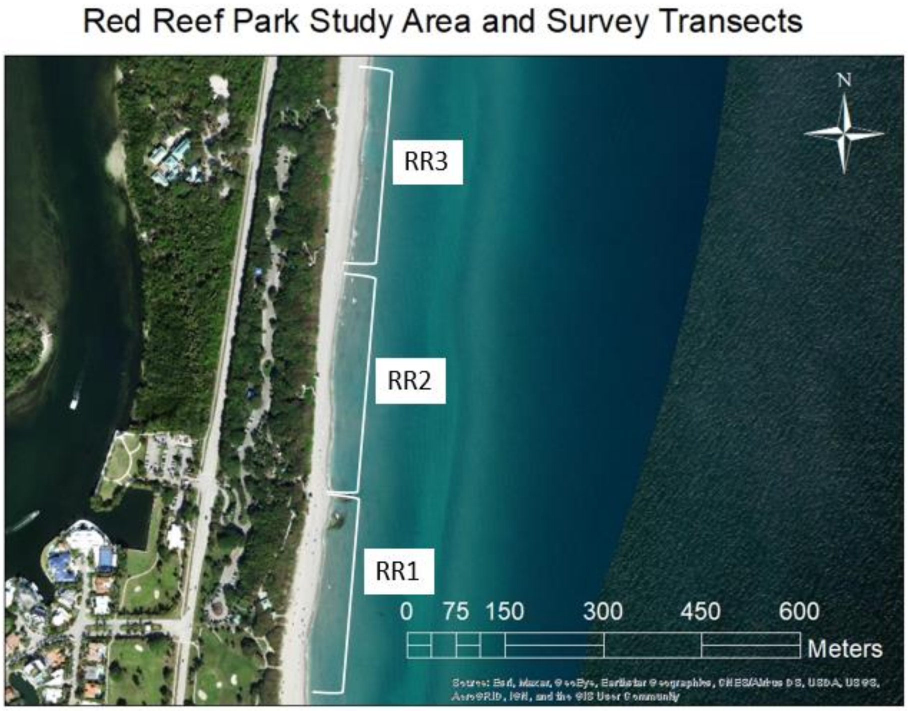


Figure 1. Results of the Optimized Hot Spot Analysis. This tool was used in ArcGIS to identify statistically significant hot spots and cold spots for the 2021 sea turtle nesting year in Boca Raton, FL.

The selected study site spans approximately 0.925 kilometers of the beach from north to south (Figure 2). The 0.925-kilometer area was further sectioned into three 308 m subzones to allow for detailed nest density comparisons and reference where a nest or feature is located. Three transects, RR1, RR2, and RR3, mark the survey area's southern, middle, and northern subzones, respectively. These transects are where GCPs and RTK survey markers were placed, and sediment was collected during each survey event. Nesting data and UAV-derived data were attributed +/- 154 m north and south of each transect.

This beach is classified as an intermediate beach with moderately well-sorted, fine-medium to coarse sediment and longshore sediment transport predominantly to the south (Brown & Briggs, 2020). This site has a high dune system with salt-tolerant vegetation such as sea oats and sea grapes, a gently sloping berm, and moderate wave action. The high, vegetated dunes block most artificial lighting in the direct vicinity of the study area and, therefore, should not be a significant factor in the study. This beach does contain numerous artificial structures, such as lifeguard towers and dune crossover stairs, which may impact nest site selection. Each subzone is backed by a different type of dune crossover (RR1 has more natural crossovers, RR2 has crossovers situated horizontally across the beach, and RR3 has high stairs that cross the dunes).



Sources: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2. Map of 0.925 km study area that is further sectioned into three 308 m subzones. Within each subzone are survey transects RR1, RR2, and RR3. Transects are the locations of Ground Control Points, RTK survey markers, and sediment collection sites. Nesting data and UAV-derived data are attributed +/- 154 m north and south of each transect.

Nesting Data

Gumbo Limbo Nature Center (GLNC) shared their sea turtle nesting data that was collected during the 2021 and 2022 nesting seasons. The 2021 nesting dataset was used to identify the study area, and the 2022 dataset was used for the analyses in this project. GLNC staff surveyed the beach every morning during the nesting season to record GPS coordinate locations of nests and false crawls that occurred the previous night, which can be identified by tracks left on the beach. Loggerhead tracks are identified by their staggered, comma-shaped indentations that are unique to the species. False crawl locations were recorded based on the turn-around point of the crawl. All successful nest and false crawl locations were recorded with a handheld GPS device and entered into the GLNC database. The sea turtle nest dataset provided by Gumbo Limbo includes coordinates for each nest laid on the beach, coordinates of false crawl events, species, the date it was laid, as well as hatching success and hatchling emergence success for each nest surveyed. Nesting data was provided in both the form of an excel file and a shapefile, the latter of which was imported into ArcMap 10.8.1 to integrate into the DSMs that were created from the aerial survey data. Nests were characterized by the following schema: early-season nests (March 1-June 30), and late-season nests (July 1-October 31). Nests were further sorted based on what section of the study area they were found in (RR1, RR2, or RR3), as well as if they were laid near the mean high-water (MHW) line (less than or equal to 5 m distance from MHW line), mid-beach (between 5 m and 15 m from the MHW line) or backbeach (greater than 15 m from the MHW line). This allowed for detailed comparison of nest preferences based on the morphological characteristics of the beach in each sub-section of the study area.

UAV Surveys and Photogrammetry Workflow

Two UAV surveys were conducted, the first on April 25, 2022, and the second on July 20, 2022 (i.e., early and late nesting season). Each survey covered the same study area to allow for the assessment of changes in beach morphology throughout the duration of the nesting season. A Delair UX11 drone was used to collect aerial data, which is equipped with a fully integrated camera and uses Post-Processed Kinematic (PPK) technology which allows for minimal use of GCPs and is accurate up to the centimeter. The aircraft weighs approximately 1.5 kg and can fly up to 54km/h for up to 59 minutes (Delair, 2022). A predetermined flight plan was programmed into the UAV using the Delair Flight Deck software, which reduces the chances of human error and allows for a consistent forward and side overlap between images, which is necessary to produce highly accurate DSMs (Haala et al., 2013). During the surveys, the aircraft was flown at an average altitude of 126 m. Static GPS observations were taken using a global navigation satellite system (GNSS) base station, which was used during post-processing to enhance the accuracy of the outputs. Additionally, five GCPs were placed throughout the survey area, two on both the northern and southern ends of the study site, and one in the center of the survey area. Each GCP was surveyed using an RTK GPS mounted on a pole to check the positioning and accuracy of the DSM outputs during post-processing.

Aerial data was processed using the Trimble Business Center (TBC) Photogrammetry module. The deliverables included a dense point cloud, a raster Digital Surface Model (DSM), and an orthomosaic. The DSM was exported as a GeoTiff file and imported into ArcMap for further analysis. Sea turtle crawl tracks were identified with the help of Gumbo Limbo staff by conducting a visual inspection of the aerial imagery and orthophotos created from the aerial data.

Beach Morphology & GCP Surveys

Although the Delair UX11 drone used in this study has built-in RTK positioning, real-time kinematic (RTK) GPS was also used to check the aerial imagery's accuracy. Each of the three-study area transects were surveyed using an RTK GPS to collect latitude, longitude, and elevation coordinates. Temporary site markers were placed within the dune at RR1, RR2, and RR3. This ensured that the starting point remained the same for each profile transect. RTK readings were taken every few meters from the base of the dune up to the waterline, within the first few feet of the swash zone. This allowed for the creation of time-series profiles, which provide better insight into the nature of the beach's behavior and features. These profiles were used to determine the average beach slope at each transect, calculated by dividing the measured vertical distance by the measured horizontal distance and multiplying by 100. The average slope of each transect from both the April and July surveys was later compared to early and late season nest and false crawl coordinates. Additionally, RTK GPS was used to survey GCPs to derive topographic information relative to a real-world coordinate system used to check the outputs during post-processing of aerial image data (Turner et al., 2016).

Granulometric Analysis

During each survey event, surface sediment (within ~10 cm of surface) was collected from the mean high-water line (MHW), the mid-beach (MB), and the backbeach (BB) from each survey transect, resulting in a total of eighteen sediment samples for the entirety of the nesting season. These locations were selected to assess how sediment composition varies across the beach gradient and to determine if there is a cross-shore nest site preference due to sediment variability. Although coarse sand is usually found closer to the shoreline and wind-blown fine sand is further up the beach face (Komar, 1998), spatiotemporal variability of water level and wave energy can also influence sediment distribution (Hauptman et al., 2022). Each sample was rinsed with tap water for a minimum of five rinses to remove all traces of salt. After rinsing, each sample was dried in an oven at 59 degrees Celsius for approximately three to four days or until completely dry. Each sample was sorted using a Ro-Tap Sediment Shaker, which shook the sediment and allowed it to settle onto a mesh sieve corresponding to the intermediate sediment grain size (Boggs, 2012). The mesh sieves sort the sand into size classes ranging from -4 phi (16mm) to 4 phi (63μm), each of which is weighed individually to determine the mean sorting values and grain size distribution based on the Wentworth scale (Boggs, 2012). This resulted in a mean phi grain size and sorting value for each sample, which were then compared to nest and false crawl locations to assess for influences that sediment texture may have on nest site selection.

Spatial Analyses

The georeferenced orthophotos and DSMs produced from the early and late season UAV surveys were input into ArcMap 10.8.1, along with GPS coordinates of all loggerhead sea turtle nests and false crawls recorded by Gumbo Limbo Nature Center. DSMs were clipped to only include the subaerial beach and eliminate excess noise from the ocean. Nesting data were sorted based on the time of the season (i.e., early or late) and applied to the appropriate map. To quantify preferred nest sites and false crawl hotspots, a Kernel Density Estimation (KDE) interpolation was applied using an output cell size of 1 meter and a search radius of 30 square meters (as described by Varela et al., 2019). This tool calculates a magnitude-per-unit area from features in a neighborhood using a kernel function. The KDE is calculated by the number of total successful and false crawl nesting points per km^2 and the distance between them, using ArcGIS 10.8.1 and the Spatial Analyst extension.

Locations of dune crossover stairs and lifeguard tower features were digitized into points, and the Generate Near Table tool was used to measure the proximity between nests, false crawls, and man-made beach obstructions. This tool finds the nearest feature in the layer and creates a new attribute table showing the distance between each feature. Additionally, the mean-high water line was digitized into a line graphic, and the distance between the mean high-water line and each false crawl and nest was measured. These measurements were later used to assess general trends in nesting and characterize the nests as being laid close to the mean high-water line, mid-beach, or backbeach, based on proximity to the mean high-water line. The Slope tool was used to create a slope map of the area, and both the elevation and slope at each nest and false crawl coordinate were extracted using the Extract Values to Point tool in ArcMap 10.8.1. These values were used to compare differences in slope and elevation between nest and false crawl locations during the statistical analyses.

Statistical Analyses

All statistical analyses were conducted using R software (version 4.2.2). Boxplots compare the median range of each morphology characteristic (beach slope, slope at each nest/FC coordinates, beach width, sand grain size and sorting) and proximity to manmade structures differentiated by nest and false crawl presence (Figures 11-17). These boxplots serve as tools that can be used to examine general nesting patterns and examine influences of morphological and anthropogenic variables on nesting and false crawl ratios. Welch's two-sample t-tests were conducted for early and late season data comparing the means of environmental and anthropogenic variables (average beach slope, slope at each nest or false crawl coordinate, elevation at each coordinate, beach width, sand texture, and proximity to beach obstructions) between nests and false crawls. Significance was determined by a p-value >0.05. Generalized linear regression models were used to assess the relationships between loggerhead nest site selection and multiple environmental and anthropogenic variables and evaluate the capacity of these variables in predicting nest presence (Culver et al., 2020). A generalized linear regression model was used because of its capacity to model response variables with non-normal distributions (Zuur et al., 2009). The best-fit model was selected using Akaike Information Criterion (AIC) (Bevans, 2022). A DHARMa residual diagnostic was conducted to calculate quantile residuals for the generalized linear model. Finally, a Type III ANOVA was run to compare the possible impacts that different dune crossovers have on nest site selection. Types of dune crossovers were sorted based on what section of the beach they were located in.

Results

UAV Products

DSMs were created from UAV data to further explore the morphological influences on loggerhead sea turtle nest-site selection (Figure 3). The DSMs created from the April and July surveys had similar elevations and morphology characteristics throughout, reaching a maximum height of 21 m at the tree line that backs the dunes, and a minimum elevation of -4 m along the shoreline.

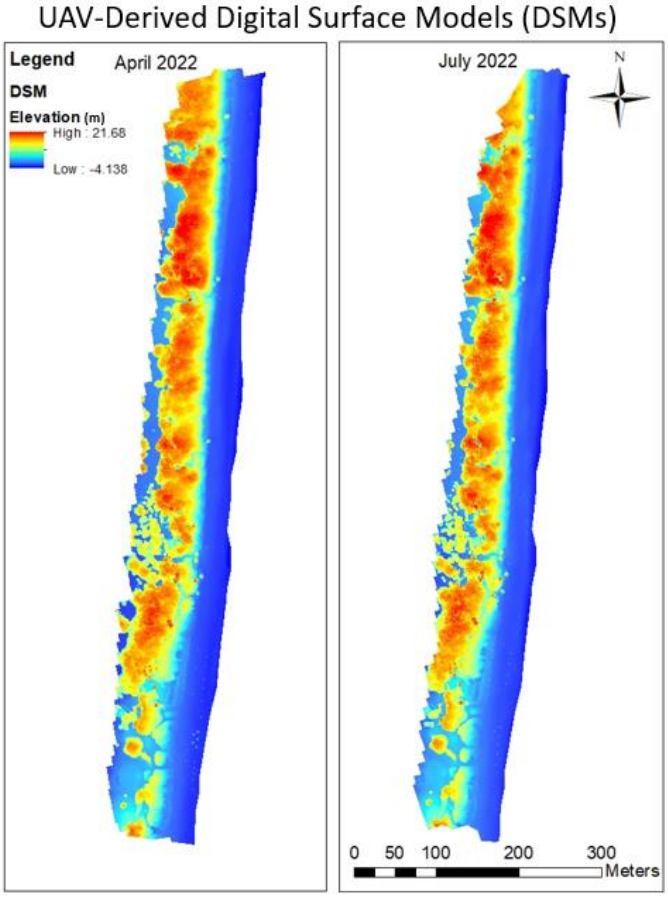


Figure 3 . UAV-derived DSMs from April and July 2022 surveys.

Characterization of Nest Distribution

Results of the KDE for the early season nesting data revealed higher nesting densities distributed throughout the northern and central regions of the study site and lower nesting densities at the southern end (Figure 4). False crawls were more evenly distributed throughout the entirety of the study site, with a high number of incidences at the southern end of the site, notably, in the same area where only three nests had been laid for the duration of the early season. A greater number of false crawls occurred in the backbeach (n=68) than the mid-beach (n=55) and mean high-water line (n=40). The mid-beach had the greatest number of nests (n=33) associated with the early season data, as opposed to the backbeach (n=26) and the mean high-water line (n=14). Overall, there was a greater number of false crawls (n=163) than nests (n=73) during the early season (Figure 6).

Results of the KDE on late season nesting data showed that nesting hotspots were clustered in the northern and central regions of the study site, while false crawl hotspots were located throughout the entirety of the site (Figure 5). Late season nesting data revealed a higher number of false crawls occurring near the mid-beach (n=58) than the backbeach (n=37) and the mean high water line area (n=22). There was a greater number of nests located at the backbeach (n=15) than the mid-beach (n=12) and the mean high water line area (n=5) (Figure 6). There were significantly more false crawls (n=117) than nests (n=32) associated with the late-season survey dataset.

Figure 4. Orthophotos with kernel density estimations of early season nests and false crawls from loggerhead sea turtles at Red Reef Park in Boca Raton. Contour colors are shaded according to the density of nests or false crawls per area and increase from yellow to red as nesting habitat utilization increases.

Figure 5. Orthophotos with kernel density estimations of late season nests and false crawls from loggerhead sea turtles at Red Reef Park in Boca Raton. Contour colors are shaded according to the density of nests or false crawls per area and increase from yellow to red as nesting habitat utilization increases.

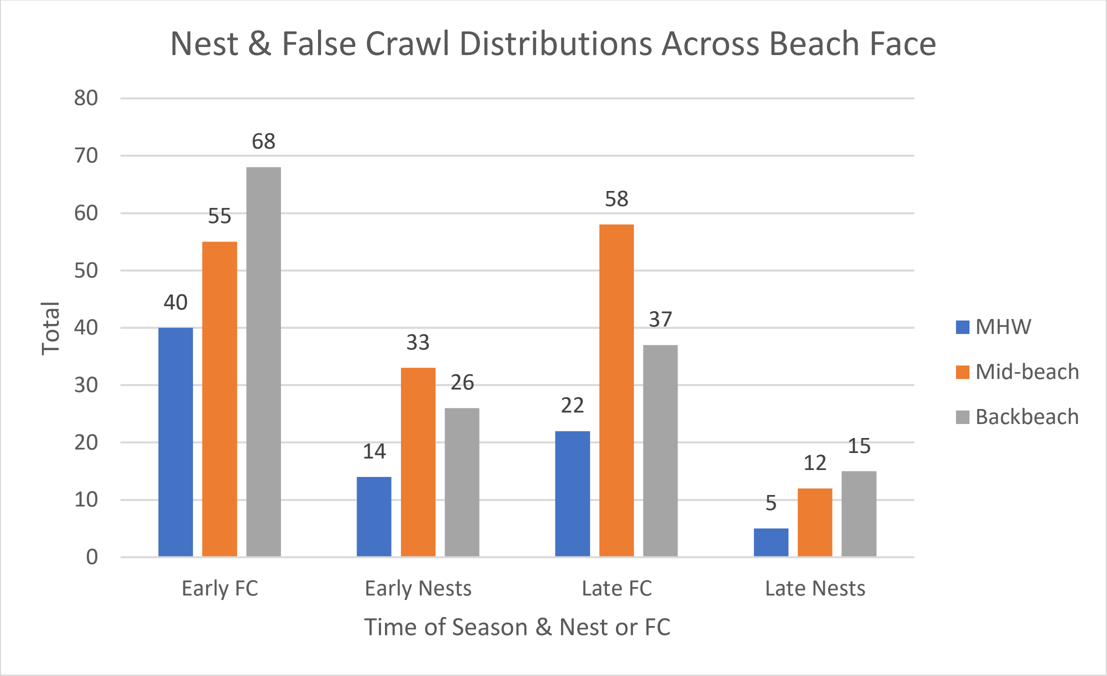


Figure 6. Distribution of nests and false crawls (FC) across the beach face during the 2022 sea turtle nesting season. Nests were sorted based on proximity to the mean high-water (MHW) line. MHW is less than or equal to 5 m distance from MHW line, mid-beach is between 5 m and 15 m from the MHW line, or backbeach is greater than 15 m from the MHW line.

Identifying Sea Turtle Crawl Tracks

There were no sea turtle crawl tracks identified in UAV imagery taken during the April survey, likely because it was early in the nesting season for loggerhead sea turtles, and based on the data provided by GLNC, there were very few crawls occurring at that time within the study area. Crawl tracks were observed in the aerial imagery collected during the July survey; and were identified at the species level with the help of Gumbo Limbo Nature Center staff. Both loggerhead and green sea turtle crawls were identified, however it was not determined as to whether the crawls resulted in successful nests or if they were false crawls. (Figure 7).

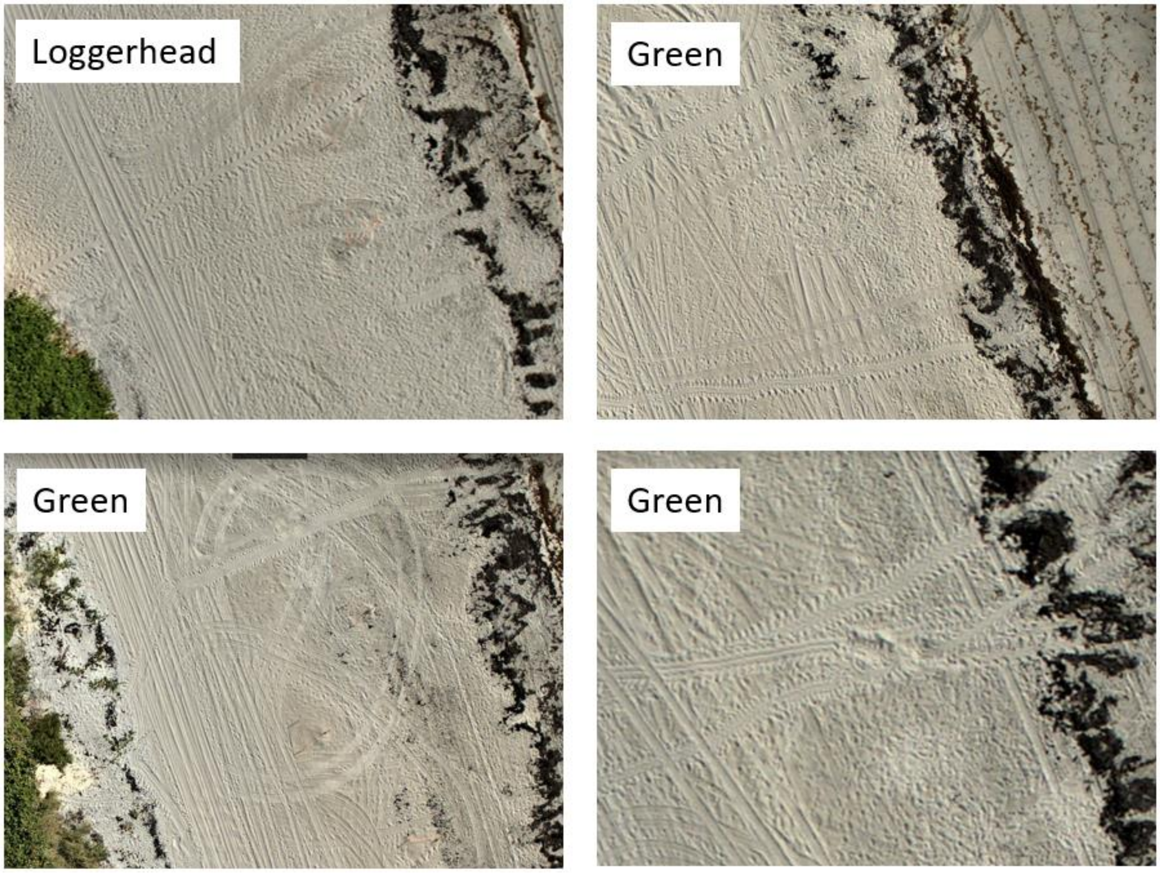


Figure 7. Loggerhead and green sea turtle crawl tracks identified in the late season UAV imagery by employees of Gumbo Limbo Nature Center.

Morphology Change

Time-series beach profiles from the April and July surveys show alongshore variability in beach morphology for the three transects. The beach profile graph depicts the elevation of the beach at the y-axis, while the x-axis represents the distance from the dune to the shoreline (Figure 8). During the April survey, the southernmost transect, RR1, had the widest profile and the highest elevation. This section of the beach is also closest to the nourished beach, which may have benefited from lateral spreading of a nourishment. The berm width in April was 28 meters (from the base of the dune to the berm crest). Between April and July, RR1 accumulated sediment, and the shoreline advanced approximately 8 m, possibly due to sediment accretion from longshore sediment transport predominantly to the south or waves more conducive to sediment accretion (Brown & Briggs, 2020). The average slope of the beach at this transect was 1:13 (7% elevation grade) during the April survey, and 1:16 (6% elevation grade) during the July survey. RR1 was the widest and most gently sloping survey transect.

The RR2 beach profile, located in the central region of the study site, revealed a more gently sloping beach face with a 15-meter berm during the April survey. The overall elevation here was approximately 0.5 to 1 meter lower than the elevation of the beach at RR1. The late season survey showed that RR2 had minimal changes in the beach profile between survey dates, aside from a slight loss of elevation throughout the profile. The slope at this survey transect was 1:12 (8% elevation grade) during the April survey and 1:12 (8% elevation grade) during the July survey.

The third and northernmost survey transect, RR3, had two berm crests during the April survey, the first occurring 20 meters from the base of the dune and the second approximately 27 meters from the dune base. It is unclear whether these were “storm” and “active” berms, respectively, or if the lower berm was really an accretionary feature (e.g., attaching ridge). Between surveys, some erosion occurred, resulting in the shoreline retreating about 2 m landward. The slope at transect RR3 was 1:12 (8% elevation grade) during the April survey and 1:11 (9% elevation grade) during the July survey; this was overall the most steeply sloped transect throughout the nesting season.

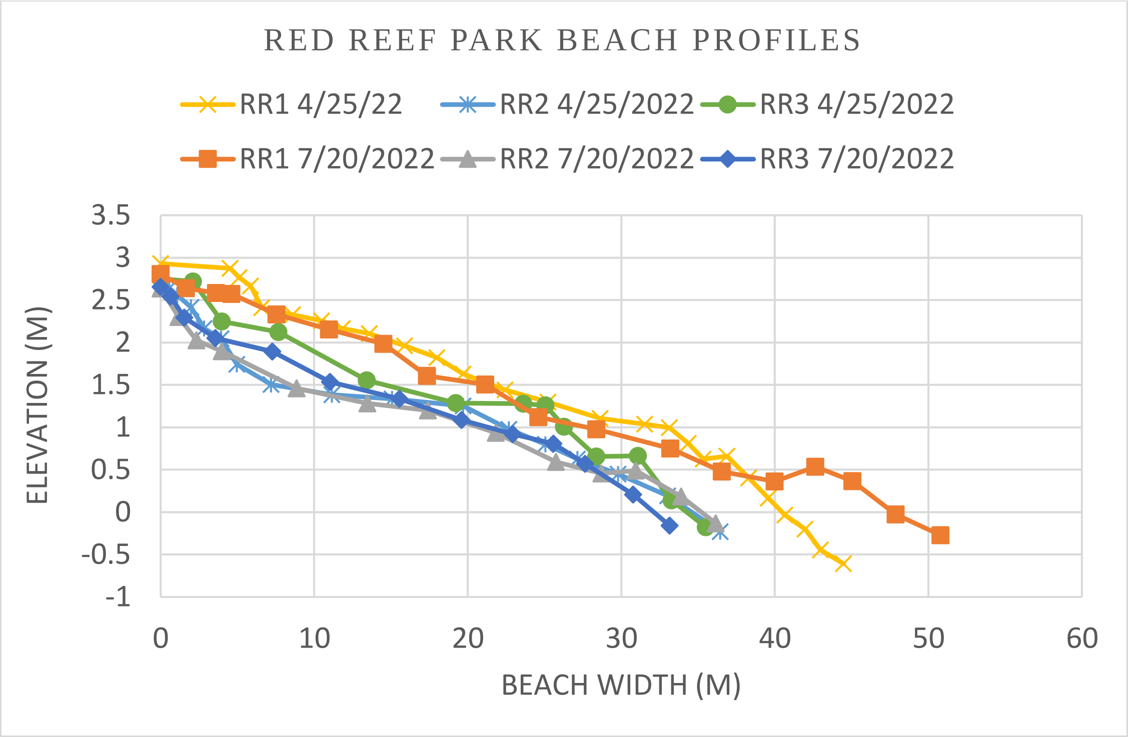


Figure 8. Red Reef Park beach profiles from April and July 2022 surveys.

Sedimentology

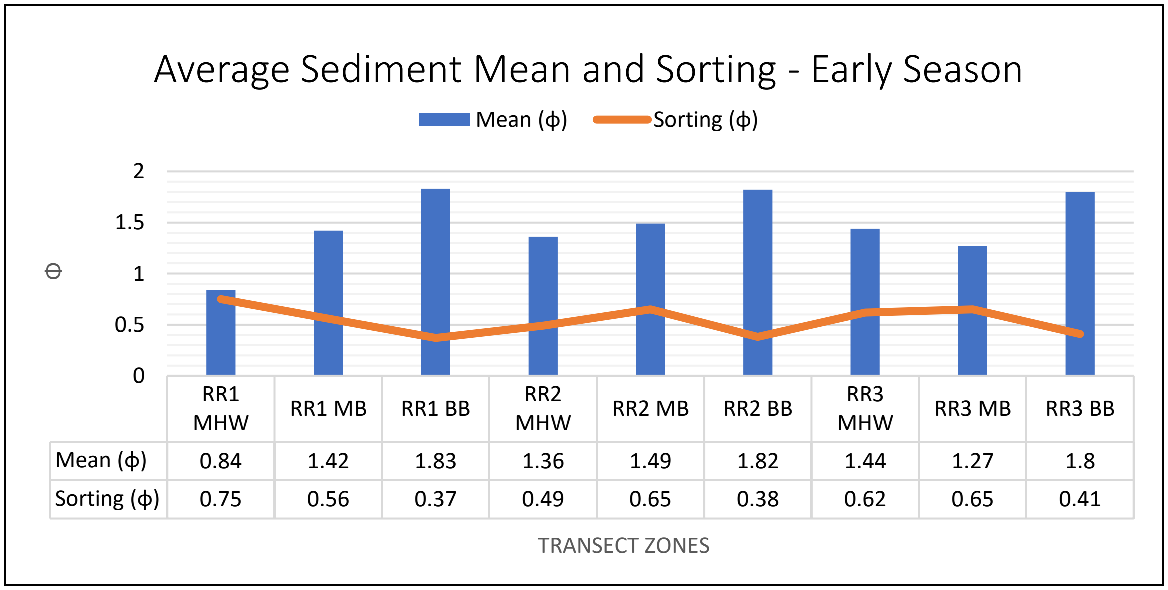
Sediment samples were taken from the mean high-water line (MHW), mid-beach (MB), and backbeach (BB) along each profile transect to show cross-shore and alongshore distribution of sorting (σϕ) and mean grain size ($\bar{X}$ϕ). Sediment collected during the April survey revealed variable sediment grain sizes and sorting throughout and across the beach survey transects (Table 1; Figure 9). Sediment collected at the RR1 MHW location was composed of moderately sorted (0.75 ϕ) coarse sand (0.84 ϕ) and was the only location along all three transects consisting of coarse sand. RR1 MB consisted of moderately well-sorted (0.56 φ) medium sand (1.42 φ), and RR1 BB consisted of well-sorted (0.37 φ) medium sand (1.83 φ)**.** RR2 MHW was composed of well-sorted (0.49 φ) medium sand (1.36 φ), while RR 2 MB was comprised of moderately well-sorted (0.65

φ) medium sand (1.49 φ), and RR2 BB well-sorted (0.38 φ) medium sand (1.82 φ). Similar results were obtained for samples taken along the third transect, with RR3 MHW consisting of moderately well-sorted (0.62 φ) medium sand (1.44 φ), RR3 MB moderately well-sorted (0.65 φ) medium sand (1.27 φ) and RR3 BB well sorted (0.41 φ) medium sand (1.80 φ). The backbeach sediment had the finest grain size. The poorest sorting was measured at the southern end of the study site at RR1 MHW. Therefore, although slight alongshore variability was found, the cross-shore distribution followed the expected landward fining trend (i.e., aeolian-dominated).

Sediment collected during the late-season survey revealed a more uniform grain size and sorting across and throughout the three survey transects (Table 2; Figure 10). RR1 MHW was composed of moderately well-sorted (0.57 φ) medium sand (1.29 φ) and had the poorest sorting out of the three survey transects. RR1 MB consisted of well-sorted (0.36 φ) medium sand (1.81 φ) and RR1 BB well-sorted (0.43 φ) medium sand (1.70 φ). RR2 MHW was composed of well-sorted (0.49 φ) medium sand (1.70 φ), while RR2 MB was comprised of well-sorted (0.48 φ) medium sand (1.65 φ), and RR2 BB well-sorted (0.41 φ) medium sand (1.81 φ). RR3 MHW was composed of well-sorted (0.44 φ) medium sand (1.79 φ), RR3 MB well-sorted (0.49 φ) medium sand (1.57 φ), and RR3 BB well-sorted (0.38 φ) medium sand (1.77 φ). Similar to the April survey, the results of the July survey indicate a trend of fining towards the dune.

Table 1. Sediment properties along beach transects collected during the April, 2022 survey. Sediment size classes ranged from coarse sand (C) to medium sand (M). Sorting values included moderately sorted (MS), moderately well-sorted (MWS), and well-sorted (WS) sand.

Transect	**Location on Beach**	**Sediment Size (Xϕ)**	**Sediment Sorting (σϕ)**
RR1	Mean High Water	0.84 (C)	0.75 (MS)
	Mid-Beach	1.42 (M)	0.56 (MWS)
	Backbeach	1.83 (M)	0.37 (WS)
RR2	Mean High Water	1.36 (M)	0.49 (WS)
	Mid-Beach	1.49 (M)	0.65 (MWS)
	Backbeach	1.82 (M)	0.38 (WS)
RR3	Mean High Water	1.44 (M)	0.62 (MWS)
	Mid-Beach	1.27 (M)	0.65 (MWS)
	Backbeach	1.80 (M)	0.41 (WS)

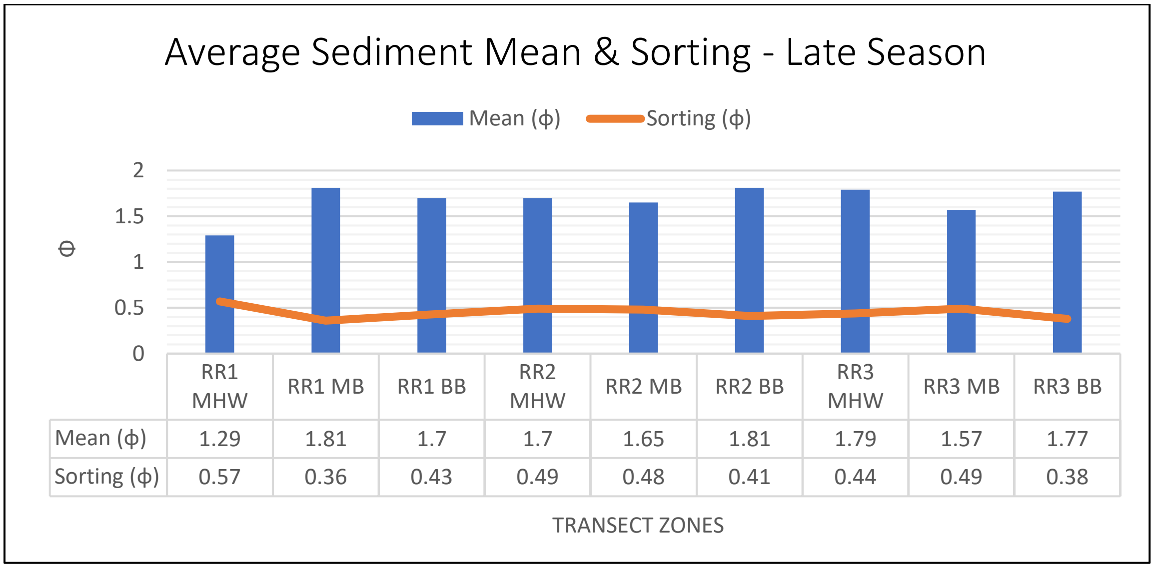


	RR1 MHW	RR1 MB	RR1 BB	RR2 MHW	RR2 MB	RR2 BB	RR3 MHW	RR3 MB	RR3 BB
Mean (ϕ)	0.84	1.42	1.83	1.36	1.49	1.82	1.44	1.27	1.8
Sorting (ϕ)	0.75	0.56	0.37	0.49	0.65	0.38	0.62	0.65	0.41

Figure 9. Results of granulometric analysis for sand collected at the Mean High Water (MHW), Mid-Beach (MB), and Backbeach (BB) from sites RR1, RR2, and RR3 during the early season survey.

Table 2. Sediment properties along beach transects collected during the July, 2022 survey. Sediment size classes included only medium sand (MS). Sorting values included moderately well-sorted (MWS), and well-sorted (WS) sand.

Transect	**Location on Beach**	**Sediment Size ($X\phi$)**	**Sediment Sorting ($\sigma\phi$)**
RR1	Mean High Water	1.29 (MS)	0.57 (MWS)
	Mid-Beach	1.81 (MS)	0.36 (WS)
	Backbeach	1.70 (MS)	0.43 (WS)
RR2	Mean High Water	1.70 (MS)	0.49 (WS)
	Mid-Beach	1.65 (MS)	0.48 (WS)
	Backbeach	1.81 (MS)	0.41 (WS)
RR3	Mean High Water	1.79 (MS)	0.44 (WS)
	Mid-Beach	1.57 (MS)	0.49 (WS)
	Backbeach	1.77 (MS)	0.38 (WS)



	RR1 MHW	RR1 MB	RR1 BB	RR2 MHW	RR2 MB	RR2 BB	RR3 MHW	RR3 MB	RR3 BB
Mean (ϕ)	1.29	1.81	1.7	1.7	1.65	1.81	1.79	1.57	1.77
Sorting (ϕ)	0.57	0.36	0.43	0.49	0.48	0.41	0.44	0.49	0.38

Figure 10. Results of granulometric analysis for sand collected at the Mean High Water (MHW), Mid-Beach (MB), and Backbeach (BB) from sites RR1, RR2, and RR3 during the late season survey.

Nest Site Selection and Beach Morphology

The results of the boxplots and Welch's t-tests indicated no significant differences in average beach slope at each survey transect between early-season loggerhead sea turtle nests and false crawls (t = 1.595, df = 159.74, p-value = 0.113), as well as late-season nests and false crawls (t = 0.175, df = 48.727, p-value = 0.862) (Figure 11). The beach slope at every nest and false crawl coordinate was not significantly different for early season data (t = -1.555, df = 185.52, p-value = 0.122) and late season data (t = 0.357, df = 85.547, p-value = 0,.722) (Figure 12). The beach elevation was not significantly different between early season nests and false crawls (t = 0.663, df = 166, p-value = 0.509) and late season nests and false crawls (t = 1.128, df = 48, p-value = 0.265). Additionally, no significant differences were found in beach width between early-season loggerhead sea turtle nests and false crawls (t = -1.599, df = 159.68, p-value = 0.112) and late-season nests and false crawls (t = -0.148, df = 48.947, p-value = 0.883) (Figure 13). There was no significant difference in distance crawled from the mean high-water line between early season nests and false crawls (t = 0.594, df = 142.05, p-value = 0.553) and late season nests and false crawls (t = 1.343, df = 46.074, p-value = 0.186). The means and standard deviations for environmental and anthropogenic variables associated with nests and false crawls are summarized in Table 3.

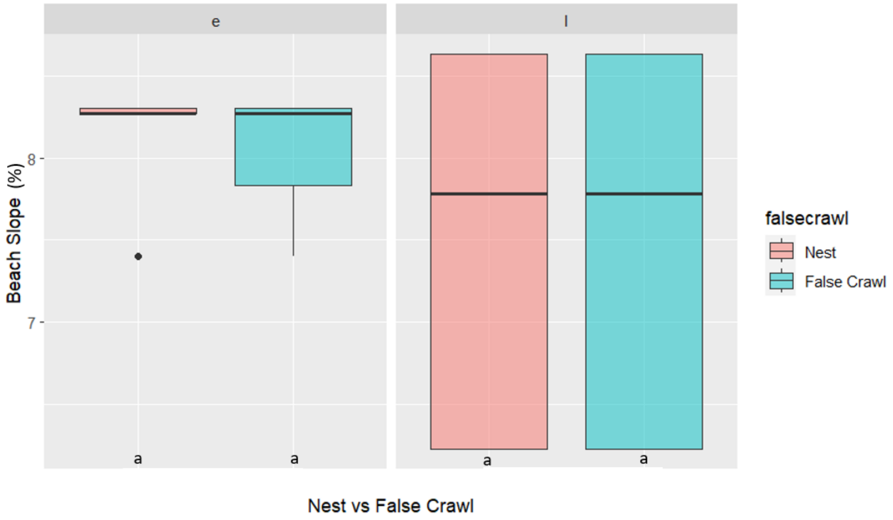


Figure 11. Boxplots showing average beach slope (% elevation grade) between early (e) and late (l) season nests and false crawls. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

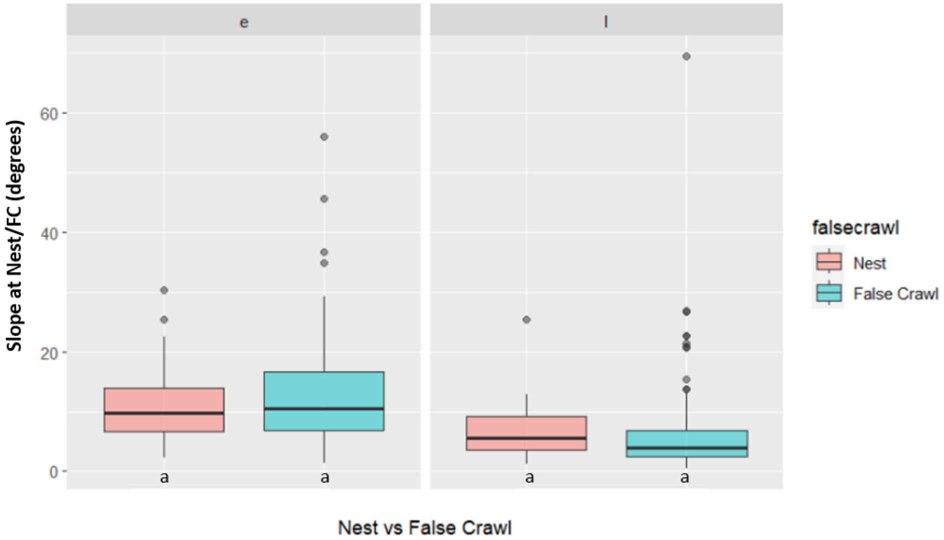


Figure 12. Boxplots showing beach slope (degrees) at every coordinate point differentiated by early (e) and late (l) season nests and false crawls. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

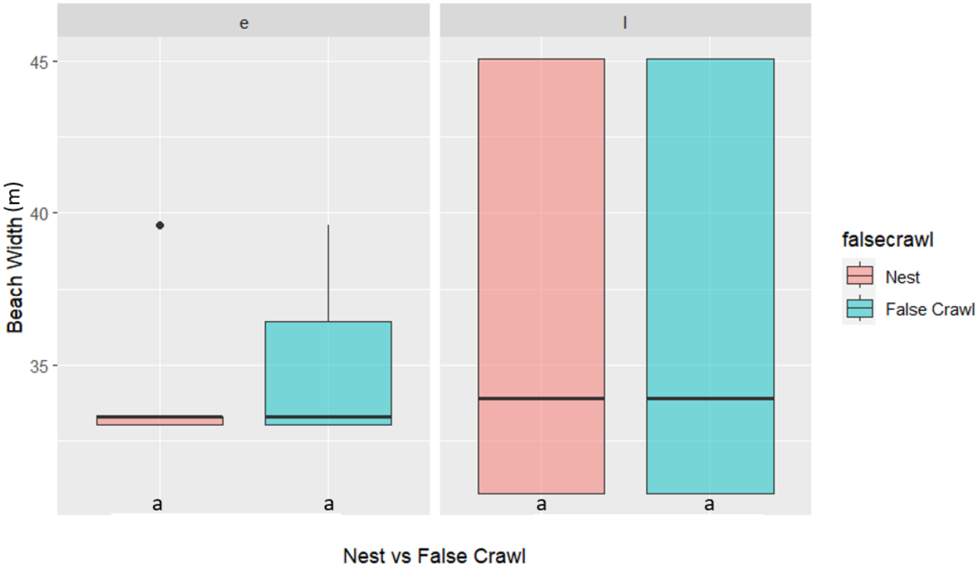


Figure 13. Boxplots showing average beach width (m) between early (e) and late (l) season nests and false crawls. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

Nest Site Selection and Sedimentology

For sand sorting value, there was no significant difference between early-season nests and false crawls (t = 1.586, df = 134.88, p-value = 0.115) as well as late-season nests and false crawls (t = -0.871, df = 73.387, p-value = 0.386) (Figure 14). There was no significant difference found in sand grain size between early-season nests and false crawls (t = -0.688, df = 138.63, p-value = 0.493) and late-season nests and false crawls (t = 1.758, df = 88.853, p-value = 0.082) (Figure 15). Results of the t-tests for early season and late season data are summarized in tables 4 and 5, respectively.

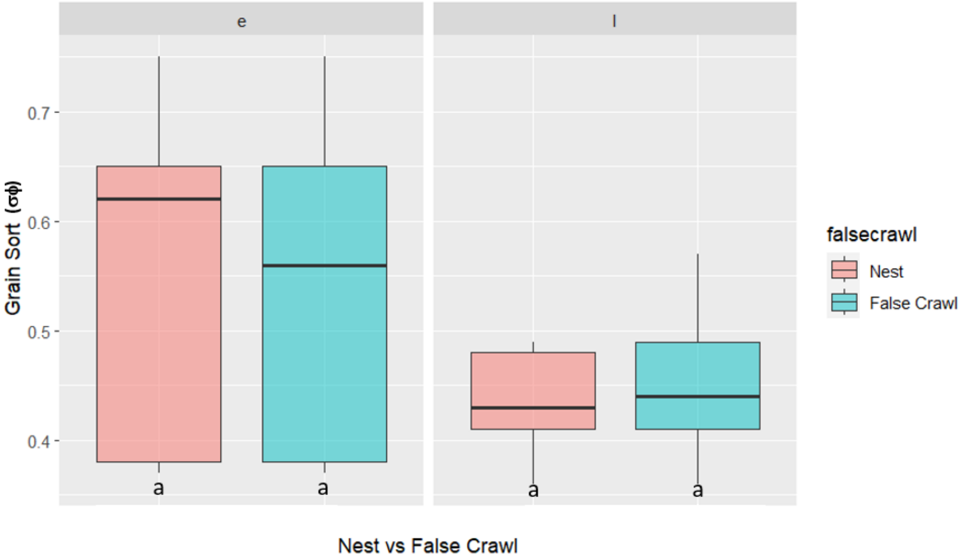


Figure 14. Boxplots showing average sand grain sorting (σϕ) between early (e) and late (l) season nests and false crawls. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

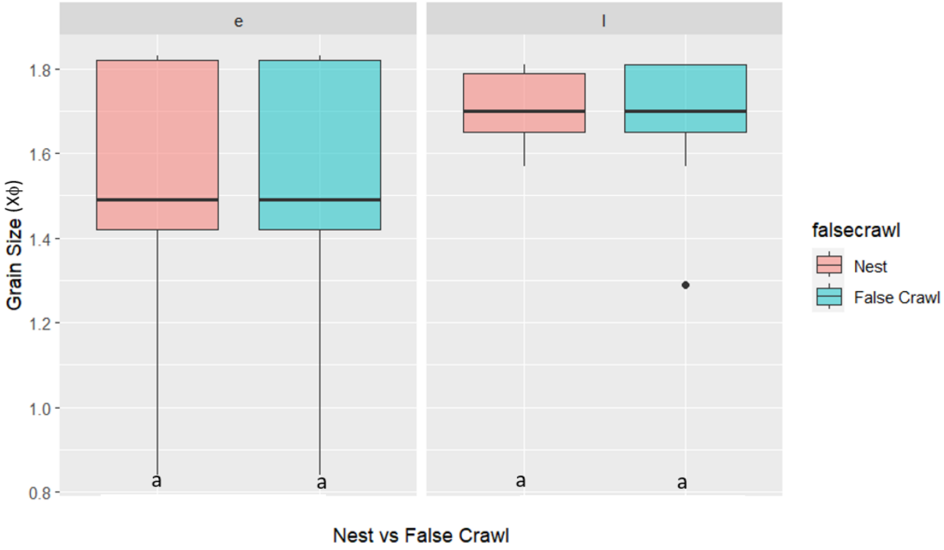


Figure 15. Boxplots showing average sand grain size (Xϕ) between nests and false crawls in early (e) and late (l) season data. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

Nest Site Selection and Anthropogenic Influences

Proximity to stairs was found to be significantly different between early-season nests and false crawls (t = 2.313, df = 127.37, p-value = 0.022); however, there was no significant difference found between distance to stairs and late-season nests and false crawls (t = -0.010, df = 51.691, p-value = 0.921) (Figure 16; Tables 4 & 5). This could be due to insufficient data points from late-season data to establish a meaningful relationship. There was no significant difference between nests and false crawls' proximity to lifeguard towers for both early-season data (t = 0.932, df = 120.4, p-value = 0.353) and late-season data (t = 1.206, df = 50.312, p-value = 0.234) (Figure 17; Tables 4 & 5).

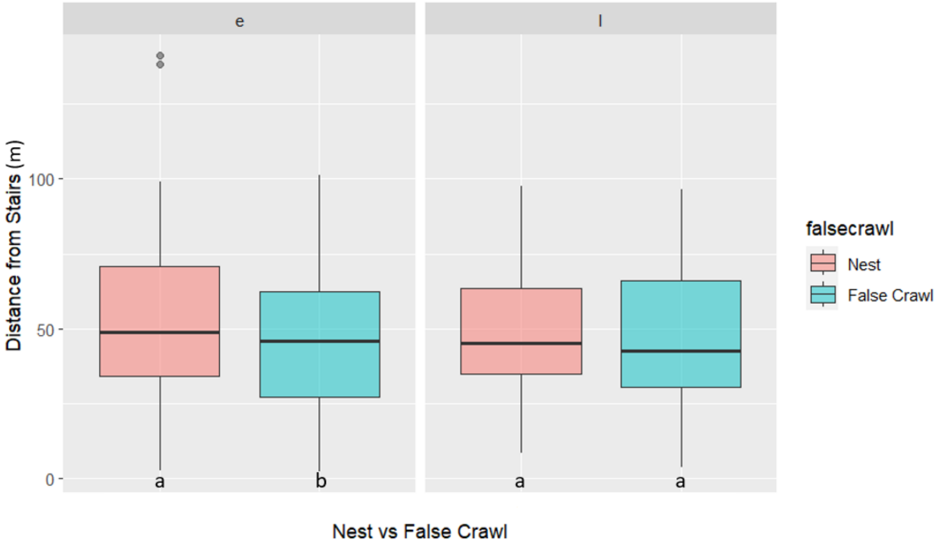


Figure 16. Boxplots showing average proximity to dune crossover stairs (m) between nests and false crawls in early (e) and late (l) season data. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

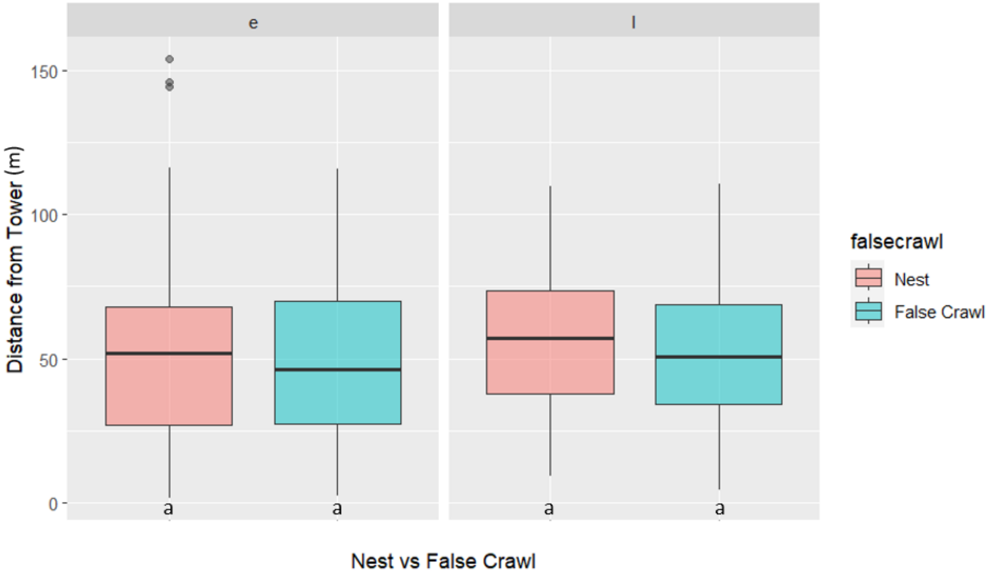


Figure 17. Boxplots showing average proximity to lifeguard towers (m) between early (e) and late (l) season nests and false crawls. The lower boundary line of the box represents the 25th percentile, the line in the middle represents the median, and the upper boundary line represents the 75th percentile. Dots represent outliers, and the error bars depict the 10th and 90th percentiles. Significance is depicted using letters, boxes with different letters have significantly different means.

Table 3. Mean and standard deviations for environmental and anthropogenic variables associated with nests and false crawls.

	Early Season Nests	**Early Season FC**	**Late Season Nests**	**Late Season FC**
Mean Beach Slope (Grade %)	8.14 (SD 0.33)	8.06 (SD 0.38)	7.61 (SD 0.93)	7.58 (SD 0.93)
Mean Slope at Nest/FC (Grade %)	10.77 (SD 5.76)	12.20 (SD 7.92)	6.66 (SD 4.61)	6.26 (SD 7.96)
Mean Elevation at Nest/FC (m)	1.97 (SD 0.60)	1.91 (SD 0.73)	1.71 (SD 0.76)	1.54 (SD)
Mean Beach Width (m)	34.21 (SD 2.39)	34.78 (SD 2.79)	36.07 (5.78)	36.24 (SD 5.79)
Mean Grain Size (Χϕ)	1.53 (SD 0.25)	1.55 (SD 0.25)	1.72 (SD 0.07)	1.69 (SD 0.13)
Mean Sorting Value (σϕ)	0.55 (SD 0.13)	0.52 (SD 0.12)	0.44 (SD 0.04)	0.44 (SD 0.06)
Mean Dist. To Stairs (m)	54.04 (SD 26.27)	45.66 (SD 23.96)	48.19 (SD 21.53)	48.63 (SD 23.10)
Mean Dist. To Towers (m)	53.53 (SD 31.59)	49.54 (SD 26.92)	58.08 (SD 24.58)	52.04 (SD 25.52)
Mean Dist. From MHW (m)	14.23 (SD 9.16)	13.45 (SD 9.45)	15.56 (SD 9.61)	12.99 (SD 8.87)

Table 4. Welch’s t-test statistical output for early season data comparing the means of environmental and anthropogenic variables associated with loggerhead nests and false crawls. Statistical significance is indicated by * and bold.

Correlation	**Df**	**t-value**	**p-value**
Mean Beach Slope at Early FC vs. Nests	159.74	1.595	0.113
Slope at Early FC vs. Nests	185.52	-1.555	0.122
Elevation at Early FC vs. Nests	166	0.663	0.509
Beach Width at Early False Crawls vs. Nests	159.68	-1.599	0.112
Grain Size at Early False Crawls vs. Nests	138.63	-0.688	0.493
Sand Sorting at Early False Crawls vs. Nests	134.88	1.586	0.115
Proximity to Stairs at Early False Crawls vs. Nests	127.37	2.313	**0.022***
Proximity to Lifeguard Towers at Early False Crawls vs. Nests	120.4	0.932	0.353
Distance to MHW at Early False Crawls vs. Nests	142.05	0.594	0.553

Table 5. Welch’s t-test statistical output for late season data comparing the means of environmental and anthropogenic variables associated loggerhead nests and false crawls. Statistical significance is indicated by * and bold.

Correlation	**Df**	**t-value**	**p-value**
Mean Beach Slope at Late FC vs. Nests	48.727	0.175	0.862
Slope at Late FC vs. Nests	85.547	0.357	0.722
Elevation at Late FC vs. Nests	48	1.128	0.265
Beach Width at Late False Crawls vs. Nests	48.947	-0.148	0.883
Grain Size at Late False Crawls vs. Nests	88.853	1.758	0.082
Sand Sorting at Late False Crawls vs. Nests	73.387	-0.871	0.386

Proximity to Stairs at Late False Crawls vs. Nests	51.691	-0.010	0.921
Proximity to Lifeguard Towers at Late False Crawls vs. Nests	50.312	1.206	0.234
Distance to MHW at Late False Crawls vs. Nests	46.074	1.343	0.186

Generalized Linear Models & ANOVA

Generalized linear models were created using multiple environmental and anthropogenic variables as predictors to estimate whether a turtle will nest or false crawl. Only early-season data was included in the model, as the results of the t-tests and boxplots from late-season data suggest that there is not enough data to establish a meaningful relationship between environmental and anthropogenic factors and nest placement. The model of best fit was selected based on the AIC value (287.72) and by examining residual diagnostics. This model uses the distance from the mean high-water line, beach slope, and proximity to stairs as predictors to estimate whether a turtle will false crawl or not (Table 6). The model output indicated that beach slope (p=0.028) and proximity to stairs (p=0.003) have a statistically significant relationship with nesting activity, i.e., whether a turtle will nest or false crawl. The probability of a false crawl occurring decreases as the beach slope increases (Figure 18), and the probability of a false crawl occurring decreases as distance from beach access stairs increases (Figure 19). The DHARMa residual diagnostic conducted on the generalized linear model for the early season data suggested that the data is normally distributed (Figure 20). The results of the Type III ANOVA indicated no significant differences (p=0.1638) between dune crossover type and the presence of nests or false crawls (Table 7).

Table 6. Generalized linear model statistical output done on early season data using beach slope, distance from stairs, and distance from MHW line as predictive variables for occurrence of nests and false crawls. Statistical significance is indicated by * and bold.

	Estimate	**Std. Error**	**z-value**	**Pr (> | z |)**
Intercept	9.896	3.726	2.656	0.00792
Early False Crawls vs. Beach Slope	-0.970	0.441	-2.199	**0.028***
Early False Crawls vs. Distance to Stairs	-0.018	0.006	-3.007	**0.003***
Early False Crawls vs. Distance to MHW	-0.023	0.016	-1.454	0.146

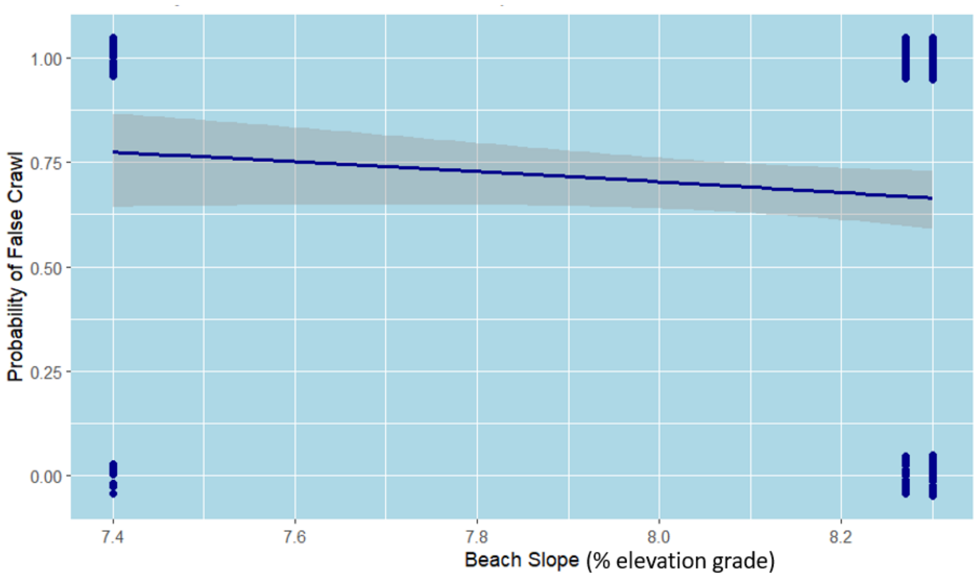


Figure 18. Linear regression statistical output showing correlation between nest placement and percent beach slope. The line shows the linear model, and the gray area is the 95% confidence interval. Nests are represented with a value of 0 and false crawls with a value of 1. The probability of a false crawl decreases as the average beach slope increases.

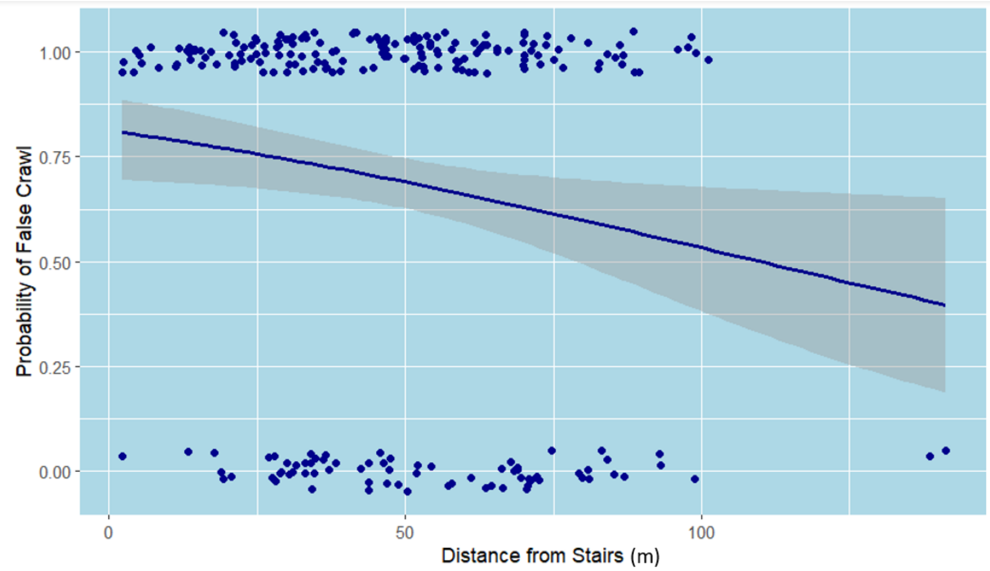


Figure 19. Linear regression statistical output showing correlation between nest placement and proximity to dune crossover stairs. The line shows the linear model, and the gray area is the 95% confidence interval. Nests are represented with a value of 0 and false crawls with a value of 1. The probability of a false crawl decreases as the distance between crawl and dune crossover stairs increases.

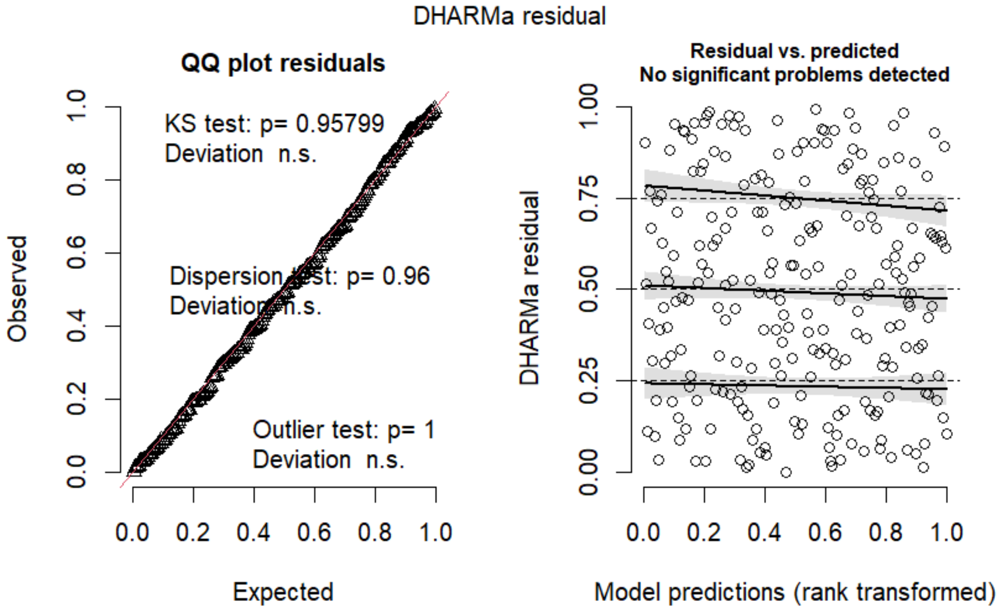


Figure 20. DHARMa residual diagnostic test output for the generalized linear model. The QQ plot suggests that the data is normally distributed.

Table 7. Results of the Type III ANOVA logistic regression testing dune crossover type as the independent variable and presence of nest or false crawl as the dependent variable. There were no statistically significant differences between dune crossover types.

	LR Chi-square	Df	Pr(>Chisq)
Presence of nest or FC based on dune crossover type	1.939	1	0.164

Discussion

Characterization of Nest Distribution

The kernel density estimation (KDE) carried out on early and late season nesting data provided a mechanism to recognize the areas that had the highest number of nests and false crawls over the course of the 2022 nesting season. Subsequently, this allowed for further exploration of the environmental and anthropogenic factors that may affect nesting patterns in this area. Overall, a higher number of nesting and false crawl incidences occurred in the central (RR2) and northern sections (RR3) of the study area. These areas have steeper beach slopes compared to the southernmost site, and notably have much higher dunes that are backed by dense vegetation. RR1 is backed by sparsely vegetated, gently domed dunes. Additionally, the digitization of the mean high-water line allowed for nests to be categorized as being laid in the backbeach, mid-beach, or near the mean high-water line. During the early season, a higher number of false crawls occurred at the backbeach, and more nests were laid in the mid-beach (Figure 6). Late season data revealed that more false crawls occurred in the mid-beach, and that a higher number of nests were laid in the backbeach. It should be noted that there was a greater number of nests and false crawls associated with early season data than late season data.

Identifying Crawl Tracks

One of the objectives of this study was to assess the effectiveness of using UAV surveys to identify sea turtle crawl tracks and nests. Crawl tracks were observed in the late-season aerial survey imagery; and were confidently identified at the species level by the sea turtle conservation team at Gumbo Limbo Nature Center. The crawls were identified as those of loggerhead and green sea turtles, as they leave distinct tracks in the sand that are unique to the species. Loggerhead sea turtles leave alternating comma-shaped indentations in the sand, whereas green sea turtles leave parallel flipper marks in the sand, as well as a distinct tail-drag indentation. This finding suggests that the resolution of the UAV imagery is sufficient to identify sea turtle crawls. However, it could not be determined as to whether the crawls led to a successful nest, or if they were false crawls. Future studies looking to ID crawl tracks using aerial imagery must take into consideration that to collect accurate crawl track data, flights must be conducted on a daily (or near-daily) basis. Additionally, it may be difficult to determine whether the crawl results in a successful nesting attempt or a false crawl, depending on how far along in the nesting process the turtle gets.

UAV surveys could provide a mechanism to remotely observe and map crawl tracks, allowing researchers to identify sea turtle nests and false crawls in remote locations that may be otherwise inaccessible. Additionally, current sea turtle nest monitoring methods involve the use of vehicles to drive on the beach, which may be disruptive to other sensitive fauna, such as nesting shorebirds. The use of UAV surveys removes this disruption, assuming the line of sight with the aircraft is maintained.

Nest Site Selection and Beach Morphology

Previous studies have suggested that the morphological features of the beach, such as slope and width, may have an influence on loggerhead sea turtle nest site selection (Wood & Bjorndal, 2000; Mazaris eet al., 2006; Siquiera-Silva et al., 2020). However, there appear to be some contradictions in the results of these studies, with some identifying steeper beach slopes as a proximal cue for nesting and others finding that width is most crucial, with wider beaches having greater densities of nests. Due to the inverse relationship between beach slope and width, these two findings challenge each other. This study aimed to identify which of these factors, if any, serves as a cue for nest site selection in Boca Raton, FL. The results of the paired t-tests and boxplots show there is no statistically significant difference in beach slope between nests and false crawls. Additionally, there was no significant difference found in beach width when comparing nests and false crawls. However, the result of the generalized linear model shows that when beach slope, distance from stairs, and distance crawled from the mean high-water line are used as predictive variables, beach slope and distance from stairs have a statistically significant relationship with nesting activity. The probability of a false crawl occurring decreases as the average beach slope increases, and the probability of a false crawl decreases as the distance between the crawl and dune crossover increases. The generalized linear model was only included for early season data, as no significance was established for late season data, likely because nesting activity decreased further into the nesting season.

It should be noted that the study site in this research was small; therefore, beach morphology was relatively similar throughout the site. Past studies may also have had contradictory findings due to the scale of their study site as well, therefore future research should include larger study areas, or multiple study areas that exhibit more variation in morphology to collect accurate data and further examine the relationships between beach slope, width, and nest site selection. Additionally, dune height and vegetation coverage could be explored as variables influencing nest site selection.

Nest Site Selection and Sedimentology

Sediment sorting and mean grain size were assessed for variability across the beach gradient and to determine if there is a cross-shore nest site preference due to sediment variability. While there was some variability across the beach face, almost all samples from the April survey consisted of medium sand that was well-sorted to medium-well sorted, apart from coarse sand collected from RR1 MHW. Similarly, all samples collected from the July survey consisted of medium sand that was well-sorted to medium-well sorted. The results of the t-tests carried out on early and late-season nests and false crawls suggest that there were no statistically significant differences in sand grain size and sorting between nest and false crawl locations. This may be due to the small scale of the study site leading to minimal sediment variability, or because sand grain size and sorting is not a significant factor in the nest site selection process at this location.

Nest Site Selection and Anthropogenic Influences

The single most important variable for emergence type for early season data was the dune crossover stairs, with false crawls more likely to occur in closer proximity to the stairs (Figure 21). Late-season data showed no significant differences between false crawls and nests' proximity to stairs. However, this may be due to there being an insufficient amount of data points associated with the late-season data, as there were fewer crawls recorded as the nesting season progressed. There were no significant differences in proximity to lifeguard towers between nests and false crawls for both early and late season data, possibly because lifeguard towers are at higher elevations, and it may be more difficult for the turtle to visually detect.

Results of the Type III ANOVA indicated no differences in nest or false crawl presence between the different types of dune crossovers; therefore, it can be assumed that all dune crossovers may be acting as an obstruction on the beach, similar to a seawall. Rizkalla & Savage (2011) found that the presence of a seawall impacts loggerhead sea turtle nesting by reducing nesting success, and that false crawls were more likely to occur at regions of beach backed by seawalls. Sea turtles may choose not to nest after encountering an obstruction such as dune crossover stairs, and in some instances, nesting females may even become trapped under the stairs (Sella & Fuentes, 2019). Other possible explanations are that lighting or movement near the stairs deters the turtles from nesting; however, this beach park is closed to the public at night, and Gumbo Limbo Nature Center monitors beachfront lighting during sea turtle nesting season.

Figure 21. Dune crossover stairs that may act as a physical barrier on the beach and deter nesting sea turtles.

UAV Surveys & Technical Errors

Beach profiles were extracted from the UAV-derived DSMs to compare to RTK GPS profile data and assess for accuracy. There was a difference of approximately 0.5 m in the vertical data, however it could not be determined as to whether the RTK GPS or the DSM was responsible for the discrepancy in accuracy. The GNSS base station was used to take static GPS observations throughout the flight, and this data was used to process the UAV data and correct location, therefore it is possible that there was an error in the base station observations. Slope and elevation were extracted from the DSM at each nest and false crawl coordinate; however, slope is calculated in ArcGIS using a 3 by 3 window of cells, therefore the values derived were accurate and all data extracted is relative to itself.

Conclusions

This study used UAV-derived aerial data in conjunction with data collected in-situ to examine environmental and anthropogenic factors that may affect loggerhead sea turtle nest site selection, which builds on previous studies using UAV-derived data to assess the relationships between beach morphology and sea turtle nest placement (Long et al., 2011; Yamamoto et al., 2015; Dunkin et al., 2016). Additionally, general spatial trends of nesting were examined. This study found that there were no significant differences in average beach slope, width, and sand texture between successful nesting attempts and false crawls; however, proximity to dune crossover stairs was significantly different between nests and false crawls. When used as predictive variables in a generalized linear model, average beach slope and proximity to stairs have a statistically significant relationship with nesting activity. The probability of a false crawl occurring decreases at further proximity to dune crossover stairs, and the probability of a false crawl occurring decreases as the average beach slope increases.

This study can serve as a template for future studies looking to create a holistic view of the geomorphological and anthropogenic factors involved in sea turtle nest site selection, as well as studies assessing beach morphology. Projects of this nature could be applied to larger-scale study sites; however, additional drone flights may be necessary to capture data on a larger scale. UAVs provide a relatively low-cost alternative to satellite imagery and LiDAR data yet still preserve the high resolution necessary to derive accurate elevation and topographic data. Future studies could evaluate the relationship between nesting success and dune height and vegetation coverage, which would provide more in-depth information on the environmental factors affecting nest site selection. Additionally, relationships between environmental and anthropogenic influences on other species of sea turtles, such as green sea turtles and leatherbacks, could be examined. The dynamics of sandy beach systems are highly complex; therefore, detailed studies looking to examine nest site selection should be conducted over a more extensive period and include a larger study area, or multiple study areas, to verify the conclusions found in this research (Mazaris et al., 2006).

Finally, this research will contribute to the conservation of loggerhead sea turtles, as it will provide insight into their terrestrial habitat and nesting preferences and has many applications for beach management and species conservation efforts. As beach nourishment becomes more common due to increased erosion and sea level rise, understanding the effects that beach morphology has on nest site selection is vital to properly manage nourishment projects. Coastal development is expected to increase as coastal regions become more populated and it is beneficial to understand how modifications to the coastal system, such as the construction of dune crossovers, may impact sea turtle nesting success (Sella & Fuentes, 2019). The findings of this study provide insight into the nesting behavior of loggerhead sea turtles populations and can inform decisions for the conservation and monitoring of nesting beaches.

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