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Urban pocket beaches as nesting habitat for marine turtles: Their importance and risk from inundation

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ABSTRACT

Sandy areas between rocky uplands, or natural pocket beaches, provide important habitat for coastal wildlife. On developed coasts, similar sandy areas, called urban pocket beaches, occur in the gaps between properties with coastal armoring (sea walls or revetments). These urban pocket beaches provide important nesting, foraging, and resting habitat for wildlife, particularly on extensively armored beaches. However, it is unclear if urban pocket beaches provide the same function as natural pocket beaches or offer benefits (e.g., reduced risk of inundation or erosion) lost at nearby armored areas. To address these knowledge gaps, we analyzed loggerhead marine turtle nesting patterns and reproductive success to determine if urban pocket beaches represent preferred nesting habitat along armored coastlines. We also determined if nests at urban pocket beaches are more likely than nearby armored and unarmored beaches to be inundated from wave runup, which could alter the incubation environment and nest productivity of marine turtles. The linear extent of urban pocket beaches in Florida was identified, then loggerhead marine turtle nesting success, nest density, and hatching success was compared between urban pocket beaches with armoring and beaches without armoring. We also modeled differences in wave runup exposure at these beaches under current conditions (2016–2019) without and with tropical storms and future (2060) intermediate-low and high sea level rise scenarios. Overall, pocket beaches account for less than 2% of Florida's nesting beaches with higher abundance on more heavily armored shorelines. Nesting density in pocket beaches were similar to nearby beaches without armoring. However, female turtles were more likely to nest in urban pocket beaches compared to adjacent armored areas, and pocket beach nests had a higher hatchling success rate than unarmored and armored beaches. Our models suggest that exposure to wave runup varies by geographic location, but overall pocket beaches provided viable nesting habitat in all areas

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surveyed. Thus, managers should advocate for preserving urban pocket beaches on armored shorelines.

1. Introduction

Coastal beaches are an important transition zone between the ocean and the land (Álvarez-Romero et al., 2011; Harris et al., 2019; Talley et al., 2003). They provide foraging, breeding, and migration destinations for a range of species (Harris et al., 2015; Nel et al., 2014). Many sandy beaches also provide recreational areas for residents and tourists alike (Fleming et al., 2014; Littles et al., 2019; Pascoe, 2019; Small and Nicholls, 2003). Consequently, many coastal areas have been extensively developed (Fuentes et al., 2016; Nelson Sella and Fuentes, 2019). Development can cause changes to characteristics of beach habitat and disrupt natural beach processes (Defeo and Elliott, 2021; Pillet et al., 2019; Schoonees et al., 2019). For example, alterations to dune structure, elevation, or

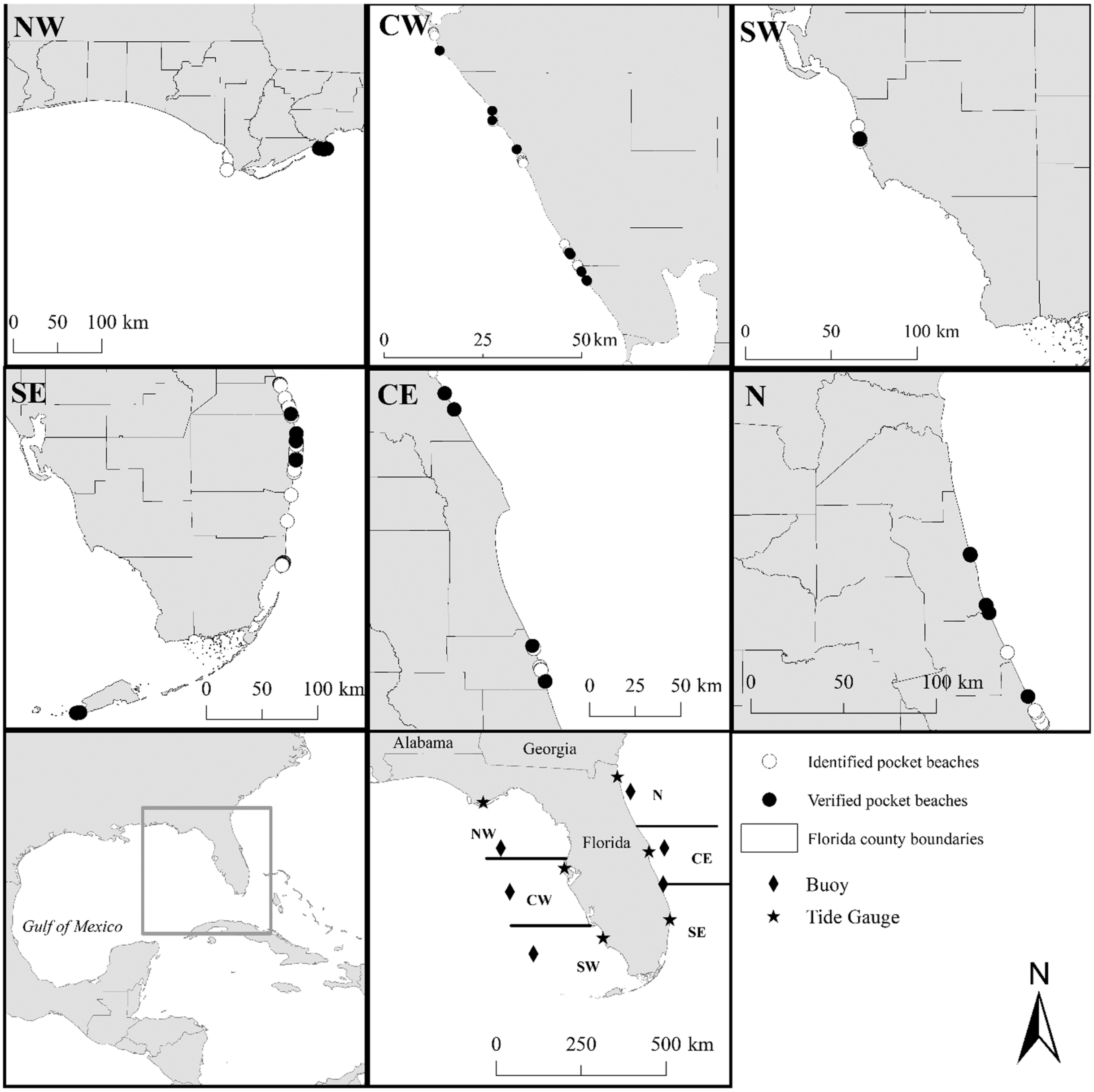

Fig. 1. Locations of the identified pocket beaches, verified pocket beaches, and buoys and tide gauges by loggerhead turtle MU; N = northern, CE = central eastern, SE = southeastern, SW = southwestern, CW = central western, NW = northwestern.

cross-shore slope to protect upland development may increase beach susceptibility to tidal or storm inundation (Basco, 2006; Dugan et al., 2008). In developed areas exposed to erosion from high frequency storms, long stretches of seawalls or other coastal armoring structures are typically installed to protect coastal property (Gittman et al., 2015; Witherington et al., 2011a). Where there are gaps in armoring, small pockets of sandy beach habitat may remain, forming what are termed "urban pocket beaches" (Debrot and Pors, 1995; Toft et al., 2013; Young and Carilli, 2019).

Urban pocket beaches are similar in form to naturally occurring pocket beaches. Natural pocket beaches occur globally in areas where rocky headlands border small, embayed beaches composed of sand or other sediment (Young and Carilli, 2019). In urban pocket beaches, armoring replaces the role played by rocky headlands. Natural pocket beaches can have limited sediment input resulting in reduced width and elevation which makes these beaches more susceptible to inundation by waves and tides (Brunel and Sabatier, 2007). However, it is unknown if urban pocket beaches are similarly susceptible to inundation when compared to unarmored beaches. As storm activity and erosion are projected to increase with changes in climate, coastal armoring is likely to increase, resulting in a greater prevalence of urban pocket beaches (Fish et al., 2005; Mazaris et al., 2009; Wong et al., 2014). Thus, it is important to understand if urban pocket beaches provide habitat worthy of preservation.

The threat of exposure to inundation is of particular concern for marine turtles which bury their eggs in beaches during reproduction (Fuentes et al., 2010; Patrício et al., 2021). If beach configuration changes due to coastal armoring, marine turtle nests on developed beaches may be exposed to increased risk of inundation (Kraus et al., 1996; Pilkey and Cooper, 2014; Plant and Griggs, 1992). Wave action can affect the incubation environment by limiting gas exchange, altering nest temperatures, and changing salinity (Ackerman, 1981; Caut et al., 2010; Lolavar and Wyneken, 2017; Pike et al., 2015; Sifuentes-Romero et al., 2018). All have the potential to affect hatching success or the number of hatched eggs divided by the total clutch size (Foley et al., 2006, 2000; Limpus et al., 2020; Ware and Fuentes, 2018a, 2018b). If urban pocket beaches provide suitable habitat comparable to natural, unarmored beaches, these areas may act as refugia within an otherwise armored coastline (Rizkalla and Savage, 2011; Vousdoukas et al., 2009; Witherington et al., 2011b).

The coast of Florida offers an excellent opportunity to assess urban pocket beach nesting habitat since coastal areas in Florida are 1) important nesting areas for loggerhead (*Caretta caretta*), green (*Chelonia mydas*), and leatherback (*Dermochelys coriacea*) turtles (Ceriani et al., 2019; Chaloupka et al., 2008; Meylan et al., 1995; NMFS and USFWS, 2008; Stewart et al., 2014), and 2) and are highly developed with a significant amount of coastal armoring (Fuentes et al., 2016; Gittman et al., 2015; Nelson Sella and Fuentes, 2019; Witherington et al., 2011a). Thus, to determine the importance of urban pocket beaches to marine turtle nesting and assess the exposure of these areas to wave runup and inundation, we 1) quantified the extent of urban pocket beaches along the coast of Florida, 2) determined the relative use of these areas by marine turtles and the hatching success of the nests when compared to adjacent armored and nearby unarmored beaches, and 3) evaluated the relative risk of exposure to wave runup during typical sea conditions, tropical storms, and projected sea level rise.

2. Methods

2.1. Extent of urban pocket beaches in Florida

To quantify the number of urban pocket beaches in Florida and their extent, we first identified locations where coastal armoring exists along the coast. To do this, we used coastal permitting data from the Florida Department of Environmental Protection (data collected from March 7, 1980, through May 31, 2019 from http://geodata.dep.state.fl.us/). We used the most recently available images from Google Earth Pro (2018–2019) to determine whether or not urban pocket beaches (i.e., beaches up to 1 km in length with armoring on adjacent beaches (Young and Carilli, 2019)) existed adjacent to permitted beach armoring. For each identified pocket beach, a polygon was created along the visible extent of the pocket beach during the analysis of aerial images and exported into ArcGIS 10.7.1. Each pocket beach was given an identification code based on its location within one of the six loggerhead genetic management units (MU): northern, central eastern, southeastern, southwestern, central western, and northwestern Florida (Shamblin et al., 2012, 2011, Fig. 1).

We validated our identification method and determined the area available for marine turtles nesting at urban pocket beaches by ground-truthing up to 10 identified urban pocket beaches within each of the six-loggerhead turtle MUs examined from June to November of 2019. If more than 10 pocket beaches were identified from the images, we selected 10 beaches to ground-truth based on their accessibility from public access points to avoid trespassing on private property. Forty-six urban pocket beaches were considered for this study (northern = 10, central eastern = 4, southeastern = 9, southwestern = 4, central western = 10, and northwestern = 9, Fig. 1).

At each verified urban pocket beach, we collected data on the type of adjacent armoring (e.g., vinyl, steel, or concrete seawalls, or rock revetments) and noted if vegetation (either naturally occurring or planted) was present as it may indicate beach habitat had experienced less disturbance (Grafals-Soto et al., 2020; Miller et al., 2009). Three cross-shore transects from the water to the seaward dune toe or armoring were conducted using a Trimble Catalyst GNSS unit to obtain the slope of the beach and create a digital elevation model for the wave runup processing (as per Ware et al., 2019). A polygon was delineated at the extent of the nesting area for each beach. For comparative purposes, the same information was also collected along the beach seaward of the adjacent armoring and at the closest available unarmored beach (Appendix A). The average distance between urban pocket beaches and unarmored beaches was 1.7 km with a range of 0.06–8.5 km.

2.2. Relative use and reproductive output of marine turtles at urban pocket beaches

To determine the relative importance of urban pocket beaches for marine turtles nesting in Florida, we obtained GPS coordinates for loggerhead turtle nests at our sampled beaches from the Florida Fish and Wildlife Conservation Commission (FWC). These data were collected by Florida Marine Turtle Permit Holders (permit holders) authorized by FWC during the 2016–2019 nesting seasons (May - August). While Florida beaches are also important nesting grounds for green and leatherback turtles (Chaloupka et al., 2008; Stewart et al., 2011), they nest in lower numbers than loggerhead turtles. Therefore, we excluded these species from our analysis. Nest GPS locations within and adjacent to the urban pocket beaches were isolated using the previously delineated beach polygons, resulting in a usable sample size of nests from 19 beaches representing five of the six loggerhead MUs considered (there were no GPS data for nests on the urban pocket beaches in northwestern Florida, Appendix B). This allowed us to determine the relative nest density of each of the beach types considered here (urban pocket beach, armored, and unarmored). A smaller number of beaches ($n = 12$) also had spatial information for non-nesting emergences (i.e., false crawls) which allowed us to compare nesting success (i.e., nests/total crawls), which can indicate a lower expenditure of reproductive energy (Meylan et al., 1995). These data were grouped together for analysis, as the sample size for each MU was too small to compare across the management units.

Hatching success (i.e., eggs hatched/estimated clutch size) was used as a measure of nest productivity (Brost et al., 2015). Nest inventories were conducted by permit holders at least three days after hatching or once the incubation duration exceeded 70 days to determine the number of hatchlings that emerged from the nest (Brost et al., 2015; Ceriani et al., 2021; FWC, 2016). Hatching success from undisturbed nests (i.e., no predation, wave exposure, or erosion) was evaluated by beach type to determine baseline productivity estimates in the absence of disturbance and determine if there were underlying differences between beach types which could impact the interpretation of subsequent analyses. Analyses including washed over and eroded nests were then conducted to evaluate hatchling production in relation to this disturbance (see Section 2.3 for wave exposure analyses). Nests that had been predated were excluded from this analysis. The nesting success, density, and productivity related to beach type were analyzed using generalized linear models (negative binomial for density, binomial for nesting and hatching success) with R version 4.0.3 (Team, R.C, 2020). Post hoc comparisons (Tukey-adjusted pairwise comparisons with a 95% confidence level) were implemented in R using the "emmeans" package for a more detailed assessment of the differences in our nesting data among the three beach types. These pairwise contrasts were presented as rate-ratios (RR) for the negative binomial regression and odds-ratios (OR) for the binomial regression to express the strength of the association between the beach types. The rate-ratios and odds-ratios are used to compare the odds of an event in one group to the odds of the event in another group. An RR or OR of 1.0 indicates that there is no difference in risk or odds between the compared groups.

2.3. Exposure of urban pocket beaches to wave runup

Wave runup is a measure of the maximum elevation of water on the foreshore of the beach above the still water level and can be used as a proxy for inundation (Osorio et al., 2014; Stockdon et al., 2006; Ware et al., 2019). The wave runup elevation is related to the slope of the beach, the wave height offshore, and the wave period (Stockdon et al., 2006). To develop the wave runup models, water level data (tide height + wind surge) were obtained from the closest U.S. National Oceanic and Atmospheric Administration (NOAA) tidal gauges (https://tidesandcurrents.noaa.gov/map/index.html). Wave data was downloaded from the appropriate offshore buoys from the National Data Buoy Center (https://www.ndbc.noaa.gov/) for the selected study sites from 2016 through 2019 (Fig. 1). These data were then analyzed as described in Ware et al. (2019) using the empirical equation from Stockdon et al. (2006) and beach slope, deep-water wave height, and deep-water wavelength for each location (reverse-shoaled and transformed, as appropriate).

The resulting wave runup models were used to identify the proportion of urban pocket beach nesting area inundated under four different scenarios: 1) present day conditions from 2016 to 2019, 2) current tropical storm conditions from 2016 to 2019, 3) projected intermediate-low sea level rise conditions for 2060 as designated by NOAA (Sweet et al., 2022), and 4) projected high sea level rise conditions for 2060 as designated by NOAA (Sweet et al., 2022). Present-day conditions were based on the median wave height, wave period, and high tide elevation calculated from the tide gauge and buoy data for typical sea and tropical storm conditions during the years 2016 through 2019 corresponding to the years of analyzed nesting data. To determine current tropical storm conditions, the dates and times of tropical storm conditions were determined based on the locations of final storm paths and wind swaths from the NOAA National Hurricane Center (https://www.nhc.noaa.gov/data/) and their intersection with the respective buoys and tide gauges. A total of 12 storms were included in the analysis. These were Tropical Storm Colin, Hurricane Hermine, and Tropical Storm Julia in 2016; Tropical Storm Emily and Hurricane Irma in 2017; Tropical Storm Alberto, Tropical Storm Gordon, and Hurricane Michael in 2018; and Hurricane Dorian, Hurricane Humberto, and Tropical Storm Nestor in 2019. Present day median sea conditions were derived from observations excluding tropical storm dates and times.

To describe potential future conditions, projected sea level rise was determined for each tide gauge location based on projections from NOAA's Office for Coastal Management (https://coast.noaa.gov/slr/) for the year 2060 (Sweet et al., 2022). The year 2060 was chosen because the approximate generation time for marine turtles ranges from 14 to 63 years with an average of 40–45 years (Avens et al., 2015; Hatch et al., 2019; Scott et al., 2012) and the offspring of the turtles nesting currently could be expected to return to their natal nesting beach by this time (Brothers and Lohmann, 2018; Shamblin et al., 2020). The projected intermediate-low sea level rise varied from 0.35 to 0.39 m with an average of 0.37 m for the six MUs considered. The projected high sea level rise varied from 0.67 to 0.72 m with an average of 0.70 m. These projections were used with a bathtub approach where the sea level rise projections were added to current median high tide levels as determined during non-storm conditions (similar to Fuentes et al., 2020; Mazaris et al., 2009; Reece et al., 2013; Varela et al., 2019; Veelenturf et al., 2020). We then applied the wave runup model using the projected median high tides with current median wave conditions to estimate the proportion of beach exposed to wave runup and inundation for each of the scenarios considered. To do this, we assumed that future wave conditions will be comparable to present day (as per Fuentes et al., 2020; Ware et al., 2019). The differences in proportional wave exposure between beach types and scenarios were analyzed using a beta regression after data transformation in R version 4.0.3 (Team, R.C, 2020). Post hoc contrasts of the differences (False Discovery Rate) were implemented in R using the "emmeans" package to provide a more detailed assessment of the differences in wave runup exposure between the three beach types.

3. Results

3.1. Extent of urban pocket beaches in Florida

A total of 142 urban pocket beaches were identified via aerial imagery in Florida (Fig. 1, Table 1), comprising 23.64 km of beach. This is less than 2% of the 1327 km of sandy beaches utilized by turtles in Florida (FDEP, 2020). The greatest number and proportion of pocket beaches were found in the southeastern, central western, and central eastern Florida MUs. The remaining MUs comprised less than 1% of the overall linear extent of urban pocket beaches per MU (Table 1).

Of the 46 pocket beaches that were ground-truthed, 26.2% (n = 16) of those that had been previously identified with aerial imagery were not visible in the field due to recent beach nourishments (i.e., false positive). An additional 9.8% (n = 6) were identified in the field but not in aerial imagery (i.e., false negative). The types of armoring adjacent to the urban pocket beaches included seawalls (73.8%) and rock revetments (26.2%) (Appendix C). Forty-one percent of the pocket beaches surveyed had dune vegetation present. The unarmored beaches had the greatest length of cross shore transects (Avg. 31.3 m, range 10.3 – 75.3 m) followed by the urban pocket beaches (avg. 25.7, range 3.3 – 66.9) and the armored beaches had the shortest length of cross shore transects (avg. 13.2, range 3.0 – 44.9 m).

3.2. Relative use and reproductive output of marine turtles at pocket beaches

Loggerhead turtles nested in similar densities in all three beach types with rate ratios equal to 1 between all beach types (Table 2). However, nesting turtles were more likely (OR = 1.48 ± 0.23 SE) to nest after emergence on urban pocket beaches than armored beaches, but less likely (OR = 0.62 ± 0.09 SE) to nest on the urban pocket beaches when compared to the unarmored beaches (Table 2, Appendix D). The nesting success for loggerhead turtles was highest at the beaches without armoring (0.47 ± 0.14 SE), followed by urban pocket beaches (0.35 ± 0.12 SE), and then adjacent armored beaches (0.27 ± 0.11 SE, Table 3).

When we evaluated the reproductive output of the three beach types, we found that nests in pocket beaches were more likely to hatch than at the unarmored beaches (OR = 1.61 ± 0.04 SE) and on armored beaches (OR = 1.19 ± 0.27 SE, Table 2). Hatching success was greatest at urban pocket beaches (0.82 ± 0.03 SE), followed by beaches without armoring (0.79 ± 0.03 SE), and armored beaches (0.73 ± 0.03 SE, Table 3). When over washed, inundated, or washed-out nests were removed from the data, pocket beach nests were also more likely to hatch than nests on the armored (OR = 1.75 ± 0.54) or the unarmored beach (OR = 1.61 ± 0.27, Table 3). Hatching success was greatest at the urban pocket beaches (0.87 ± 0.02 SE), followed by the unarmored beaches (0.81 ± 0.02 SE), and armored beaches (0.80 ± 0.03 SE, Table 3).

3.3. Exposure of urban pocket beaches to wave runup

Wave exposure varied between the six genetic management units for each of the four scenarios (no storm, storm, intermediate low SLR, and high SLR). Under typical, or no storm conditions, pocket beaches in the central eastern and northern MU were more exposed to wave runup than the unarmored beaches. In the northwestern MU, armored beaches were more exposed to wave runup than pocket beaches during no storm conditions (Appendices E and F). Under storm conditions, pocket beaches in the northern and southeastern MUs were more exposed to wave runup than unarmored beaches. In the northwestern MU, armored beaches were more exposed to wave runup than the pocket beaches (Appendices E and F).

Under intermediate low sea level rise conditions, the northern MU both pocket beaches and armored beaches were more likely to be exposed to wave runup than the unarmored beach. In the northwestern and southwestern MUs, the armored beaches were more likely to be exposed wave runup than the pocket beaches in intermediate low sea level rise conditions (Appendices E and F).

Under high sea level rise conditions, the northern, southeastern, and southwestern MUs had pocket beaches that were more likely to

Table 1
The number of pocket beaches identified for each loggerhead management unit using Google Earth aerial imagery. Coverage (%) is the total length of pocket beaches divided/ the total length of beach for that management unit.

	Number of pocket beaches	Mean length ± SD (km)	Total length (km)	Coverage (%)
Southeastern Florida	70	0.16 ± 0.18	11.54	4.51
Central western Florida	35	0.19 ± 0.18	6.62	2.54
Central eastern Florida	9	0.29 ± 0.45	2.61	1.26
Southwestern Florida	5	0.20 ± 0.14	1	0.86
Northern Florida	14	0.10 ± 0.20	1.42	0.55
Northwestern Florida	9	0.05 ± 0.03	0.45	0.1
Total	142	0.17 ± 0.20	23.64	1.57

Table 2
Pairwise contrasts presented as rate-ratios or odds-ratios (Ratio), standard errors (SE), lower and upper 95% confidence limits, and p-value from the regression models (negative binomial -NBR and binomial -BR). These relate beach type to nest density (nests per linear kilometer), nesting success (nests divided by all crawls), and hatching success (hatched eggs/clutch size) for non-predated nests, and then for a subset of these nests not impacted by over wash, wash out, or inundation. Rate or odds ratios equal to 1 indicate no difference between groups.

	Contrast	Ratio	SE	Lower	Upper	P-Value
Nest density (NBR, RR)	Pocket Beach / Armored Beach	0.95	0.20	0.59	1.55	0.971
	Pocket Beach / Unarmored Beach	0.78	0.16	0.48	1.25	0.4242
	Armored Beach / Unarmored Beach	0.81	0.17	0.49	1.35	0.5988
Nesting success (BR, OR)	Pocket Beach / Armored Beach	1.48	0.23	1.03	2.14	**0.0303**
	Pocket Beach / Unarmored Beach	0.62	0.09	0.45	0.86	**0.0026**
	Armored Beach / Unarmored Beach	0.42	0.08	0.27	0.66	**0.0001**
Hatching success (BR, OR)	Pocket Beach / Armored Beach	1.61	0.04	1.52	1.70	**< 0.0001**
	Pocket Beach / Unarmored Beach	1.19	0.27	1.13	1.26	**< 0.0001**
	Armored Beach / Unarmored Beach	0.74	0.02	0.70	0.79	**< 0.0001**
Hatching success subset (BR, OR)	Pocket Beach / Armored Beach	1.75	0.54	1.63	1.89	**< 0.0001**
	Pocket Beach / Unarmored Beach	1.61	0.27	1.51	1.72	**< 0.0001**
	Armored Beach / Unarmored Beach	0.92	0.02	0.86	0.99	**0.0164**

Table 3
Marginal means (Estimate), standard errors (SE), and lower and upper 95% confidence limits from the regression model (negative binomial - NBR and binomial - BR) relating beach type to nest density (nests per linear kilometer), nesting success (nests divided by all crawls), and hatching success (hatched eggs/clutch size) for non-predated nests, and then for a subset of non-predated nests not impacted by over wash, wash out, or inundation. Values are back-transformed from the natural log or logit scale.

	Beach Type	Estimate	SE	Lower	Upper
Nest density (NBR)	Pocket Beach	24.00	11.90	9.00	64.00
	Armored Beach	25.20	12.60	9.35	67.70
	Unarmored Beach	30.90	15.30	11.63	82.10
Nesting success (BR)	Pocket Beach	0.35	0.12	0.16	0.62
	Armored Beach	0.27	0.11	0.11	0.53
	Unarmored Beach	0.47	0.14	0.22	0.73
Hatching success (BR)	Pocket Beach	0.82	0.03	0.76	0.86
	Armored Beach	0.73	0.03	0.66	0.80
	Unarmored Beach	0.79	0.03	0.72	0.84
Hatching success subset (BR)	Pocket Beach	0.87	0.02	0.83	0.90
	Armored Beach	0.80	0.03	0.74	0.84
	Unarmored Beach	0.81	0.02	0.76	0.85

be exposed to wave runup than the unarmored beaches and the northwestern MU had armored beaches that were more exposed to wave runup than the pocket beaches (Appendices E and F). There were no significant differences in wave runup exposure between the beach types for all four scenarios in the central western MUs (Appendix E). In the southwestern MU, the model had false convergence in the storm scenario as well as the high sea level rise scenario, resulting in unreliable estimates and standard errors (Appendix E). Similarly, the central eastern MU also had false model convergence in the high SLR scenario. This occurred as the wave runup exposure approached a ratio of 1 (full inundation) across all beach types and so our model did not produce reliable estimates and standard errors for these particular groups.

4. Discussion

Urban pocket beaches were found within developed coastlines throughout most of Florida. They occur in approximately 2% of the overall available nesting habitat for marine turtles in the state while armoring and hardened structures (jetties and groins) are present in approximately 8–14% of the Florida shoreline (Gittman et al., 2015; Witherington et al., 2011a). This is currently a small proportion of the overall shoreline, which may mean these beaches may not biologically relevant to the overall population, at this stage. We did find that the prevalence of pocket beaches varied by management unit, with the southeastern unit having the highest proportion. This is also one of the two management units with the highest nesting populations (Ceriani et al., 2019). So pocket beaches may be of greater importance in some areas more than others. Additionally, the prevalence of both armoring and urban pocket beaches are likely to increase as climate change progresses due to increased erosion from sea level rise and more frequent storms (Sanò et al., 2011). This could be of concern since nesting success was found to be lower at armored beaches and urban pocket beaches when compared to unarmored, or natural beaches. A greater nesting success relates to more turtles choosing to deposit a nest upon emergence instead of completing a “false crawl” and is an indication of nest site preference (Fujisaki and Lamont, 2016; Rizkalla and Savage, 2011; Rumbold et al., 2001). This suggests that when turtles emerge at the different beach types, they are likely to spend less energy when they nest at unarmored as compared to urban pocket beaches and armored beaches. Additionally, hatching success was found to be significantly different among the beach types. This is likely due to the fact that nests seaward of armoring may be laid closer to the water and thus may be more exposed to wave runup and inundation (Rizkalla and Savage, 2011; Witherington et al., 2011b). When over washed, inundated, or washed out nests were removed from the dataset, hatching success was still significantly different among beach types; however, the hatching success at the armored beaches was more similar to the hatching success at unarmored beaches. While there was a significant difference between these, the estimates of hatching success at the three beach types are not likely to be biologically significant as they were all relatively high.

Even though urban pocket beaches provide suitable incubation habitat comparable to beaches without armoring throughout Florida, in the northern management unit, the wave runup models suggests that, under the four scenarios explored, on average urban pocket beaches are more likely to have a higher proportion of beach exposed to wave runup than nearby unarmored beaches. The central eastern genetic MU in non-storm conditions also indicated that pocket beaches will have the greatest proportion of exposure to wave runup as compared to the other beach types. This is consistent with studies of natural pocket beaches which are likely to experience inundation and are at risk from sea level rise (Brunel and Sabatier, 2007; Durán et al., 2016). It is possible that there is some interaction between the wave runup and adjacent seawalls (Plant and Griggs, 1992). While some genetic management units had pocket beaches and unarmored beaches with relatively low exposure to wave runup under the non-storm scenario (less than 35%), the exposure to wave runup increased with the tropical storm scenario throughout the genetic management units.

In our study region, tropical storms are most frequent during a significant portion of the loggerhead nesting and incubation season (July through October) (Dewald and Pike, 2014). The marine turtle reproductive strategy of laying several nests over the course of the season has traditionally mitigated for impacts from storms (Dewald and Pike, 2014; Fuentes and Abbs, 2010; Fuentes et al., 2019); however, recent research indicates that tropical storms may become more evenly distributed throughout the nesting season, subsequently impacting more nests (Fuentes et al., 2019). Climate change may result in additional changes to the frequency and intensity of storms, thus increasing the risk of exposure to wave runup from storm events (Fuentes and Abbs, 2010; Fuentes et al., 2019; Kossin et al., 2020; Patrício et al., 2021). Increases in storm events are not the only impact of climate change on nesting beaches, as sea level rise is also likely to increase the risk of exposure to wave runup (Lentz et al., 2016).

Under the intermediate-low sea level rise scenario, all beach types may still provide some nesting habitat less exposed to inundation. However, in the southwestern and central eastern management units, all beach types had a high exposure (greater than 70% exposed) to wave runup under the high sea level rise scenario, suggesting that some portions of Florida are more susceptible to sea level rise than others. This may be related to differences in beach slope and nearshore bathymetry between the different regions of Florida. The central eastern management unit is particularly important to loggerhead nesting as the central and south eastern management units together account for 82% of loggerhead nesting in Florida (Ceriani et al., 2019). However, the unarmored beaches in these locations are more likely to retreat and move inland under sea level rise (Defeo et al., 2009), thus they are more likely to maintain nesting habitat. Further, our bathtub model approach to predict wave runup exposure under sea level rise scenarios has some inherent limitations as it does not account for alterations in beach topography or the ability of a natural beach to migrate inland (Lentz et al., 2016; Patrício et al., 2021). Beaches that are armored further seaward without pocket beaches will be inhibited from migrating inland, thus resulting in a loss of habitat. However, pocket beaches may retain some ability to provide some nesting habitat less exposed to inundation. While exposure to wave runup may increase, that does not always indicate a decrease in hatching success as eggs are able to tolerate some inundation during portions of their incubation (Foley et al., 2006; Limpus et al., 2020).

It is important to note that our analysis looked at the average proportion of beach exposed to wave runup over time. To better understand the actual impacts from these projections, we need a better understanding of the implications of nests being exposed to wave runup (Pike et al., 2015; Ware and Fuentes, 2018b). The impact of wave runup on hatching success and mortality is related to frequency, duration, and the timing of exposure during the stages of embryonic development of the eggs (Foley et al., 2006; Limpus et al., 2020; Pike et al., 2015; Ware et al., 2021). While our study looked at the wave runup exposure among the beach types, further analysis is needed to determine the implications of our results for the reproductive output of marine turtles and long-term population stability (Foley et al., 2006; Limpus et al., 2020; Pike et al., 2015; Ware and Fuentes, 2018b). Additionally, beach environments are highly dynamic, our study showed a 26% false positive rate in identifying pocket beaches from aerial photographs, likely due to pocket beaches being covered by sand accretion, either naturally or by beach nourishment. Future studies could focus on monitoring local conditions at pocket beaches over time, including monitoring groundwater intrusion in the nest environment. Nevertheless, our study provides insights to wave runup exposure at urban pocket beaches not previously available. Future studies could take a more in-depth look at the effects of sea level rise on urban pocket beaches in areas where there are relatively high numbers of these beach types. Assessing the risks of inundation for individual nests relative to their hatching success on these beaches would provide additional insight to their value to nesting sea turtles.

Urban pocket beaches were found to comprise a small percentage of the overall nesting beaches in Florida, but female turtles have a higher nesting success at adjacent armored beaches resulting in spending less reproductive energy there. These urban pocket beaches have a higher hatching success as compared with armored beaches and in some portions of the state are less exposed to wave runup than the adjacent armoring. This is true even in future scenarios of sea level rise. This study is an initial effort to evaluate the importance of urban pocket beaches to marine turtles and also expands the work done by other studies that examine the impacts of coastal armoring on marine turtle nesting habitat (Rizkalla and Savage, 2011; Witherington et al., 2011b, 2011a). The total percentage of nesting that occurs at pocket beaches remains unknown, as we were only able to look at a subset of pocket beaches. Further studies could work with permit holders to look at the total number of nests at pocket beaches to compare with total nests in Florida. While pocket beaches may provide nesting habitat in the short term, our findings indicate that beach managers should minimize the use of coastal armoring when possible to ensure that beaches can continue to provide nesting habitat for marine turtles in the future.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02366.

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