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Anthropogenic Effects on Loggerhead Turtle Nest Success and Predation in the Gulf of Mexico

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***Abstract*.—Predators can easily consume many sea turtle eggs during nesting season. They can reduce the recruitment of hatchlings, ultimately resulting in long-term decreases in breeding populations. Researchers have collected data for decades on nest success rates and the increase in predation frequency on one of the largest nesting aggregations of Loggerhead Sea Turtles (*Caretta caretta*) in the Gulf of Mexico; however, these data have never been analyzed to identify what spatial factors may affect hatchling mortality. Understanding these factors can guide the development and deployment of efficacious measures to reduce or mitigate hatchling predation and, ultimately, increase site-specific sea turtle recruitment. We analyzed nest success data collected from 2010–2020 on two Sarasota, Florida, USA, beaches and show that nest predation rates were correlated with distance from buildings; specifically higher predation of nests laid further from buildings, nests laid near high-rise buildings (high number of occupants), and higher predation of nests in 2016–2020. Northern Raccoons (*Procyon lotor*) and Nine-banded Armadillos (*Dasypus novemcinctus*) were the most prolific predators on these beaches. We found higher observed emergence rates from caged nests than from non-caged nests, regardless of when the cages were installed over the incubating eggs. We conclude that the high density of coastal high-rise buildings can negatively impact sea turtle hatchling emergence. Nest caging may help mitigate predation events on certain nesting beaches. Beach managers can use these findings to understand the impact of humans on predator populations and the impact of increased predation on hatchling survival and, ultimately, on site-specific sea turtle recruitment.**

Key Words.—Caretta caretta; coastal development; geospatial analysis; nesting behavior; predation mitigation

Introduction

Over 40% of the human population in the USA lives along the coasts (National Oceanic and Atmospheric Administration 2013). Increasingly, residential development on the coastlines of the U.S. consists largely of high-rise buildings. Historically, coastal residential development consisted of predominantly single-family housing (https://www.census.gov/quickfacts/fact/table/FL/PST045222). Since 2011, urban sprawl has increased by 11% as existing urban centers in the U.S. continue to grow spatially and more previously underdeveloped land is developed (Bounoua et al. 2018). Habitat fragmentation and loss substantially threaten wildlife habitat and animal survival, likely decreasing species recruitment (Oliver de la Esperanza et al. 2017).

The total human population in Florida has increased by 15% since 2010 (https://www.census.gov/quickfacts/fact/table/FL/PST045222), with the highest population density and subsequent development occurring on or near the coast of the state. Humans are encroaching on places critical to the life cycle of Loggerhead Sea Turtles (*Caretta caretta*). The Florida coastline accounts for 90% of all sea turtles nesting in the U.S. (Ceriani and Meylan 2017). In fact, the most significant Loggerhead Sea Turtle nesting grounds in the western hemisphere are on the Florida coast (National Marine Fisheries Service and U.S. Fish and Wildlife Service 2008), making these beaches essential for continued sea turtle nesting and population recruitment. Additionally, the endangered Loggerhead Sea Turtles are crucial to the ecosystem by contributing to benthic invertebrate population control and boosting the rate of nutrient recycling on the ocean floor as they consume mollusks, crustaceans, and other shelled species (Heithaus 2013). Sea turtles also contribute to nutrient cycling on nesting beaches by digging, displacing, and depositing organic matter (unhatched eggs or underdeveloped hatchlings) in the sand (Bouchard and Bjorndal 2000). Sea turtles are charismatic megafauna that attract tourists from around the world to the shores of Florida, assisting the economy through ecotourism and acting as environmental liaisons (Mendez et al. 2019).

Coastal nesting habitat, fundamental to the persistence of Loggerhead Sea Turtle populations (Fuentes et al. 2016), is increasingly at risk as global shores are developed, reducing the amount of suitable nesting habitat (Nelson Sella and Fuentes 2019) and associated lower nesting and hatching success (Oliver de la Esperanza et al. 2017). The increase in coastal infrastructure can affect sea turtle nesting, causing nesting abandonment as a direct consequence of the proximity of nocturnal human presence (Drobes et al. 2019). Reduced available nesting habitat also increases the risk of nest destruction by other nesting females, predators, and microbes (Fowler 1979; Tiwari et al. 2006) and the likelihood of predation impacting recruitment (Engeman et al. 2016).

Many predators can locate and successfully prey on sea turtle eggs with minimal energetic costs or risks, jeopardizing survival of sea turtle hatchlings (Leighton et al. 2009; Burger and Gochfeld 2014). The most resourceful predators may repeatedly consume multiple sea turtle eggs and hatchlings within a nesting season, decreasing the number of live hatchlings that leave these nests or make it to the waterline (Stancyk et al. 1980; Barton and Roth 2007). Over time, predation can substantially reduce population growth and hinder sea turtle recovery efforts (Butler et al. 2020). Additionally, nocturnal predators are adept at hunting hatchlings, and predation rates are significantly higher at night, when hatchlings emerge, than during the day (Martins et al. 2021). Historically, high predation rates of hatchlings in Florida are attributed to Northern Raccoons (*Procyon lotor*), Ghost Crabs (*Ocypode quadrata*), Nine-banded Armadillos (*Dasypus novemcinctus*), Coyotes (*Canis latrans*), Red Foxes (*Vulpes vulpes*), Feral Pigs (*Sus scrofa*), and Dogs (*Canis familiaris*), all of which are primarily nocturnal predators (Peterson et al. 2012; Marco et al. 2015; O'Connor et al. 2017; Pheasey et al. 2018; Martins et al. 2022).

Some of the most resourceful predators of sea turtle nests are mammalian predators, which rely primarily on smell to locate eggs (Stancyk et al. 1980; Cornelius 1986; Lamarre-DeJesus and Griffin 2015). Specifically, nocturnal predators use this olfactory cue effectively to detect nests (Lamarre-DeJesus and Griffin 2015). Northern Raccoons are an endemic species to the southeastern U.S. that prey on sea turtle hatchlings and eggs and have been documented consuming up to 96% of eggs in Loggerhead Sea Turtle nests (Stancyk et al. 1980; Hopkins and Murphy 1982). Over the last decade, the loss of sea turtle nests caused by raccoon predation rivals egg losses from high tides and storms (Butler et al. 2020).

On nesting beaches, some predation mitigation methods that are specific to the predator can be effective. Rarely is there one method that effectively stops all predators. For example, applying caging over sea turtle nests has significantly deterred large canines and lizards but appears ineffective in eliminating feral pig predation (Lei and Booth 2017, 2018). Removal of Northern Raccoons varies in success and cost by location (Ratnaswamy et al. 1997; Garmestani and Percival 2005). Conditioned taste/food aversion methods aimed at changing raccoon behavior to avoid nests also vary in success between the wild (unsuccessful; Ratnaswamy et al. 1997) and controlled settings (successful; Duesser et al. 2018). Wire and plastic cages effectively prevent predation by Northern Raccoons and Red Foxes for an acceptably small price per unit (Kurz et al. 2011). A significant drawback is that the implementation of metal caging has been shown to alter the local magnetic field of the developing eggs and, therefore, can cause changes in the magnetic orientation and navigation behavior of hatchlings (Irwin et al. 2004). Plastic caging effectively reduces Coyote predation events, but further research is required to investigate efficacious methods of reducing Northern Raccoon predation (Lovemore et al. 2020). A downside to plastic caging, more so than metal caging, is that it can contribute to marine debris during high tide and storm events (Kurz et al. 2011). Because managing predation can dramatically improve marine turtle nesting success on Florida beaches (Engeman et al. 2005, 2016), researchers continue to develop and study the pros and cons of various predator management techniques. Although it is established that predator presence reduces sea turtle hatchling survival, anthropogenic variables that significantly affect the predation rates of sea turtle nests are not well studied.

For our primary goal, we investigated the extent to which building density and beach proximity resulted in differential hatchling mortality and predation rates on two high predation beaches in the Gulf of Mexico: Longboat Key and Casey Key, Florida. For our secondary objective, we assessed the effectiveness of the predation mitigation technique (specifically nest caging) on these beaches. We identified if building density and proximity affected the efficacy of caging. Our results provide beach and conservation managers and public policymakers with critical information about predators in developed environments to aid in designing and deploying management strategies.

Materials and Methods

Study area.—The Sea Turtle Conservation and Research Program (STCRP) of the Mote Marine Laboratory has been monitoring sea turtle nesting on beaches in the Sarasota, Florida region, USA, since 1982. Volunteers, staff, and interns from STCRP collect nesting data on 35 miles of beaches annually, including our two study sites: Longboat Key and Casey

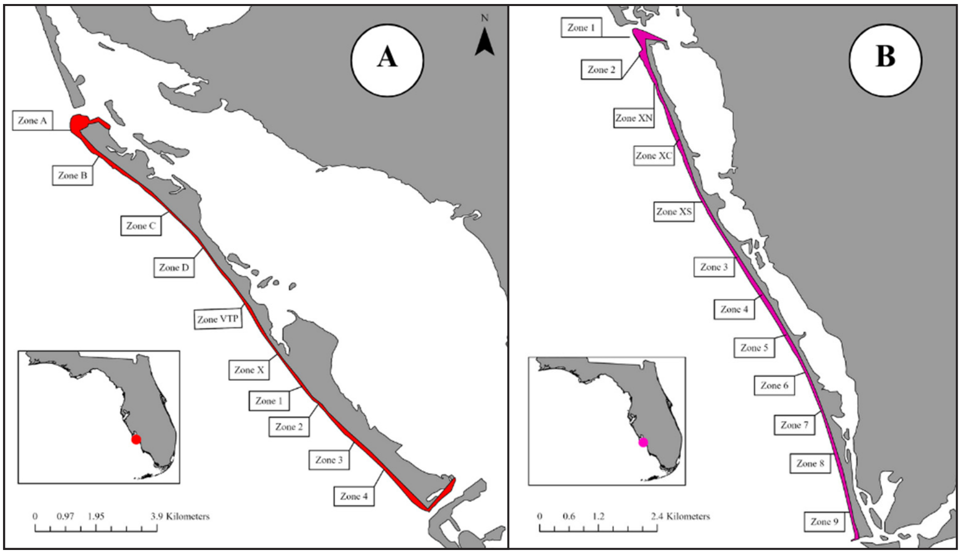

Figure 1. Island divisions (zones) used for Sea Turtle monitoring by the Mote Marine Laboratory on (A) Longboat Key and (B) Casey Key, Florida, USA.

Key (Appendix A). Longboat Key was an island characterized by high-rise buildings and multiple-family homes/condominiums with multiple public beach access points (Fig. 1). The north portion of the island is in Manatee County, and the southern portion is in Sarasota County, though no physical separation exists between the two counties on the island. The second site is Casey Key, which is entirely within Sarasota County (Fig 1). Unlike Longboat Key, Casey Key was characterized by large, single-family homes, and most of the beach was only accessible by private property. We divided both islands into zones to track daily patrols (Fig. 1).

Nest and predation counts.—Personnel of STCRP patrolled the beach prior to sunrise at civil twilight to identify sea turtle nests, false crawls, predator activity, and hatching events. Patrollers identified sea turtle tracks by species and verified nesting events using methods established by the Florida Fish and Wildlife Conservation Commission (Florida Fish and Wildlife Commission 2016). From 1982–2012, personnel of STCRP monitored and inventoried all nests laid in Sarasota County annually. Starting in 2013, however, the monitoring schema was changed to count and identify every false crawl and nest but only to monitor and inventory a subset of those nests. The sea turtle population grew too fast to inventory every nest effectively. We only analyzed monitored nests from 2010–2020 and excluded 2013 during the transition to account for this change. We define a false crawl as the result of an abandoned nesting attempt (a non-nesting crawl; Florida Fish and Wildlife Commission 2016). A predation event is when a predator digs into the egg chamber of the nest and brings hatchlings and/or eggs to the beach surface (Florida Fish and Wildlife Commission 2016) as predators often eat the contents of nests or leave remnants of eggs and dead hatchlings on the surface near the nest. Patrollers for STRCP determined the type of predator by their track type and style of digging and eating (Appendix B). We define an observed emergence as an event in which a patroller observes the presence of more than one hatchling track from a nest. It is important to note that occasionally patrollers might have missed hatchling emergences when tracks were not visible (e.g., because rain washed away the tracks).

Caging.—Patrollers from STCRP caged a subset of monitored nests to prevent predation by placing a metal wire box over the nest. Administrators of the Mote Marine Laboratory changed caging protocols over the course of the study. At the beginning of the study (2010–2017), personnel caged nests after an initial predation event if at least 10 eggs remained in the nest. Before 2018, caging was primarily based on existing predator activity, where nests were left uncaged until a predator found them. Some places were preemptively caged, however, such as Casey Key Zone 1–XS in 2010. Several zones were preemptively caged throughout Casey Key in 2011 and 2012, but this was case-by-case. Patrollers of STCRP employed unique protocols in 2013. Therefore, this study excluded data from 2013. From 2013 on, there were very few preemptive caging on Loggerhead Sea Turtle nests due to limited resources. Starting in 2018, patrollers stopped caging after depredation and instead preemptively caged only in areas where it was feasible (Zone XN for this study). Nests in most areas were no

Table 1. Caging of nests of Loggerhead Sea Turtles (*Caretta caretta*) differed throughout the study period on the two study sites: Longboat Key (LBK) and Casey Key (CK), Florida, USA. Caging was usually implemented after the first predation event.

Time Caged	Year	Key	Comment
After First Predation Event	2010–2012	CK and LBK	All nests were monitored.
	2013–2015	LBK	Nests laid on Wednesdays, and any nests monitored for nourishment projects (varied by year and in quantity).
	2016–2020	LBK	Nests laid on Wednesdays and Saturdays, and any nests monitored for nourishment projects (varied by year and in quantity).
	2013–2020	CK	Nests laid on Wednesdays, and any nests monitored for nourishment projects (varied by year and in quantity).
No Cages	2018	CK and LBK	No cages were applied.
The Morning After Deposition	2019–2020	CK Zone XN	Remote experienced higher predation in the year prior.

longer caged, while nests in some locations were all caged on the morning after egg deposition, regardless of whether predation occurred (Table 1). Cages were self-releasing, so hatchlings could exit through mesh holes without assistance. By 2019, the only area that people caged before predation was zone XN on Casey Key due to its inaccessibility to patrollers and the observed increase in predation (Table 1).

***Statistical analyses*.**—We completed all analyses using ArcGIS (version 10.7.1; Esri, Redlands, California, USA) and R Statistics (version 4.1.3; R Development Core Team 2020). We mapped nest GPS locations that were preyed on and used these points to generate heat maps, a two-dimensional representation of data in which various values are represented by color. In our heat maps, purple represents an area with no nests preyed upon by predators, and yellow represents an area with a dense aggregation of nests that were preyed upon more than once. We georeferenced Longboat Key and Casey Key buildings using the NAD 1983 2011 Florida Albers projection (Fig. 2). We created urban-density shapefiles by characterizing the building heights as referenced by the Manatee County and Sarasota County Appraiser Offices (https://www.sc-pa.com/downloads/download-data/ [Accessed 15 October 2020]). Then, we generated building categories as either single-family detached, low-rise condominiums (one to three stories), mid-rise condominiums (four to six stories), or high-rise condominiums (seven or more stories) according

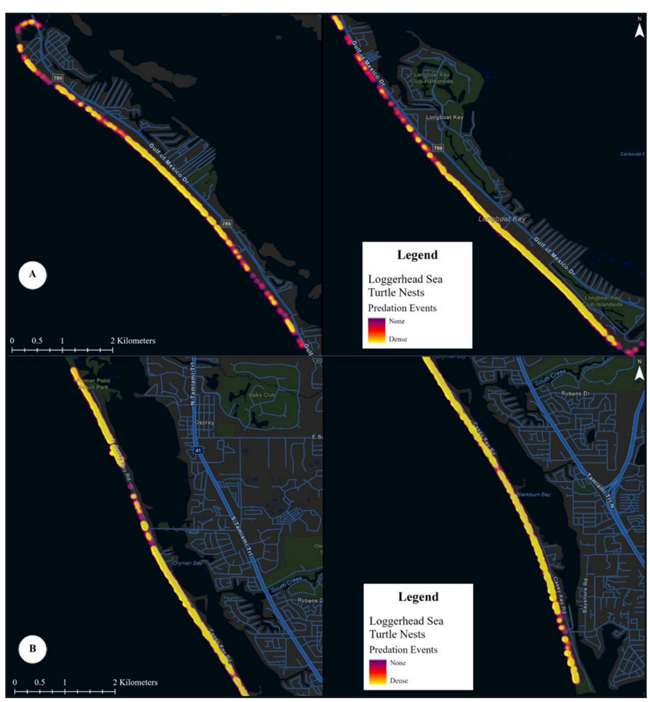

Figure 2. Hot spots analysis of Loggerhead Sea Turtle (*Caretta caretta*) nest predation at (A) Longboat Key and (B) Casey Key, Florida, USA, during 2010–2020. Denser predation is indicated in yellow; lower or no predation is shown in red and purple. The left panes display a detailed view of the northern portion of the islands, and the right panes display a detailed view of the southern portions.

to existing Manatee County and Sarasota County zone district designations (Available from https://longboatkey.maps.arcgis.com/apps/webappviewer/index.html?id=b93cd164a2e64ecb9fb858983293d8ed [Accessed 15 October 2020]). It is important to note that we did not characterize properties by the length of the rental term. We found it difficult to accurately identify and isolate short-term vacation rental properties from longer-term occupations. Most properties did not have documentation on whether the property was short-term; less than a hundred properties (about 10%) fell under this category. We used county appraiser data on the number of stories in the buildings in the study areas.

We used the number of floors as a proxy for the number of inhabitants in the building. We assumed that a building with more inhabitants would produce more waste than a single-family home. Additionally, we assumed that buildings with numerous inhabitants would have centralized waste receptacles that could attract raccoons to the area for foraging. We added nesting data from 2010 to 2020 as separate years and used the inverse distance weighted (IDW) tool in ArcGIS to create a heatmap of predation events (high predation is yellow, low predation is red to purple; Fig. 2). We used the IDW tool to extrapolate between known nest sites and assign values to unknown points by calculating a weighted average of the values available at the known points to predict areas that experienced high predation rates each year. In ArcGIS, we used the Optimized Hot Spot Analysis tool to consider the building attributes. This tool creates a map of statistically significant hot (areas of high predation rates) and cold spots (areas of low predation rates) using the Getis-Ord Gi* statistic (Getis and Ord 1992) by evaluating the characteristics of a set of variables; here the number of floors per building and the distance of each nest to the closest building, to produce the hot spots of predation on each key.

We tested all data for normality using Shapiro-Wilk tests and performed an additive Generalized Linear Model (GLM) using a binomial distribution to assess which variables statistically explained predation frequency. The binomial distribution was used because we recorded predation as an all (1) or none (0) quantification. We compared the models using the Akaike's Information Criterion (AIC) with the difference between the best model and other models (ΔAIC) to identify the best-fitting model (Hu et al. 2018). The number of predation events was the dependent variable for the first set of models, and the independent variables were the beach (Longboat Key or Casey Key), the number of floors (1–7+), the distance to the closest building (all buildings in this study were within 8 km of the nearest building), and the year the nest was laid (2010–2020). The second set of models assessed the effect of predation on the observed emergence if the nest was caged. In this case, the dependent variable was observed emergence, defined as at least one visible hatchling track (0 or 1). Predation (presence or absence) was an independent variable, and whether the cage was placed over the nest before (1) or after (2) a predation event. The final model examined how different types of predators affected observed emergence when caging was employed. The dependent variable was observed emergence, and the independent variables were the predator type and the total number of days the cage was in place.

Table 2. GLM and results for Loggerhead Sea Turtle (*Caretta caretta*) nest predation at Longboat Key and Casey Key, Florida, USA.

Parameter	Estimate	Standard Error	Z-Value	P-value
Distance to Closest Building	13.6727	2.4594	5.56	< 0.001
Key	-0.1847	0.0445	-4.15	< 0.001
Floors	0.2163	0.0099	21.76	< 0.001
Year	0.0077	0.0008	9.72	< 0.001

Results

Predation trends.—Over our study (2010–2020), personnel of STCRP documented 13,886 Loggerhead Sea Turtle nests on Casey Key and 8,929 on Longboat Key. Our Shapiro-Wilk test showed that the predation data were not normal (W = 0.83768, df = 21,280, P < 0.001), and all tests we ran were non-parametric. The proportion of nests with predation events differed significantly between sites (Z = -4.148, df = 21,280, P < 0.001; Table 2), with a slightly higher predation rate occurring on Casey Key than on Longboat Key (17.83% to 15.94%, respectively; Fig. 3). Predation was not evenly distributed along the available beach on Longboat Key. Instead, sections (Zones 3 and 4) consisting of only 28% of the total beach contained more than half (57 %) of the annual predation of nests on the island. These sections of the beach on Longboat Key were characterized by dense groupings of high-rise condominiums (Fig. 2). Northern Raccoons accounted for 99% of the predation in these areas. Regions with single-family homes on Longboat Key had a lower predation density (Fig. 2).

On Casey Key, predation increased throughout the study (from 8.13% in 2010 to 15.23% in 2020). Unlike Longboat Key, predation hotspots did not overlap with multi-family homes (Fig. 2). There were more predators on Casey Key than on Longboat Key: on Casey Key, in order of prevalence, we recorded Nine-banded Armadillos (68%), Northern Raccoons (29%), domestic dogs (< 1%), Red Foxes (< 1%), and Coyotes (< 1%) as predators.

The best-fitting GLM model included interactions of all variables (distance to closest building, beach, number

Table 3. Summary of the top seven models evaluating predation on Loggerhead Sea Turtle (*Caretta caretta*) from Longboat Key and Casey Key, Florida, USA. All df values were 21,280.

Model	AIC	ΔAIC	AICc Weights	# Parameters	QDeviance
Distance to Closest Building + Key + Floors + Year	19,228	0	1.00	16	19202
Floors + Year	19,284	55	< 0.001	14	19261
Key + Floors	19,468	94	< 0.001	10	19461
Distance to Closest Building + Floors	19,493	119	< 0.001	6	19486
Key + Year	19,728	503	< 0.001	10	19706
Distance to Closest Building + Year	19,727	505	< 0.001	10	19705
Distance to Closest Building + Key	19,945	571	< 0.001	2	19939

of floors, and year; Table 3). All variables significantly affected sea turtle nest predation (Fig. 3, Table 2). Nests laid farther from buildings were more likely to be preyed upon. On both islands, nests had a significantly higher chance of predation during the later years of the study period (2016–2020: 20%) than at the beginning (2010–2015: 15%; $Z = 9.591$, df = 21,280, $P < 0.001$, Fig. 3). The distance of nests from the closest buildings had a significant effect on predation probability ($Z = 5.56$, df = 21,280, $P < 0.001$, Fig. 3). Overall, the number of floors in the closest building had the most significant effect on predation probability ($Z = 21.758$, df = 21,280, $P < 0.001$, Fig. 3). Nests closest to buildings over six stories had a 30% rate of predation ($Z = 21.758$, df = 21,280, $P < 0.001$, Fig. 3).

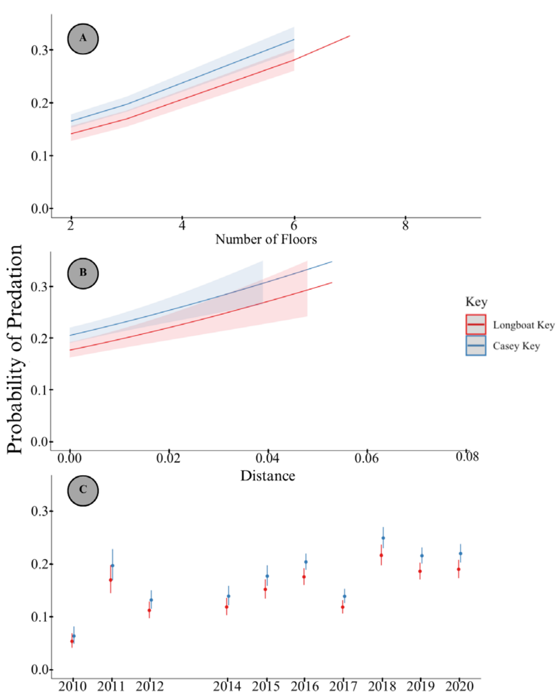

Figure 3. Relationship of building variable and predation events on Loggerhead Sea Turtle (*Caretta caretta*) at Casey Key (blue) and Longboat Key (red), Florida, USA, with 95% CI error bars. (A) Probability of predation in relation to the number of floors in surrounding buildings. (B) Probability of predation in relation to the distance to the closest building. (C) Probability of predation by year of study.

***Caging effect*.**—Caging had a slightly positive effect on observed emergence rates; caged nests had a significantly higher likelihood of observed emergence than nests that were not caged ($Z = 7.272$, df = 21,280, $P < 0.001$, Fig. 4, Table 4). Further, nests caged after egg deposition had a slightly higher observed emergence rate (49%) than nests that were caged after the first predation event (37%) and compared to all nests (42%). Still, the difference was not significant (Fig. 4, Table 4).

Regardless of location, there was a significant difference in observed emergence depending on the predator (Fig. 4). When a nest was not preyed on, or if animals other than raccoons and armadillos preyed on a nest, there was a high observed emergence rate (50%). When a nest only had Northern Raccoons as predators,

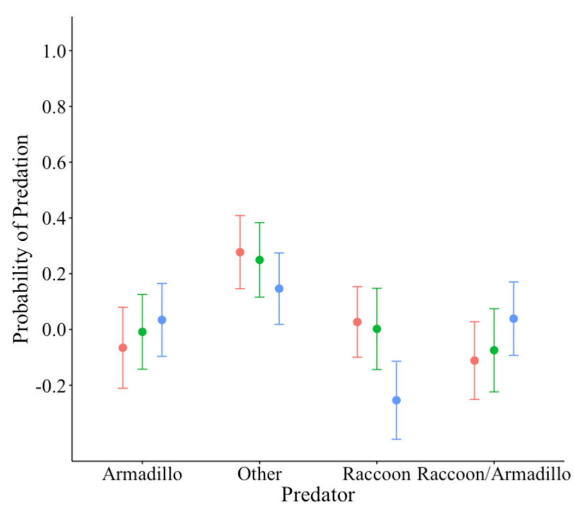

Figure 4. Predator type and observed Loggerhead Sea Turtle (*Caretta caretta*) emergence probability. Results of a Generalized Linear Model of predator type and observed emergence (see methods) at Casey Key and Longboat Key, Florida, USA, with standard error. Orange dots and lines are cages set over nests after first predation event, green for the morning after egg deposition, and blue when no cages were used over nests.

Table 4. Generalized linear model (GLM) results for Loggerhead Sea Turtle (*Caretta caretta*) nest observed emergence by cage timing and predator type at Longboat Key and Casey Key, Florida, USA.

Parameter-Predator and Cage Scenarios	Estimate	Std. Error	*t*-value	Pr(>|t|)
Raccoon/Armadillo	-0.262	0.252	-0.104	0.300
Predator: Other	0.575	0.177	3.228	0.001
Raccoon	0.571	0.148	3.860	< 0.001
Caged (all predator types)	-0.228	0.187	-1.211	0.294
Raccoon/Armadillo; Caged after 1st predation	0.823	0.420	1.960	0.050
Predator Other; Caged after 1st predation	0.058	0.315	0.184	0.854
Raccoon: Caged after 1st predation	0.070	0.210	0.333	0.739
Raccoon/Armadillo: Caged after egg deposition	-0.942	1.161	-0.812	0.073
Predator Other: Caged after egg deposition	-0.680	0.991	-0.687	0.492
Raccoon: Caged after egg deposition	-1.041	0.888	-1.172	0.241

observed emergence rates were significantly lower than nests preyed upon by other predators (Z = 3.86, df = 21,280, P < 0.001, Fig. 4). Nests caged after egg deposition had a higher chance of observed emergence regardless of the predator. Nests with no predation and those with cages placed the day the nest was laid had the highest probability of observed emergence (> 70%). Nests caged after Northern Raccoon predation had a 40% rate of observed emergence, and finally, nests caged after Nine-banded Armadillo predation had a 30% rate of observed emergence (Fig. 4).

Discussion

Predation trends.—All buildings in this study were within 8 km of sea turtle nests. We found that sea turtle nests laid 200–400 m further from the closest building (of any height) were more likely to be preyed on than those closer to buildings, and nests within 8 km of taller buildings (more than four floors) were more likely to be preyed on. We found that the number of floors (building height) was a more significant predictor of predation than the proximity of the nest to the closest building. Even though these findings may appear contradictory, a reasonable assumption can be made that predators prefer to be near human food waste (located in waste receptacles) but do not want to be in the physical presence of humans themselves. Although the effect of artificial light has not been tested on our study sites, presumably high levels of artificial light cause higher disorientation rates of hatchlings (e.g., Weishampel et al. 2016; Dimitriadis et al. 2018), possibly exposing them to predators for a more extended period of time, and therefore nests further from any building but within the viewshed of the artificial light from the building will be more likely to be preyed on.

Northern Raccoons are destructive predators (Barton and Roth 2007), accounting for more nests destroyed and more eggs lost per nest than Nine-banded Armadillos and other predators in Florida (Leighton et al. 2010; Butler et al. 2020). In this study, the predation rate was higher the closer a nest was laid to tall buildings (within 8 km). Presumably, human physical presence deters predator presence if nests are very close to a building (thus why nests laid even 200–400 m or more from any building had higher predation compared to those within 200 m). Future studies of sea turtle nesting should determine if and how human behavior discourages predator presence. Previous studies have shown Northern Raccoons near sea turtle nesting beaches in Florida have carbon signatures corresponding with human foods derived from corn (C4 plants) and the carbon signature of predatory food sources (e.g., sea turtle hatchlings; Nicholson and Cove 2022). Although Northern Raccoons have been observed preying on sea turtle nests (Kotera and Phillot 2020), it is unknown if, during sea turtle nesting season, sea turtle eggs are their primary food source or if they are a dietary supplement. Future camera trap studies could identify the minimum proximity to humans Northern Raccoons are willing to risk for food and whether they prefer sea turtle nests or human refuse during sea turtle nesting season. To implement human behavioral changes, subsequent studies should focus on the effect of secure and remote dumpsters near sea turtle nesting beaches on populations of Northern Raccoons and the eventual consequences for sea turtle populations. Wildlife-resistant dumpsters and frequent garbage pickup near nesting beaches could deplete Northern Raccoon and other predator food when sea turtle eggs are unavailable and potentially decrease predator populations.

Artificial lighting and disorientation.—In addition to garbage accumulation, high occupancy buildings can have other impacts on the beach, including introducing artificial lighting. Artificial light can impact sea turtle nesting behavior and hatchling orientation. Loggerhead Sea Turtle nest density is negatively affected by higher artificial light levels at the individual beach scale (approximately 1 km; Weishampel et al. 2016). Barrett and Nelson Sella (2022) modeled viewsheds of light visibility at different heights of dune vegetation and determined that even the tallest vegetation does not block out the lighting from the mid and upper floors. Dunes in Sarasota County rarely have high vegetation and likely provide little cover to the beach from artificial light. Further, these viewshed models provide evidence that artificial light from the upper floors of buildings affects a higher proportion of the beach and, therefore, a higher proportion of sea turtle nest sites (11.5–88.9%) than mid-story (3.5–55.6%) and ground-level buildings (0.2–4.3%; Barrett and Nelson Sella 2022). Artificial light pollution can reduce the hatchling survival rate by > 7% and can significantly affect hatchling seaward orientation (Dimitriadis et al. 2018). Nests farther away from buildings may have increased light exposure (though presumably, there is a maximum distance where this is true), resulting in higher disorientation rates and exposing hatchlings to predators for a prolonged period. Longboat Key likely had more artificial light exposure because Longboat Key has a higher density of high-rise condos with little shielding of artificial light compared to Casey Key and had a higher rate of nests with disorientation at 16.95% compared to the 1.5% of nests with disorientation on Casey Key (unpubl. data). Subsequent investigation is needed to understand better the role of artificial lighting in the mammalian predation of sea turtle nests and distances from all buildings, especially in conjunction with effects on hatchling orientation.

Predator trends.—Over the course of this study (2010–2020), predation rates of sea turtle nests increased, with the largest predation rates in 2016–2020. Of all the monitored nests on Longboat Key and Casey Key, 22% were preyed on in 2020. Biologists at STCRP adjusted the caging protocols over the course of the study to decrease predation rates as more nests were laid; however, as predator surveys were not conducted, it is unknown if the population sizes of the predators grew over this timeframe. It is possible that the increase in the number of nests laid provided more options for the same opportunistic predators but did not entice a higher number of predators. Northern Raccoon population size remained stable over six years (1992–1998) in an undisturbed habitat in central Florida (Troyer et al. 2014). Further, Garmestani and Percival (2005) noted that after the removal of Northern Raccoons from an insular beach, raccoons from other islands did not move in. Forthcoming studies should add a component of mark-recapture or removal to quantify and monitor predator populations to determine if predator populations are growing in our study area.

Caging.—Caged Loggerhead Sea Turtle nests had an average emergence success of 60%, which was higher than the nearly 52% observed emergence rate found in previous studies of Florida Loggerhead Sea Turtles (Brost et al. 2015; unpubl. data). When cages were placed on nests, we found that observed emergence was significantly higher than when no cages were installed. Nests caged the morning after the nest was laid and before any predator activity was observed had a higher observed emergence rate than those caged after the first predation event, consistent with findings of other studies (Wauson and Rogers 2021). Caging of nests is most efficacious when implemented directly after egg deposition. Even though the observed emergence rates varied the most among nests preyed on by Northern Raccoons (867 of 1,666), nests caged at any point had a significantly higher observed emergence rate than nests not caged (50% vs. 40%).

While they positively impact observed emergence, caging nests are not the ideal or attainable solution for every beach. Nest density and labor are vital factors in determining the feasibility of a caging application. In 2022, over 4,300 Loggerhead Sea Turtle nests were laid on beaches surveyed by personnel of STCRP MML, and the nesting population of Loggerhead Sea Turtles in Sarasota County is significantly growing (Lasala et al. 2023). Caging all nests is not feasible regarding either time or labor costs. Caging and lethal removal of predators can be similar in cost. Caging material costs would be approximately $30,080 USD/y (or $7.52 USD/nest multiplied by 4,000 nests/y; Ratnaswamy et al. 1997; Pilcher et al. 2000; Garmestani and Percival 2005). Lethal predator removal costs would be roughly $28,200 USD/y (or $7.05 USD/nest multiplied by 4,000 nests/y; Ratnaswamy et al. 1997; Pilcher et al. 2000; Garmestani and Percival 2005). Previous studies have found that compared to lethal predator removal, caging significantly reduces the number of sea turtle nests preyed upon (Ratnaswamy et al. 1997; Pilcher et al. 2000; Garmestani and Percival 2005). In addition to the high cost of caging and predator removal, STCRP was unable, due to financial constraints, to keep up its monitoring and inventorying schema with the growing number of nests. Instead, as stated, in 2013, administrators of STCRP cut back its monitoring and inventorying to a subset of all counted nests. This reduced percentage of nests monitored resulted in a concomitant lack of predation data on unmonitored nests. Accordingly, estimates of monitored nests that experienced predation (number of eggs/hatchlings) could be underestimated. Understanding the scope of the loss of eggs and hatchlings (number of eggs lost to predation vs. number of hatched eggs) at each nest is important in quantifying the severity and threat of different predators. In the future, researchers should apply these methods to smaller-density nesting beaches to compare our findings.

Possible solutions.—As human settlement and development of U.S. coasts expand, we must consider the impact on species for whom the coasts are a critical element of their habitat and lifecycle. Human development and infrastructure significantly impact survival rates and predator-prey dynamics of endangered species. Turning to public action, thoughtful and robust waste management focusing on deterring Northern Raccoons year-round could mitigate harm to sea turtles on the island of Longboat Key. Robust waste management is particularly needed near high-density, high-rise buildings. Secure and wildlife-resistant waste receptacles may be a cost-effective and widespread solution that elegantly and indirectly increases sea turtle recruitment. If residents knew that small changes could reduce the number of raccoons, which would then mitigate harm to the charismatic Loggerhead Sea Turtle, they might be motivated to be a part of the solution. Caging is the best way to reduce predation rates on Loggerhead Sea Turtle nests. If possible, caging should be made a priority on all nests where predation is a significant threat (Whelan and Wynekan 2007) and nesting density is low enough. Legislation could help, such as new laws that would help to ensure the availability of the requisite funds and workforce. This could result in a significant reduction in egg and hatchling mortality.

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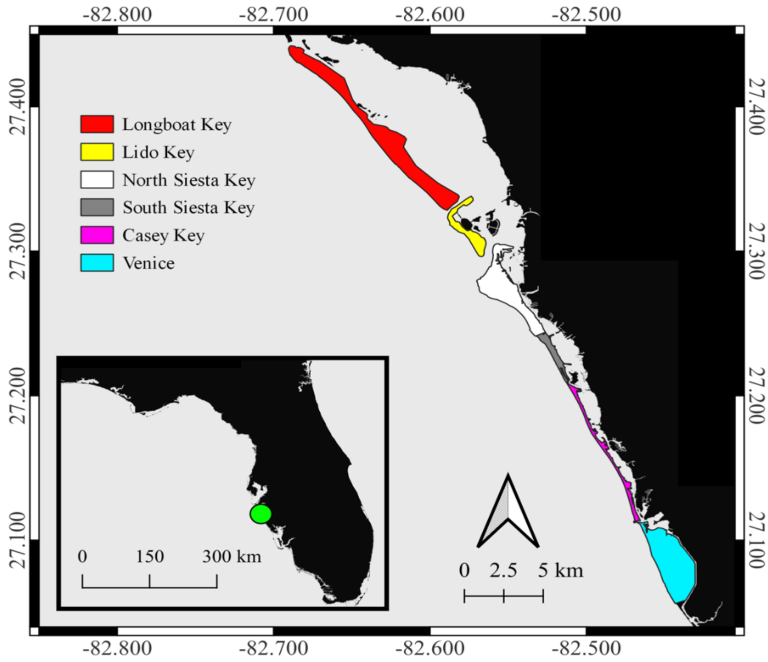
Appendices

Appendix A. Survey beaches of The Sea Turtle Conservation and Research Program (STCRP) of the Mote Marine Laboratory, Florida, USA.



Appendix B. Predator Tracks Index

Predator Identification Guide (courtesy of Mote Marine Laboratory STCRP Manual).

Raccoon

- Distinguishing track feature: Long fingers.
- Digging style: Like a human with small hands. Holes dug straight into the nest. The cage, if present, will often make several attempts to dig around it.
- Eating style: Yolks and hatchlings – cleans inside of eggs, rips yolk sacs off larger embryos, eats heads off hatchlings.
- Location of damage: Often makes small piles or creates lines of dropped eggs into the dunes. Contents not thrown, just dropped.

Coyote

- Distinguishing track feature: Dog-like.
- Digging style: Dog-like, digs from multiple sides and at an angle.
- Eating style: Yolks and hatchlings – cleans inside of eggs, eats the yolk and fluids from developing hatchlings, and eats hatchlings whole (very little blood or yolk at the nest site). Wounded hatchlings are rare. Many eggs are destroyed, but usually not total predation on the first hit.
- Location of damage: Often, "cleaned" eggshells outside of the nest cavity can be flung farther from the nest than is seen with other common predators. There can also be damaged eggs left within the nest that may not be readily visible because of sand falling back into the cavity. Secondary predators, like Crows, are often seen at Coyote predations.

Armadillo

- Distinguishing track feature: Includes S-shaped tail drag.
- Digging style: Long, deep burrows into the nest, usually at an angle. Sand is usually only thrown in one direction.
- Eating style: Prefers yolks – cleans inside of eggs, rips yolk sacs off larger embryos, will likely abandon predation attempt if live hatchlings are found.
- Location of damage: Often just as many destroyed eggs inside the nest as outside. Contents not thrown far from the nest.