Geospatial Analysis of Loggerhead Sea Turtle Hatchling Success: Do Buildings and Caging Alter Hatchling Mortality from Predators on the West Coast of Florida?

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ABSTRACT

My goal was to determine the role predation, caging and buildings have on Loggerhead sea turtle (*Caretta caretta*) nest hatching success. Predators, primarily raccoons and armadillos, can easily consume the majority of sea turtle eggs in a season, causing reduced recruitment of hatchlings and ultimately resulting in longer-term decreases in adult Loggerhead populations. Using Loggerhead nesting data collected by Mote Marine Laboratory from 2010-2020 on Longboat and Casey Keys, near Sarasota, Florida, I created a heat map indicating which spatial factors led to differential hatchling mortality. Nests further from building, nests near high-rises, nests on Casey Key, and nests found during later years of data collection (2018-2020) were more likely to be depredated. Caging of sea turtle nests before or after the first predation resulted in higher hatching rates than nests that were not caged. Hatching success was significantly higher in caged nests when there were raccoons, no predators or other predators. The findings of this study indicate that as more people move to the U.S. coast and develop these areas, important considerations must be made in relation to altering the natural habitat. Zoning and permits therefore have important repercussions on coastal species, particularly in the recruitment of sea turtles, as high-rises and buildings close to nests have been shown to have a negative effect on hatching success. In addition, the implementation of caging assists in sea turtle egg and hatchling survival and this management practice should be implemented everywhere Loggerhead nests occur.

KEYWORDS

Caretta caretta, Spatial Analysis, Predation mitigation, Nesting Behavior, and Florida

INTRODUCTION

In the United States over forty percent of the population lives along the nation's coasts (NOAA 2013). In the state of Florida, there has been a fifteen percent increase in the total population since 2010, with the highest population density and subsequent development occurring on or in the vicinity of the state's coast (U.S. Census 2019). Ninety percent of sea turtle nests in the United States are found on the Florida coasts and the largest number of *Caretta caretta*, Loggerhead sea turtle, nests in the western hemisphere are on the Floridian coast, making Florida essential to sea turtle nesting and recruitment (FWC 2015). As global coasts are increasingly developed and have been substantially altered, the amount of habitat suitable for nesting by sea turtles has been greatly reduced and consequently intensifying overall predation impacts (Engeman et al. 2016).

Sea turtle nests are especially vulnerable as predators can easily locate and successfully prey upon eggs with very minimal energetic costs or risks (Leighton et al. 2009). Predators can easily consume the majority of sea turtle eggs in a season, resulting in reduced recruitment of hatchlings and may ultimately result in longer-term decreases in the adult population (Stancyk 1995; Barton et al. 2007). The biggest predation rates in Florida are historically from raccoons, ghost crabs, armadillos, coyotes, foxes, feral pigs and dogs (Engeman et al. 2005; O'Conner et al. 2017; Pheasey et al. 2018). Raccoons are of special interest as the northern raccoons (*Procyon lotor*) can predate up to 96% of Loggerhead sea turtle nests on the southeastern United States coasts (Hopkins and Murphy 1982; Stancyk et al., 1980). Mammalian predators such as raccoons are believed to rely primarily on smell to locate eggs (Stancyk 1982; Cornelius 1986). Native raccoons have the greatest impact as predators on sea turtle eggs, resulting in losses similar in magnitude to post-management losses from tides and storms over the last decade (Butler et al. 2020).

Although it is established that predator presence decreases sea turtle recruitment, it is not well known what spatial variables subsidize predation of sea turtle nests. This study spans ten years of sea turtle nesting on Longboat Key and Casey Key, located near Sarasota Florida, where both of these islands are monitored by Mote Marine Laboratory (MML)'s Sea Turtle Conservation and Research Program (STCRP). This study aims to discover which physical attributes lead to differential hatchling mortality on Casey Key and Longboat Key. Longboat

Key is an island characterized by high rise buildings and multiple family homes. In comparison, Casey Key is characterized by large single-family homes and private beach access. In order to see the variables that increase raccoon predation, I will model building height/density, and caging technology vs. predation hotspots. I hypothesized that hotspots of predation will be positively correlated with high building density, high building height, and low caging percentage.

METHODS

Background

To establish coordinates of Loggerhead sea turtle nests and their condition, each year the MML volunteers, staff, and interns collect nesting data (STCRP database). Patrollers walk the beach at civil twilight flagging false crawls, depredation activity (depredations), and new nests. Then either staff, interns, or permitted volunteers go to the flagged activities and determine the activity type. Each permitted individual receives training on a correct assessment of activities and has supporting paperwork that they must bring on site. False crawls are the tracks of a sea turtle that has exited the ocean onto the beach but did not create a nest and then reenters the water. Depredations are when a predator, normally a small mammal, digs into the egg chamber of the nest and brings hatchlings/eggs to the surface of the beach. Most of the time predators eat the contents of eggs and parts of the hatchlings so that there are remains on the surface of the beach. The type of predator is identified by their track type (Appendix A).

My study sites are Longboat Key and Casey Key near Sarasota on the Southwest Coast of Florida, USA. Each key was divided into zones, in order to better organize nesting data and patrolling. The zones on Longboat Key (LBK) are zones 1, 2, 3, 4, X, VTP, A, B, C, and D. The zones on Casey Key are zones 1, 2, 3, 4, 5, 6, 7, 8, 9, XN, XC, and XS. All of the nests in this study were monitored nests, meaning that MML staff verified the nest location by digging to the surface of the highest egg. This study also includes nests that were caged, meaning that metal wiring is placed over the nest and rooted a few inches into the sand. In the years 2010 to 2012, every nest was caged on Longboat Key. After 2016, caging of nests occurred after the first depredation. In 2017 no cages were applied to Loggerhead nests except on LBK zones 3 & 4 and

Casey XN, XC, and XS where caging was applied after a depredation. In 2018-2020, no cages were applied to Loggerhead nests except for on Casey Key zone xn.

Analysis

I created a heat map of building heights using Google satellite imagery (Google Maps 2020) to create shapefiles in ArcGIS (ArcMap 2019) of each building on Longboat and Casey Key. I created my own shapefiles for urban density from satellite imagery, as the 30 m resolution of Landsat was too coarse. The GIS data were georeferenced to the NAD 1983-2011 Florida Albers projection and coordinate system. Once I created the shapefiles, I had to assign attributes to the buildings, including the number of floors and building type. To find building categorizations, I used the county appraiser website for Sarasota County, where Casey Key resides in and half of the Longboat Key resides in, and Manatee County, where half of Longboat Key resides in, to find building categorizations (Furst, Bill. 2020). I categorized the buildings as either, single-family detached, low rise condo (1-3 stories), mid-rise condos (4-6 stories), or high-rise condos (7+ stories) due to existing Sarasota and Manatee County zone district designations (Town of Longboat Key Zoning Lookup. 2020). Then I assigned the number of stories using the county appraiser websites, as some of the short-term vacation buildings were variable in height.

After I created the building shapefiles, I divided the MML nesting data into separate years to input into ArcGIS. I then used the IDW (inverse distance weighted) tool to create a heat map with regions of high predation in red, and regions of low predation in blue. The IDW tool was used because I had a known set of scattered points. The assigned values to unknown points were calculated with a weighted average of the values available at the known points. For the building attributes, I used the Optimized Hot Spot Analysis because polygons were created for each building. This tool took weighted features such as polygons and create a map of statistically significant hot and cold spots using the Getis-Ord Gi* statistic. It evaluates the characteristics of the input feature class to produce optimal results.

In addition, I ran generalized linear model (GLM) in R (R Core Team 2020), to understand which variables explain depredation frequency. A GLM is an extension of the traditional regression model that allows a linking function to relate a mean response variable to predictors in a linear combination. The probability distribution of the response variable Y can conform to an exponential distribution of family members. Y is assumed to be independently distributed. I used a generalized linear model because my data had a binomial distribution as many variables were defined as yes/no occurrences and this allowed for a count of number of "yes" occurrences out of N yes/no occurrences. This test also does not require a normal distribution. In this model, Depredation frequency (0, 1) was my independent variable, and Island (Nominal, categorical), Distance to the building (continuous), Number of Floors (Ordinal, categorical), and Year (Ordinal, categorical) were my dependent variables. I ran another GLM in R, to understand if caging effects hatching success, where Hatchling success (0,1) was my independent variable and Depredation (0,1) and Time caged (Nominal, categorical) were my dependent variables. Lastly, to understand the efficacy of caging differences on predators, I ran a GLM l where Hatchling success (0,1) was my independent variable and Predator type (Nominal, categorical) and Time caged (Nominal, categorical) were my dependent variables.

RESULTS

What explains depredation frequency?

Based on hot spots analysis, I found that there is more sea turtle nesting on Casey Key than on Longboat Key (Figures 1 and 2). On Longboat Key, zones 3 and 4 (3 miles out of the 16-mile-long island) each year accounts for over half of the predation on the entire island of Longboat Key. Zones 3 and 4 are characterized by dense groupings of high-rise condos, buildings over 6 floors (Figure 3). In zones 3 and 4 on Longboat Key, 99% of predators were raccoons. Regions on Longboat Key that are characterized by single family homes have lower predation density (Figure 4). Predation on Casey Key decreased over the years and currently predation is perpetrated mainly by armadillos (68%) followed by both raccoons (29%). Hotspots of predation on Casey Key do not overlap with multi-family homes like on Longboat (Figure 5). Casey Key also has many types of predators and predators other than raccoons and armadillos comprises a larger percentage of total predation as opposed to Longboat Key.

Through running a generalized linear model, I found that distance to buildings, key, the number of floors in the closest building, and year had a significant effect on sea turtle nest predation (Figures 3 and 6). Near distance to buildings (z value=5.383, $Pr(>|z|)= 7.33e-08$) had a negative effect on depredation probability, showing that nests further from buildings were more likely to be predated. Casey Key was shown to have higher rates of predation than Longboat Key, nests on Casey Key had a 17.4% chance of predation compared to 14.7% on Longboat Key (z value=-4.278, Pr(>|z|)= 1.89e-05) (Figure 6). The number of floors in the closest building to sea turtle nests had a negative effect on depredation probability, showing that nests closest to buildings over six stories had a 30% chance of predation (z value=21.843, Pr(>|z|)= < 2e-16) (Figure 7). The later years (2018-2020) in my study had higher predation odds than the earlier years (2010-2017), 2010 through 2015 had less than a 15% chance of predation and predation odds grew to over 20% in 2020 (z value=9.718, Pr(>|z|)==< 2e-16) (Figure 8).

Does caging affect hatching success?

Through running a GLM, I found that caging had a slightly positive effect on hatching probability, nests that were caged had a 50% chance of hatching while those that were not had a 40% chance of hatching (z value=7.272, Pr(>|z|)=3.53e-13) (Figure 9). I also found that caging before the first predation event on a nest, resulted in higher hatching success (Caged after: z value=4.718, Pr(>|z|)=2.38e-06; Caged before z value=9.759, Pr(>|z|) =< 2e-16) (Figure 10). Nests caged before the first predation event had a 70% chance of hatching compared to a 50% chance for nests that were caged after the first predation event and a 40% chance of hatching for all nests (Figure 11).

Does the efficacy of caging depend on predators?

From the GLM, I found that hatching success was significantly different when there was no predator (z value=3.001, Pr(>|z|)= 0.002695), predators other than armadillos and raccoons (z value=3.228, Pr(>|z|)= 0.001246) and racoons only (z value=3.860, Pr(>|z|)=0.000113). When there was no predator present or predators other than armadillos and raccoons, there was a high hatch success rate. When there were only raccoons present, hatch success rates were significantly lower (Figure 12). Nests that were caged before the first predation had a higher chance of hatching regardless of predator, while nests that had no predation and caging installed the day the nest was laid had the highest chance of hatching of over 70% while nests caged after a raccoon predation had a 40% chance of hatching and nests caged after an armadillo predation had a 30% chance of hatching. Nests that were caged before the first predation event varied greatly in the probability of hatching success for every predator.

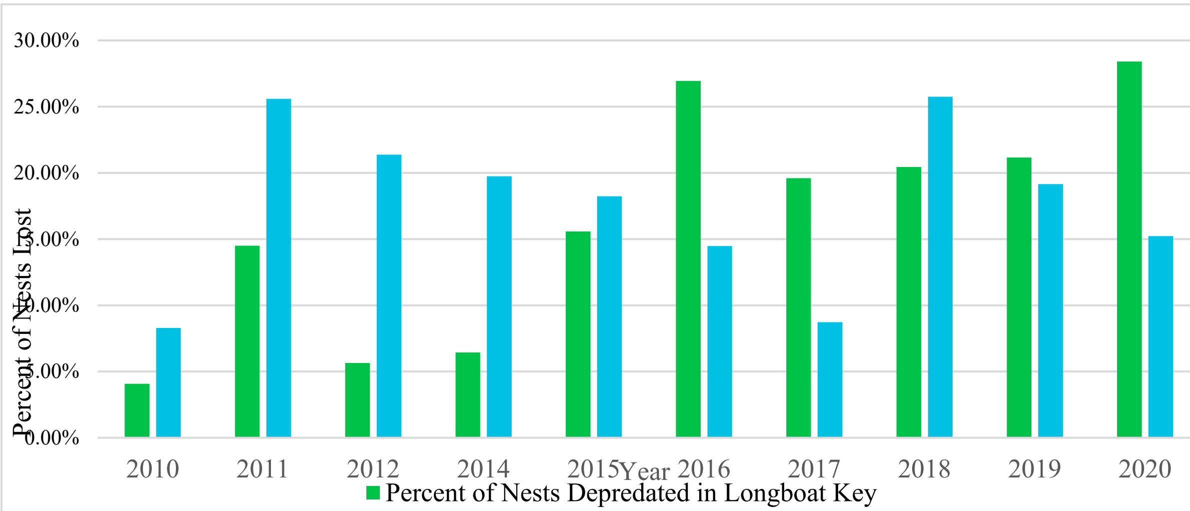

Figure 1. Percent of Nests Preyed On. Sea turtle nests were observed daily for predator activity from May 1st to October 31st, 2010-2020. Percent of nests preyed on was calculated from raw yearly data.

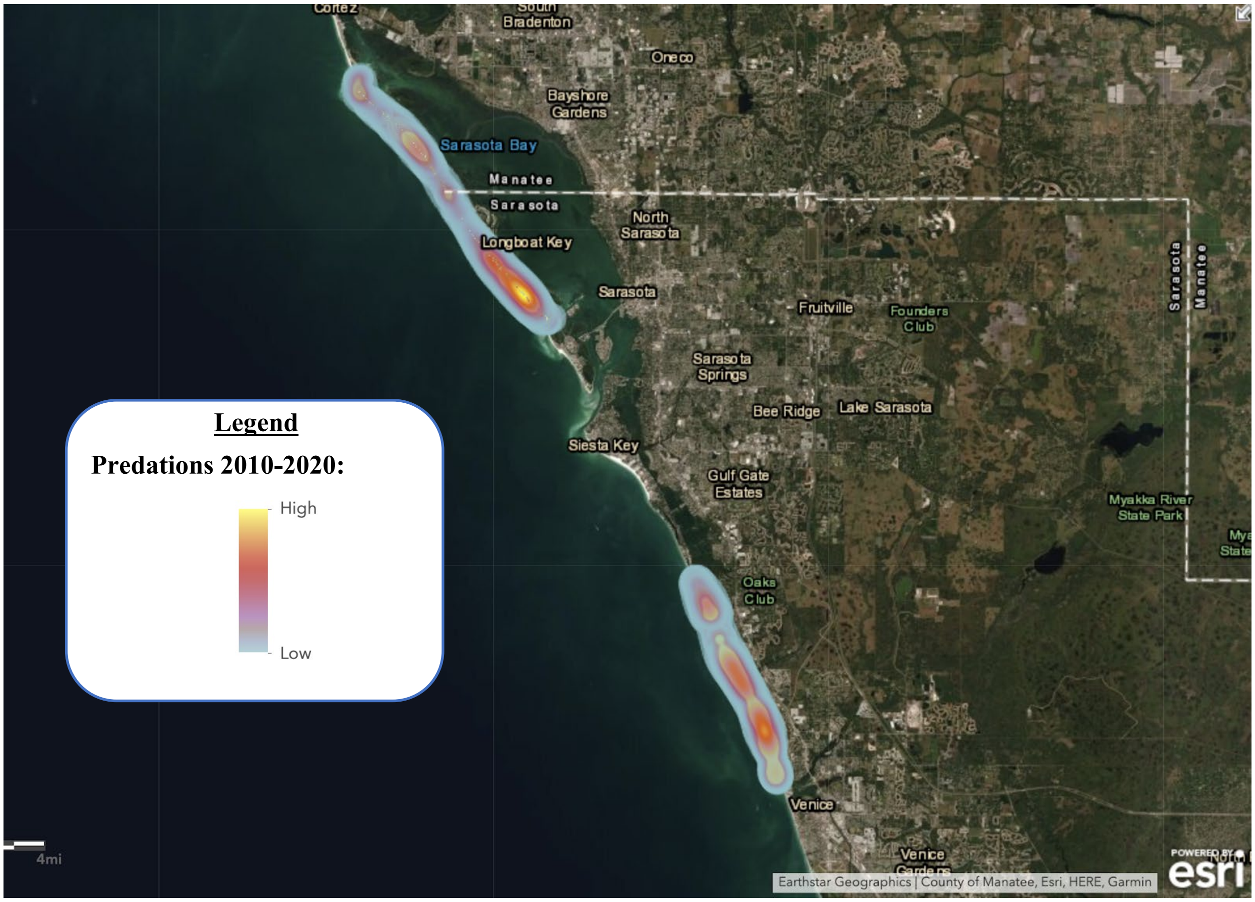

Figure 2. Predation Hotspots on Casey and Longboat Keys. Hot spots analysis of sea turtle nests that had predation events 2010-2020.

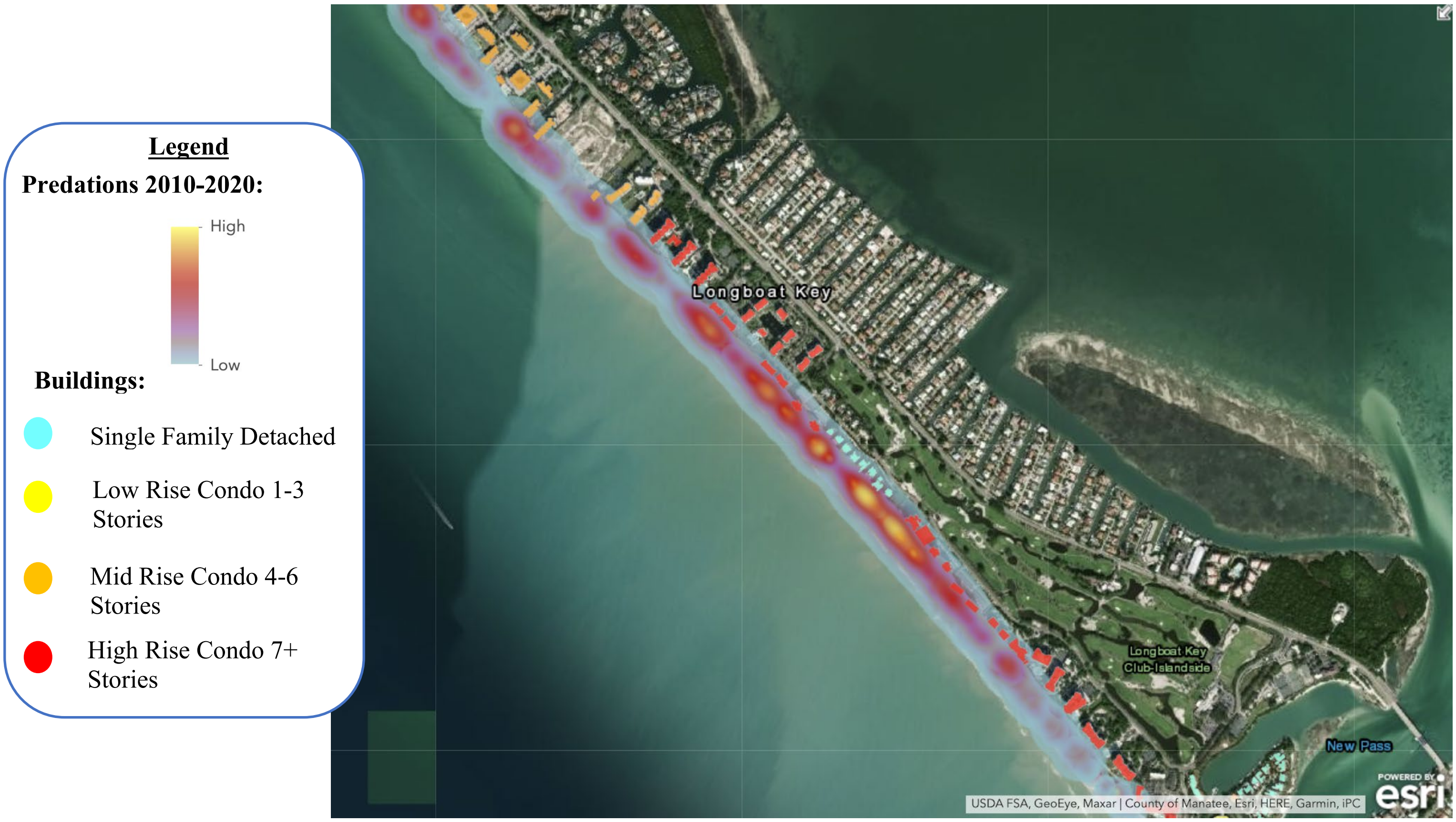

Figure 3. Predation Hotspots on Southern Part of Longboat Key. Hot spots analysis of sea turtle nests that were preyed on 2010-2020 and building types.

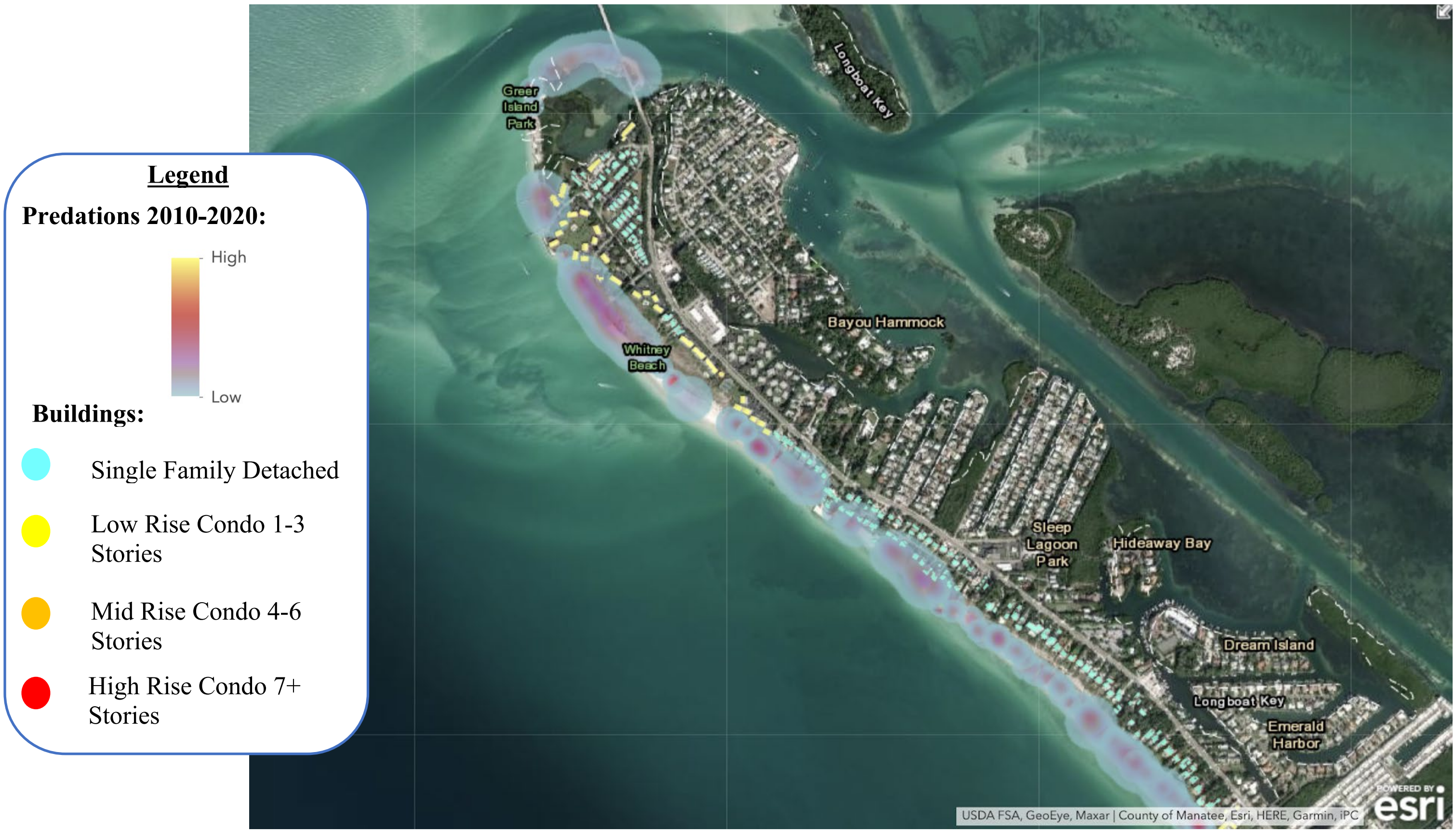

Figure 4. Low Predation Density on Northern Part of Longboat Key. Region of Longboat Key not defined by high predation, hot spots analysis of sea turtle nests that were preyed on 2010-2020 and building types.

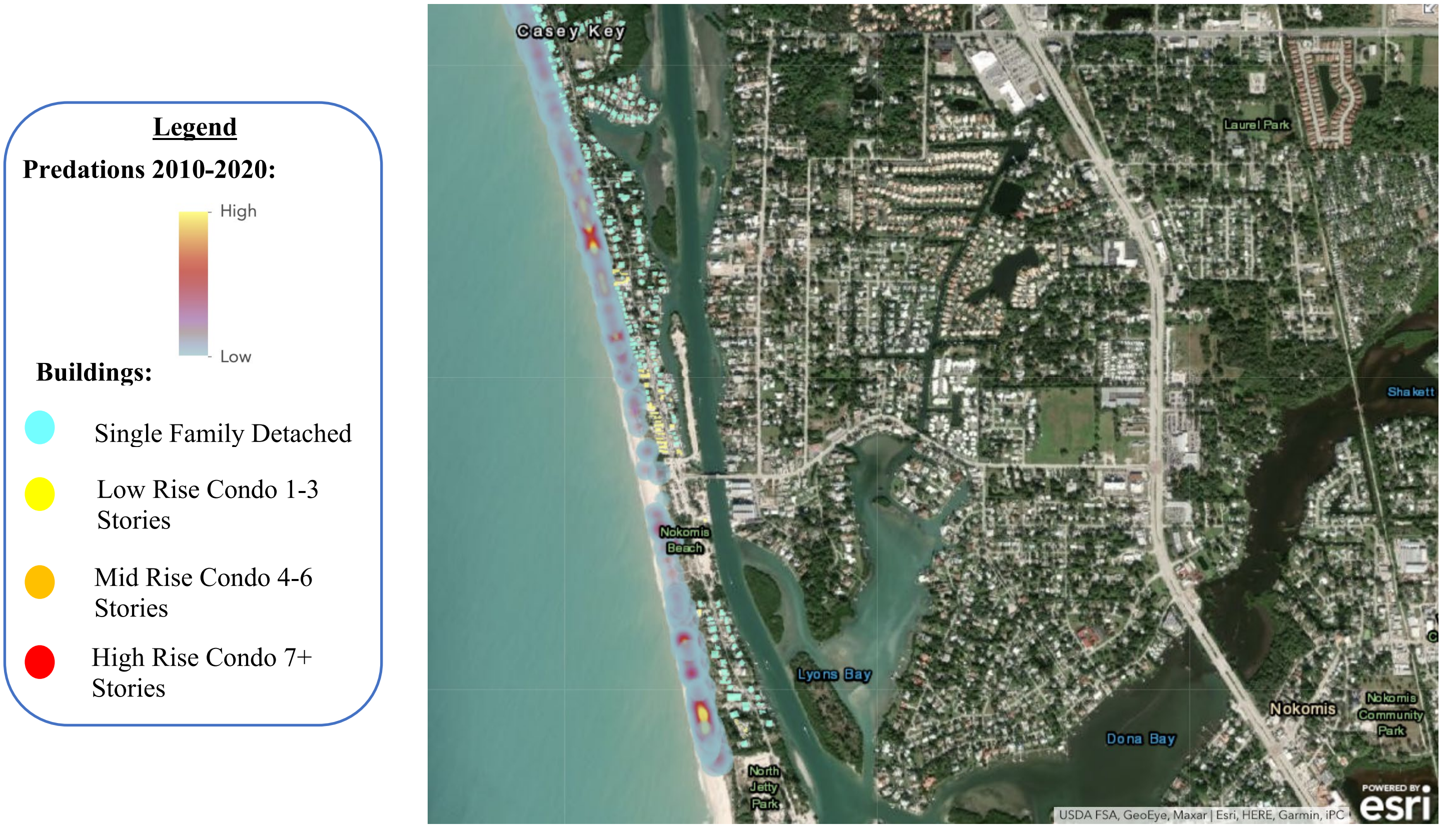

Figure 5. Predation Hotspots on Southern Part of Casey Key. Hot spots analysis of sea turtle nests that were preyed on 2010-2020 and building types.

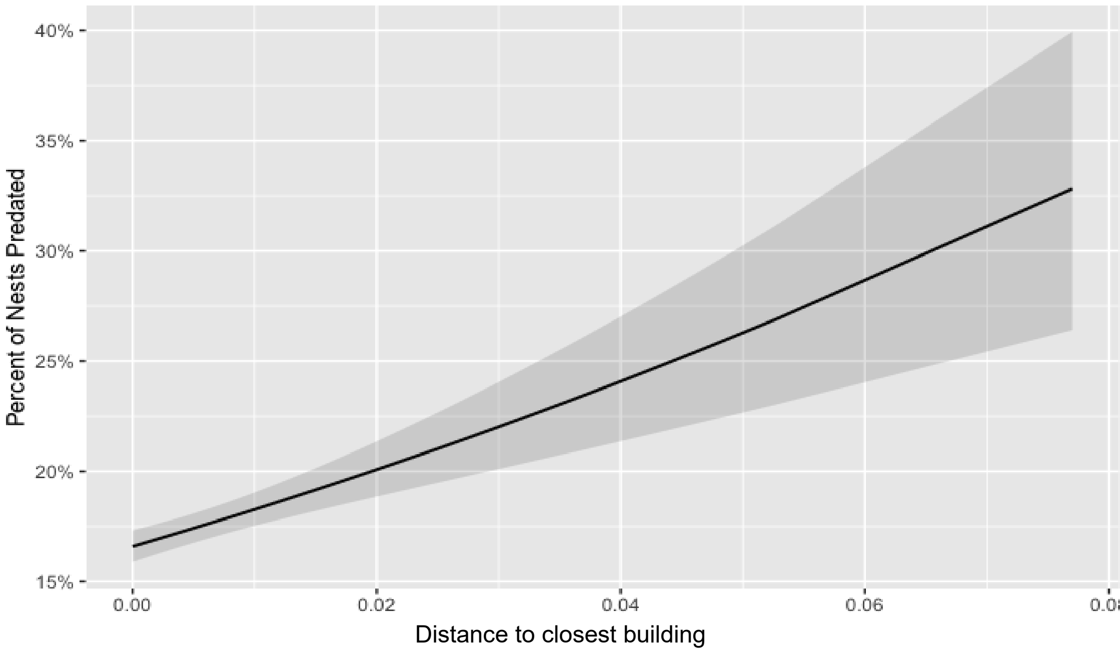

Figure 6. Distance and Probability of Predation. Generalized linear model of distance and depredations on Casey and Longboat Key, with standard error in gray. Nests that were further away from buildings had statistically higher predation rates than those closer. Pr(>|z|)=7.33e-08.

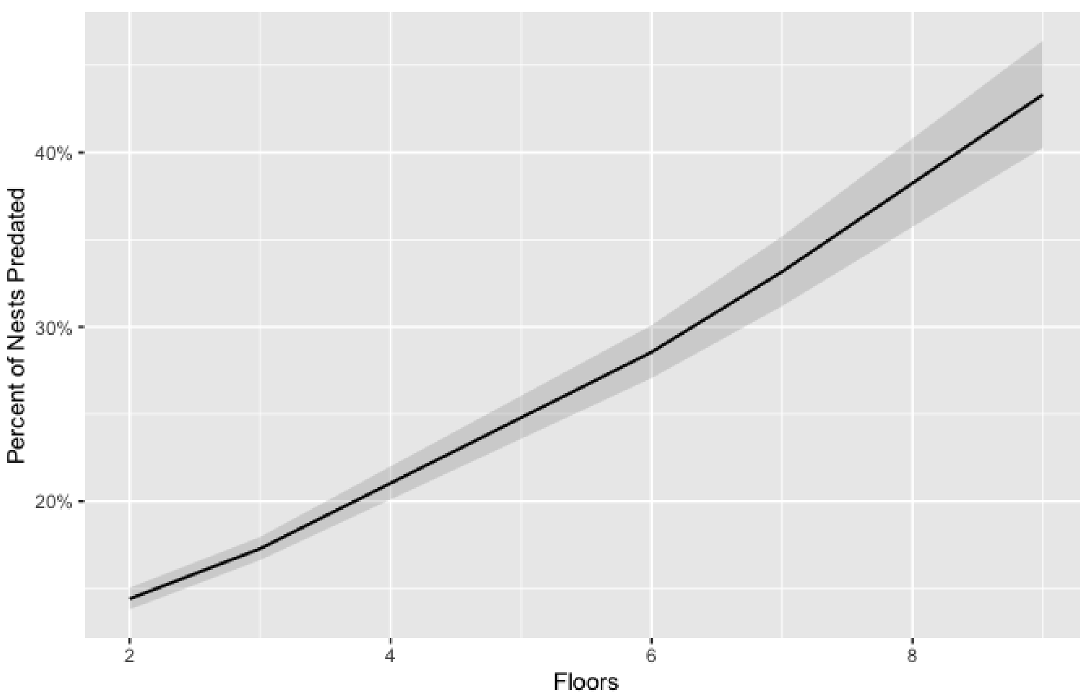

Figure 7. Numbers of Floors in Closest Building and Probability of Predation. Generalized linear model of floors in the closest building and depredations on Casey and Longboat Key with standard error in gray. More floors lead to significantly different predation rates Pr(>|z|)=< 2e-16.

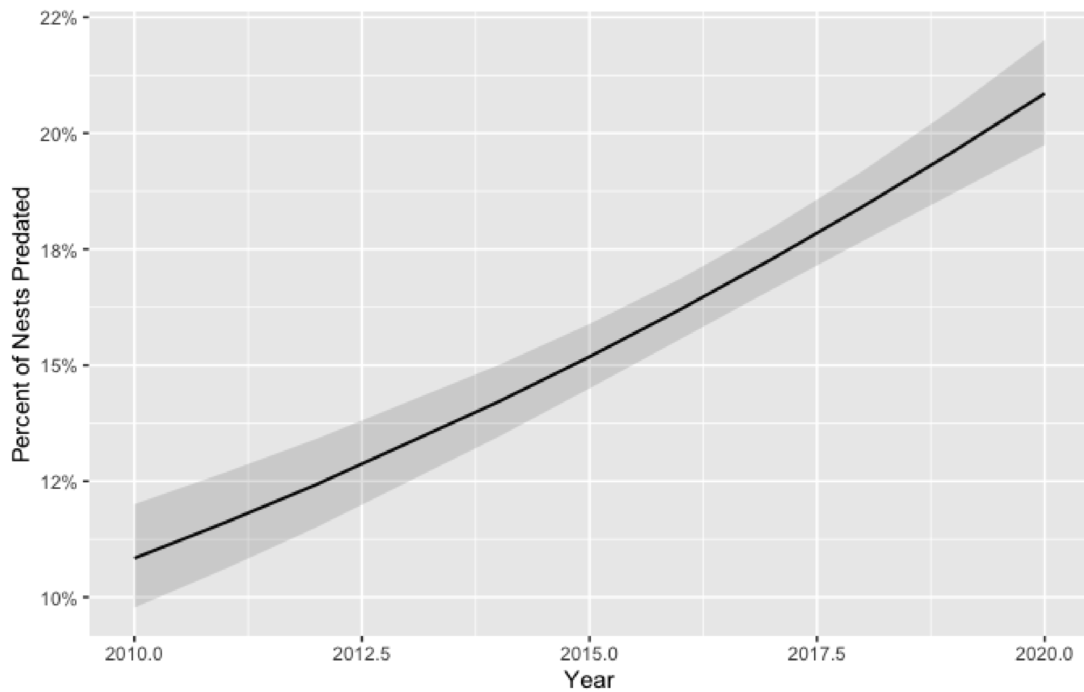

Figure 8. Year and Probability of Predation. Generalized linear model of year and depredations on Casey and Longboat Key with standard error in gray. Predation was statistically higher in later years of the study Pr(>|z|)=< 2e-16.

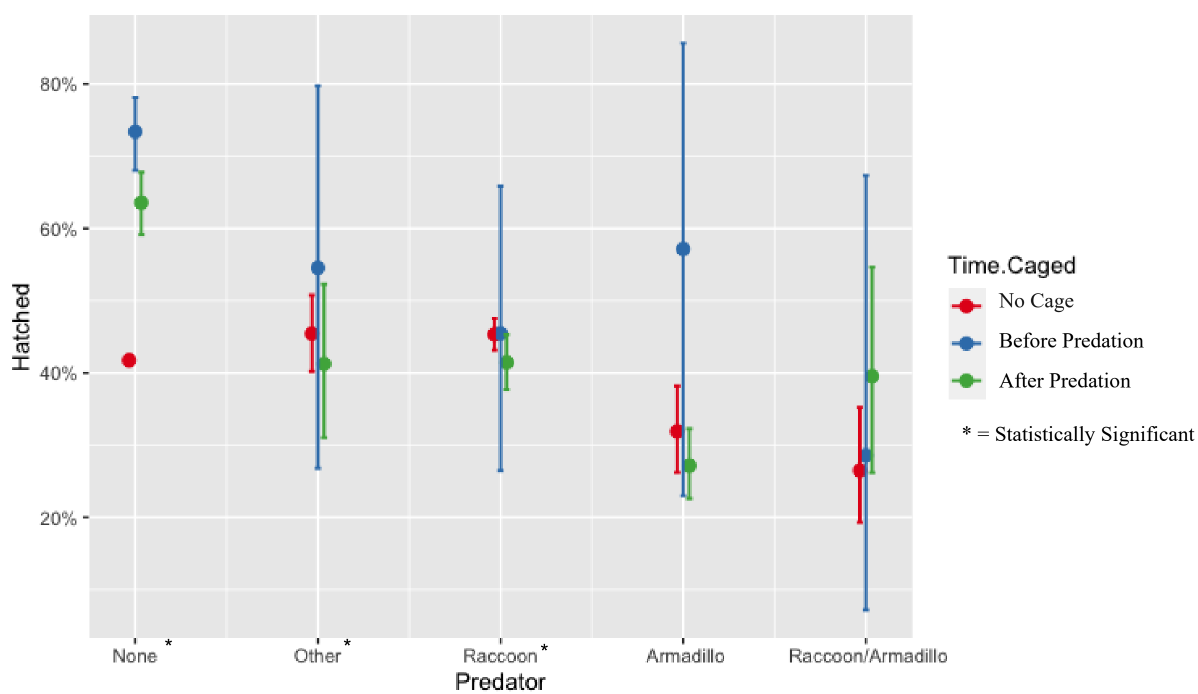

Figure 9. Predator Type and Hatching Probability. Generalized linear model of predator type and hatching success on Casey and Longboat Key with standard error. Hatching success was significantly different in the presence of other predator (Pr(>|z|)=.001246), Raccoon predator (Pr(>|z|)=0.000113) and no predator (Pr(>|z|)=0.002695).

DISCUSSION

Loggerhead sea turtles are an endangered species of special concern as they are essential to their ecosystem as ecosystem engineers (USFWS 2008). Sea turtle hatchlings on the shore and eggs are particularly vulnerable to predation. Sea turtle nests are especially vulnerable as predators can easily locate and successfully prey upon eggs with very minimal energetic costs or risks (Leighton et al. 2009). Predators can easily consume the majority of sea turtle eggs in a season, resulting in a reduced recruitment of hatchlings and may ultimately result in longer-term decreases in the adult population (Stancyk 1995; Barton et al. 2007). My results support that distance to buildings and the height of buildings affect the predation frequency of Loggerhead sea turtle nests on Casey and Longboat Key. Loggerhead Sea Turtle nests that are further distance from any building had greater predation and being near tall buildings instead of smaller homes increased the likelihood of greater predation. However, caging has proven to effectively reduce predation on Loggerhead sea turtles on both Longboat Key and Casey Key.

Depredation covariates

Distance to buildings, which key, the number of floors on a building, and year are significant factors leading to differential depredation frequency. These data demonstrates that zoning laws can have tangible effects on sea turtle nesting and coastal wildlife at large. In the United States over forty percent of the population lives along the nation's coasts (NOAA 2013). In the state of Florida, there has been a fifteen percent increase in the total population since 2010, with the highest population density and subsequent development occurring on or in the vicinity of the state's coast (U.S. Census 2019). As more people move to the nation's coasts and develop the area, important considerations must be made in relation to the altering natural habitat.

Sea turtle nests that were further from buildings were more likely to be predated but also proximity to taller buildings (greater than 4 stories) resulted in higher probabilities of depredation. The high frequency of depredations in nests further from buildings might be due to interference of artificial light with nocturnal predators such as raccoons and armadillos. Artificial lighting has been found to disrupt foraging patterns of nocturnal animals and indirectly altering predator-prey relationships (Bennie et al. 2015).

Does caging affect hatching success?

Over the span of this study (2010-2020), more sea turtle nests were depredated over time, with 22% of all nests being depredated in 2020. The growth in predation frequency might be due to the change in protocol of caging nests over the course of the study, resulting in less nests being caged overall since 2016. Caging was found to have a slight positive effect on hatching success. The time that the caging was put on the nest also had a significant effect on hatching success, with nests that were caged after the nest was laid having a higher hatching success rate than those that were caged after the first predation event.

Hatching success among Loggerhead sea turtle nests was low in this study, which is common as sea turtles experience high mortality during the early life stages, especially during the egg stage and directly after hatching (Xavier et al. 2006). Protection of sea turtle eggs is an important conservation action as the egg and hatchling stages are often the easiest and most feasible to protect and monitor (Mazaris et al. 2009). The largest limiting factor of caging implementation is the cost and time. Although the installation of cages may be time-intensive it is better than other methods of surveillance or protection. Small-scale programs have used game cameras to monitor the frequency of predator visits, time of visits, and nest predator identification (Lei & Booth 2017, 2018), but this methodology would be too costly over the scale of multiple islands with high nesting densities (20 nests/km). The removal of raccoons and other predators is also very costly and time intensive but does not result in lower predator populations because the source population often remains on the mainland and extra males will travel to natal sea turtle beaches (Barton and Roth 2006). In addition, the removal of predators such as raccoons can have secondary effects on the ecosystem structure (Butler et al. 2020). Therefore, caging may prove to be the most cost effective and efficient way to protect this species.

Does cage efficacy depend on the predator?

Caging of nests prior to the first predation event of nest depredated by armadillos or raccoons led to the highest hatch rates. Although hatch rates varied the most among nests predated by racoons, with nests caged at all having a significantly higher hatch rate than nests that were not. Caging may be more effective at preventing raccoon predation because previous studies have also found that raccoons are the most destructive predators. In my study, raccoons had a significant negative effect on the probability of nest hatching. Management strategies should focus on eliminating raccoon infiltration because they account for more nests destroyed and more eggs lost in each nest compared to armadillos and other predators (Butler et al. 2020). Previous studies have shown that for raccoon predation, nests that were relocated or treated with taste aversion, did have higher depredation rates (about four times higher) than caged nests during 1993 and 1994. Caging and lethal removal are similar in cost, $22,575/year (or $7.52/nest given 3,000 nests/ yr.) for caging and $21,166/ year (or $7.05/nest, assuming 3,000 nests/yr.) for lethal removal, but caging significantly reduced racoon depredations on sea turtle nests (Ratnaswamy et al. 1997). Therefore, it might be best to cage nests immediately after they are laid in order to minimize predation of nests and hatchlings.

Synthesis

Distance to buildings, key, the number of floors on a building, and year are significant factors leading to differential depredation frequency. My findings demonstrate that infrastructural choices on our coasts have an impact on endangered species recruitment and population dynamics. In the short-term, caging efforts on sea turtle nests should be prioritized in areas that have high raccoon predation and tall buildings, as this will result in the greatest reduction in egg and hatchling mortality. Caging efforts on sea turtle nests should also be implemented as close as the time the nest is laid as possible because this will have the largest impact on sea turtle recruitment. If possible, caging should be prioritized on all nests if the funds and workforce is available, as hatching success was higher on caged nests regardless of predator. Long term, coastal development projects should assess the direct and indirect effects of construction on coastal species, with promotion of city planning efforts that limit the number of high-rise buildings directly on beaches.

Limitations and Future Directions

This study defines hatching, depredations, and caging as success/failure variables. The number of eggs or hatchlings lost to predators can vary greatly between events and predators. Only on monitored nests are egg/hatchling loss counts recorded and for the study site of Longboat Key, most of the nests were non-monitored nests and monitored nests are determined yearly. In addition, the count of hatched sea turtles was not recorded on non-monitored nests and non-monitored nests comprising most of Longboat Key. In a future study, researchers should record the number of losses of each depredation event. Understanding the scope of the loss of eggs and hatchlings at each nest is important in quantifying the severity and threat of different predators and as such non-monitored nests should also have an egg and hatchling counts. My study also had a large sample size and was not normally distributed. My large sample size may have made comparing between groups become inflated and have shown more variables to be statistically significant.

Further research is needed to understand the role of artificial lighting in predation of sea turtle nests. A future study should investigate if raccoons feed on eggs in the presence of humans. Also, previous studies have shown that stomach contents of raccoons contained sea turtle hatchlings and human waste, and future studies should focus on the effect secure and remote dumpsters have on populations of raccoons. Removing dumpsters from areas near the beach could deplete raccoon and other predator food when turtle eggs are not available, and could potentially decrease predator populations. Further studies would need to be done on this.

Broader Implications

The findings of this study support that caging is an effective way to exclude predators and should be used by wildlife managers. The extent of predation is very high on the islands of Casey and Longboat Key and may threaten Loggerhead sea turtle populations of the future. As the development of our coasts accelerates, the effect of tall structures, such as buildings, condos, and houses on wildlife populations and ultimately recruitment must be considered. Each county should consider the benefits and ecological costs of building structures directly on our coasts. On the west coast of Florida, where nest density is high and essential to recruitment of sea turtles, legislation should be implemented to limit the height of coastal buildings to be no more than three stories high. In regions, where tall buildings over six stories exist, caging must be prioritized regardless of predator type as this is the best way to slow predator events on Loggerhead sea turtle nests.

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APPENDIX A: Predator Tracks Index

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

Raccoon

- Distinguishing track feature: Long fingers.
- Digging style: Like a human with small hands. Holes dug straight into the nest. If cage 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.

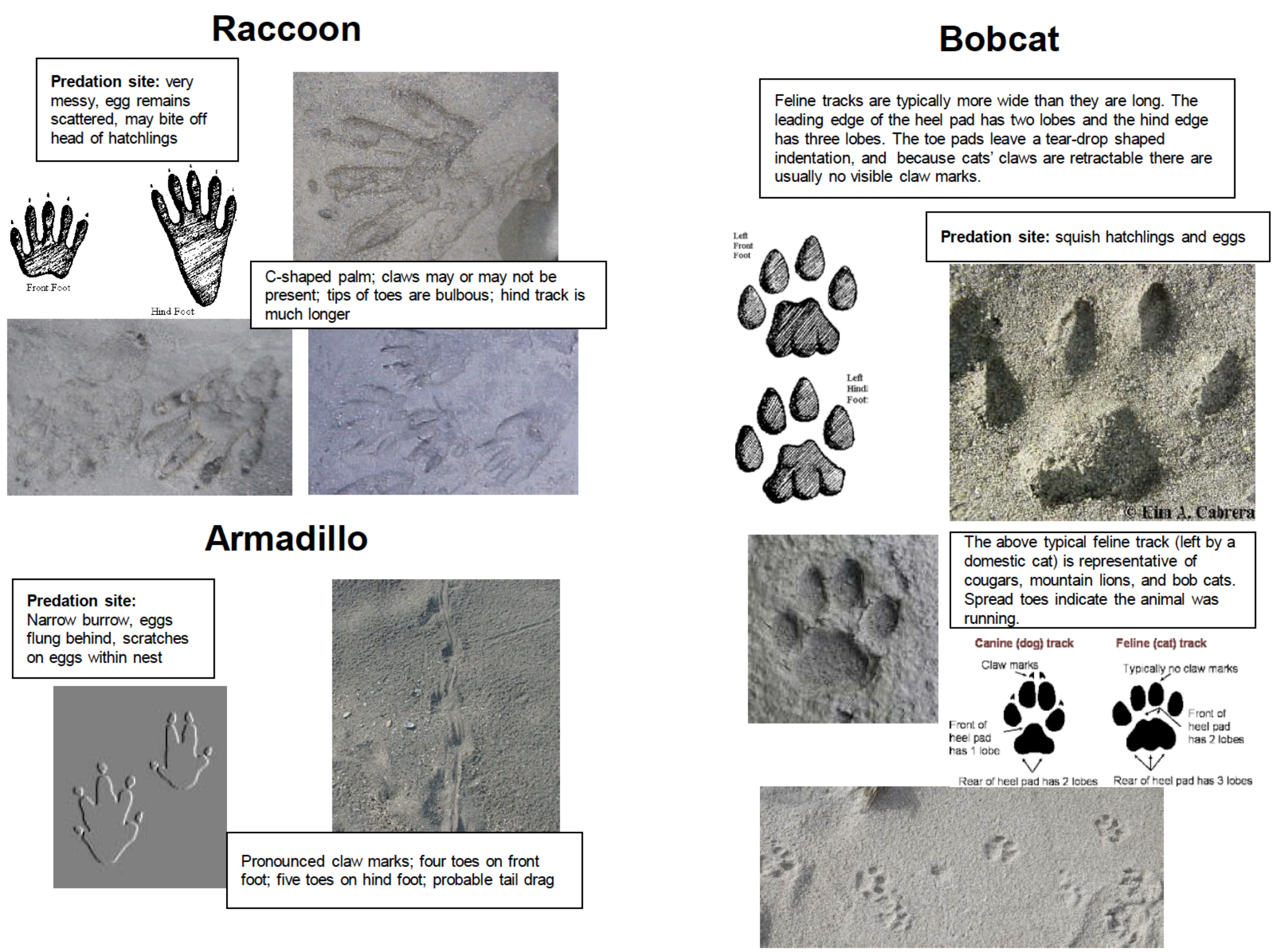
Coyote

- 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 destroyed, but usually not total depredation on first hit.
- Location of damage: Often "cleaned" eggshells outside of the nest cavity and they 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 nest cavity. Secondary predators, like crows, are often seen at coyote depredations.

Armadillo

- Distinguishing track feature: Includes S-shaped tail drag.
- Digging style: Long, deep burrows into the nest, usually on 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 depredation attempt if live hatchlings are found.

- Location of damage: Often just as many destroyed eggs inside nest as outside. Contents not thrown far from nest.



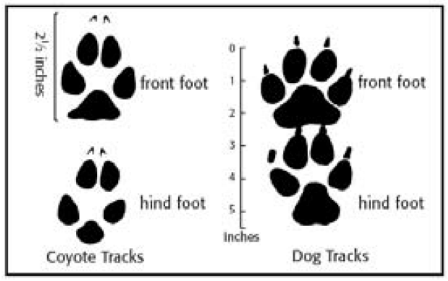
Coyote

Claws present. Claws point relatively inward, toward each other. More negative space between toes 2 and 3 and the heel pad compared to a domestic dog. X easily drawn in negative space between toe and heel pads.

Domestic Dog

Claws present. Outer toes have triangular shape. Oval shape of track is more long than wide. Less negative space between toe and heel pads than in coyotes. More difficult to draw an X in the negative space.

Overall track pattern is more "business-like", mostly in straight paths and steady gaits.

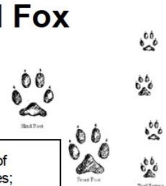


Overall track pattern is from an animal having fun and lots of energy with few straight lines and less steady gait as they zig-zag and explore more than wild coyotes.

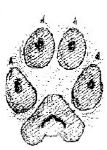
Predation site: large hole with eggs flung farther distances. Eggs and hatchlings (if present) licked clean of yolk and "goo". Often damaged eggs remain in nest cavity.

Gray and Red Fox

Predation site: neat conical hole, eggs licked dry



Straight lines of tracks; four toes; pronounced heel pad; fairly long claws; Length: less than 2"



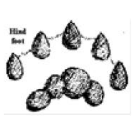
Non-native red fox have callous pads and hair on the bottom of their paws that may leave indentations.

Alligator

Large central tail drag with pairs of prints on either side. Front foot has five toes and rear foot has four toes with a narrow heal.

River Otter

River otters have partially webbed toes that have a pointed appearance. A long, thick tail drag is sometimes visible and the tracks are normally found in sets of four.



Ghost Crab

Holes are neat cylindrical hole located on or near nest mound; 2-3" in diameter often with sand pushed out on one side.

Tracks are repeating clusters of four pointed tracks sometimes with more continuous claw drags in the middle.

Predation site: unhatched eggs with small pinch slices