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Investigating the Effect of Mechanical Beach Cleaning on Nesting, Hatching and Emergence Success of Loggerhead (Caretta caretta) and Green (Chelonia mydas) Sea Turtles in Broward County, Florida

Megan A. Earney
Nova Southeastern University, me737@nova.edu

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By
Megan Earney

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Megan Earney
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Approved:

Thesis Committee

Major Professor: ______________________________
Derek Burkholder, Ph.D.

Committee Member: ___________________________
Jeremy Vaudo, Ph.D.

Committee Member: ___________________________
Kenneth Banks, Ph.D.

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Abstract

Sea turtles face many threats to their populations globally. Loggerhead sea turtles (*Caretta caretta*) and green sea turtles (*Chelonia* mydas) are listed by the International Union for the Conservation of Nature Red List as Endangered. In Florida, loggerhead and green sea turtles nest along the coastline during April-September. Mechanical beach cleaning is an aesthetic service performed daily on some beaches in Florida to clean the wrack line and/or the entire beach of debris. Alterations made to beaches by methods such as mechanical beach cleaning have the potential to impact sea turtle nesting, hatching, and emergence success. Generalized linear mixed models were performed to investigate the impacts of mechanical beach cleaning on nesting, hatching and emergence success of loggerhead and green turtles from 1997-2015 in Broward County, Florida. The results showed mechanical beach cleaning had an effect on nesting success, however, hatching and emergence success were not affected by mechanical beach cleaning. These results indicate that mechanical beach cleaning cannot solely be used to determine sea turtle management or conservation guidelines in Broward County.
Keywords: loggerhead sea turtle, green sea turtle, GLMM, nesting success, hatching success, emergence success, Broward County.

Introduction

For thousands of years, sea turtles have been hunted and harvested for their meat, eggs, oil, and shells for thousands of years leading to these declines in their population (Garcia-Martinez and Nichols 2001, Spotila 2004). As a result of these declines, all seven species of sea turtles are listed as either Vulnerable, Endangered or Critically Endangered by the International Union for Conservation of Nature (IUCN) Red List (Bowen and Karl, 2007, Casale and Tucker 2015). In the United States, there have been some conservation efforts aimed to protect and preserve sea turtle species, such as the U.S. Endangered Species Act 1973 and Florida's Marine Turtle Protection Act (379.2431, Florida Statutes). The Convention on International Trade in Endangered Species (CITES) and the Convention on Migratory Species (CMS) (Spotila 2004) promote sea turtle conservation through international policies. However, there are many countries without regulations, which continue to harvest sea turtles for profit and consumption (Humber et al. 2014). Population recovery requires protection of all sea turtle life stages including eggs and hatchlings, which surveying and management programs are easily able to monitor (Kornaraki et al. 2006).

For successful nesting, all sea turtles require a beach accessible by sea that is high enough to prevent the eggs from being flooded by tides or inundated by groundwater, and substrate that allows for gas diffusion and is damp and fine enough to prevent the egg chamber from collapsing (Mortimer et al. 1982). When nesting, the female will emerge from the water to find a suitable nesting site. When she begins to nest, she will use her front flippers to move dry, loose sand away and create a body pit. She then digs an egg chamber with her rear flippers and deposits her eggs. Once oviposition is complete, she fills in the egg chamber, and camouflages her nest before returning to the sea (Lutz and Musick 1996, Spotila 2004). If the conditions for successful nesting are not met, the female will perform a false crawl, where she returns to the ocean without depositing her eggs (Lutz and Musick 1996). False crawls may also occur as the result of human impacts, such as interactions with beach furniture, artificial lighting, foot traffic; or natural impacts, such as predator disturbance or the shape/profile of the beach, including escarpments (Lutz and Musick 1996).

Turtle nesting season varies by species around the world, but usually takes place during the summer months (Spotila 2004). In Florida, loggerhead sea turtles (*Caretta caretta*) primarily nest from April through August and green sea turtles (*Chelonia mydas*) nest from June to September. In Florida, sea turtles nest along most of the sandy beaches, except for the Big Bend area, with the densest areas of nests on the east coast, primarily between Brevard County and Broward County (Putnam et al. 2010) (Figures 1 and 2), making this an ideal location for examining sea turtle nesting and hatching success (Spotila 2004). Females of both species nest in Broward County, located in southeast Florida, resulting in an average of 4,731 loggerhead crawls per year (1,824 nests and 2,547 false crawls), and an average of 337 green turtle crawls per year (167 nests and 170 false crawls).

Most loggerhead and green sea turtle nesting beaches in Florida are also popular tourist beaches, particularly during turtle nesting season. With an increase in people, there are anthropogenic impacts including habitat degradation and ecosystem alteration (Lewison et al. 2004, Mascarenhas et al. 2004, NMFS and USFWS 2008). These impacts contribute to the loss or degradation of nesting beach habitat and can reduce nesting success (Davenport & Davenport 2006). Another threat sea turtles face is beach erosion, which occurs because of wave action and alters the shoreline. Beach erosion has caused a need for beach renourishment to replenish lost sand to allow for a wider beach (Steinitz, Michael, & Jeanette, 1998). This process protects the developments on the beach to avoid risk of destruction, but has been found to negatively impact sea turtle nesting efforts (Rumbold et al. 2001). These activities cause the beaches to change drastically from the time females hatch and return to nest ~25-30 years later (Spotila 2004). The preservation and conservation of suitable nesting habitat on beaches is crucial for sea turtle survival and population growth (Spotila 2004).

Because of the high influx of beach visitors, debris can be left behind. Debris, including plastic, manufactured materials, and natural macroalgae, regularly becomes stranded at the high tide line (HTL) and often remains after the water recedes (Gheskiere et al. 2006, Gregory 2009). Debris is also often left by beach visitors on the un-vegetated sandy beach. The debris on beaches is unsightly and can be unaesthetically pleasing to visitors; therefore, beach cleaning efforts have been implemented globally and can range from hand raking and trash pick-up to the use of large machinery for debris removal. Mechanical beach cleaning is a process that is used globally on beaches to remove unwanted debris including trash and natural material, such as sand and seaweed via large tractor machinery (Demetropoulos 2003, Dugan and Hubbard 2010, Gilburn 2012).

statewide Most Florida beaches are cleaned via mechanical beach cleaning. In Broward County, there are four organizations that facilitate beach cleaning: Beach Raker, City of Fort Lauderdale, City of Hollywood and City of Hallandale. According to their 2016 mechanical beach cleaning permits, the purpose of mechanical beach cleaning is to remove the abiotic and biotic debris left at the HTL and on the un-vegetated sandy beach. Cleaning is accomplished using a tractor with either a drag bar or a rear-mounted blade to smooth the un-vegetated sandy beach or to mix seaweed with wet sand at the HTL, respectively.

The tractors rake/pick-up the HTL debris, though some marine debris may be left behind or reburied on the sandy beach. Alteration of the beach due to mechanical beach cleaning may have an influence on turtle nesting by affecting the ecological characteristics needed for successful nesting. The biotic and abiotic material that remains on the beach moves with the sand and overtime could change the physical and chemical characteristics of the beaches, this could cause a female to produce a false crawl. In addition, the process of mechanical beach cleaning may also have a negative impact on hatch and emergence success rates (which refers to the successful number of sea turtle hatchlings that exited the nest and onto the beach) (Defeo et al. 2009). The process of mechanical beach cleaning requires heavy machinery that may disturb the sand surrounding the nest as well as inside the egg chamber (Raymond 1984). The vibrations of the equipment may also disturb the eggs, thus disrupting the incubation period and hatching success by dislodging the embryo from the wall of the egg causing mortality in early stages of incubation (Blanck and Sawyer 1981). Emergence success may also be affected by beach cleaning machinery for the same reasons listed above.

The purpose of this study is: (1) to determine the effects of mechanical beach cleaning on nesting success of loggerhead and green sea turtles and (2): to determine the effects of mechanical beach cleaning on hatching and emergence success of loggerhead and green sea turtle hatchlings.

Materials and Methods

Study Species

Loggerhead Sea Turtle

Loggerhead sea turtles are distributed circumglobally, with major rookeries and feeding grounds along the east coast of the United States, Greece, Oman, and Japan. Each of these rookeries represent a distinct breeding population (Bowen et al. 1994, Spotila 2004). The Peninsular Florida region, which includes the coast of Georgia and Florida (excluding the Florida Keys; Figure 1), has the highest nesting density (87% of all nesting effort) within the North West Atlantic subpopulation (Spotila 2004, Bolten et al. 2009, Ceriani and Meylan 2015).

Every 2-4 years, mature female loggerhead sea turtles return to their natal beach to nest at night (Addison 1986, Mortimer and Portier 1989, Meylan et al. 1990, Casale and Tucker 2015). During the loggerhead sea turtle nesting season in Southeast Florida (April- August) females will nest an average of 4 times with approximately 12-17 days in between each nesting event (Addison 1986, Casale and Tucker 2015). The nesting process takes several hours and each female will lay an average of 120 eggs per nest (Hays & Speakman 1991). The eggs incubate for 45-60 days before the hatchlings emerge at night and use visual cues to guide themselves to the ocean (Lutz and Musick 1996, Spotila 2004, Lohmann et al. 2013).

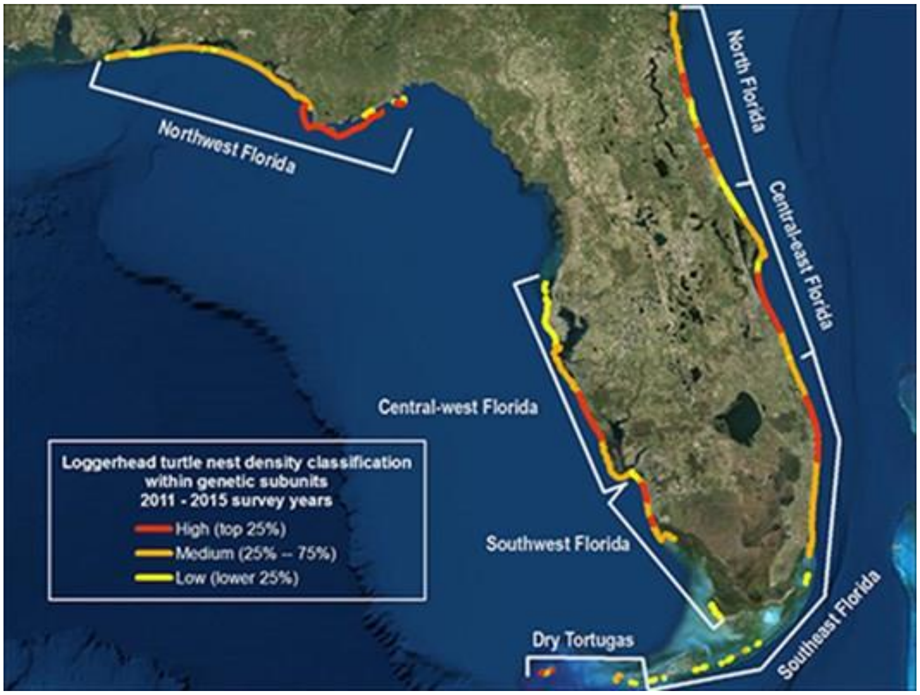

Figure 1. Map of loggerhead sea turtle nesting density (FWC/FWRI).

Green Sea Turtle

Green sea turtles are also found worldwide (Seminoff 2004). Similar to loggerhead sea turtles, Green sea turtles feed in tropical and subtropical oceans and use the same waters as loggerhead sea turtles. Their largest rookeries are found in Costa Rica, the Seychelles Islands, the Galapagos Islands, and Florida (Spotila 2004). In Florida, the females return to their natal beaches every 2 years at night to lay an average of 110 eggs per clutch (Mortimer and Portier 1989, Lutz and Musick 1996, Spotila 2004, Lohmann 2013). These females will lay an average of 2-3 nests per season (in Southeast Florida from June-September) with a span of 12-14 days between nesting events (Hirth 1997). The eggs will incubate for 45-60 days and hatchlings emerge at night to enter the ocean.

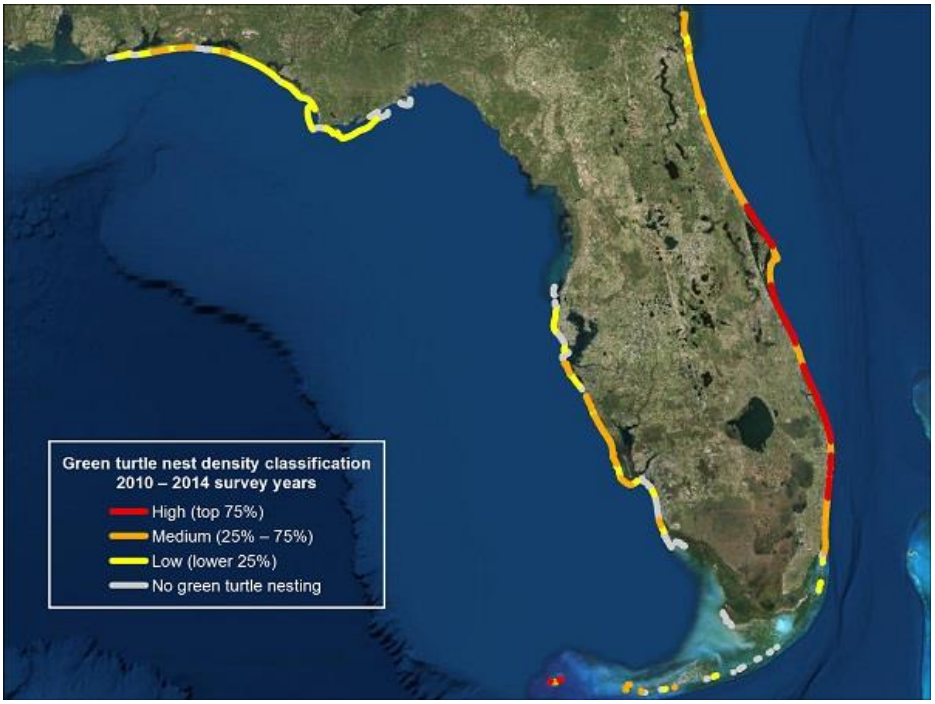

Figure 2. Green sea turtle nesting distribution of Florida (FWC/ FWRI).

Study area and surveys

From 1997-2015, between March 1st and October 31st, the Broward County Sea Turtle Conservation Program (BCSTCP) conducted morning sea turtle nesting surveys on all Broward County Beaches (except Dr. Von D. Mizell Eula Johnson State Park (MJSP)), comprising the coastal municipalities of Deerfield/Hillsboro, Pompano/Lauderdale by the Sea, Fort Lauderdale, Dania Beach and Hollywood/Hallandale (Figure 3). Overall, the BCSTCP monitors 38.62 km of sandy beach.

The Florida Department of Environmental Protection (FDEP) has marked these beaches with survey monuments, known as R Monuments, running from the Broward-Palm Beach county line (R1) to the Miami/Dade-Broward County line (R128) (Figure 3).

Figure 3. Study area of Broward County (modified from Donahou, 2014). Colored highlights indicate beach cleaning method: yellow-no cleaning, green-HTL and sandy beach, blue-HTL only.

Mechanical beach cleaning started in 1996 in Broward County and follows Rule Chapter 62B-33 of the Florida Administrative Code and section 161.053(5) of the Florida

Statues. Mechanical beach cleaning rules varies by location throughout Broward County. From R32-R35, R49-R51, R65-R66, R72-R80, R98-R102, R108-R124, it is possible to clean the un-vegetated sandy beach while avoiding the sand tolerant dune vegetation by a minimum of 10 feet. At R zones R6-R31, R36-R48, R59-R64, R67-R71, R81-R83, R103-R107, the tractor cleans at the HTL only. At R zones R1-R5, R52-R58 and R125-R128, no mechanical beach cleaning occurs (Figure 3). In addition, any tractor regardless of its raking allowances must keep a safe distance of 10 feet from any marked sea turtle nest. MJSP is contained in R zones 86-96, where no mechanical beach cleaning occurs.

The following protocols are described from the FWC Handbook. Morning nesting surveys began 30 minutes before sunrise and all crawls (i.e., those resulting in nests and false crawls) were documented (Appendix 1 and 2). Nests were marked with four stakes around the nest perimeter with red-glo flagging tape tied around all stakes. The GPS coordinates were recorded for all crawls and then the tracks were erased. All nests were monitored daily for maintenance (i.e., checking that all nest perimeter stakes and flagging tape were intact). During the nest incubation, nests were examined daily for evidence of nest hatch-outs (hatchlings that have broken out of their eggs and have successfully emerged from the egg chamber), predation, wash overs (nests where water has reached the inside perimeter of the nest), and washouts (nests that have been removed by waves). Hatched-out nests were marked with blue flagging tape on a nest stake and recorded (Appendix 3). The nest was excavated three days after evidence of a hatch-out was observed to determine the nest hatch success (Appendix 4). During a nest excavation, turtle species, egg chamber depth (CD), the hatch and excavation date, number of live turtles in the nest (LIN), number of dead turtles in the nest (DIN), number of live pipped (when the hatchling has broken the shell but has not completely escaped the egg; LPIP), and number of dead pipped (DPIP), any eggs with white coloration (suggesting the embryo had attached to the shell) (W), number of hatched eggs (H), whole eggs, and any abnormalities (e.g., presence of fungus) were recorded. All whole eggs were counted, sorted by coloration and were opened to see if there was visual development (VD) or no visual development (NVD) (Miller 1999). If a nest had not hatched after 70 days, an attempt was made to locate the egg chamber, termed a pulled nest. If the egg chamber was found, then an excavation was performed; if not, the nest perimeter was removed (Appendix 5).

For this study, data collected by the BCSTCP from 1997 - 2015 were analyzed. Data from sea turtle nesting on MJSP (R85-R96) from 1997-2015 were also used as another beach where no mechanical beach cleaning occurs. Ecologically, MJSP is similar to surrounding beaches in Broward County (Schmitt and Osenberg 1996). The data for MJSP, which were collected using the same protocols as listed above, were obtained from the MJSP park office and datasets were combined with data from Broward County beaches to create one continuous dataset. Each individual crawl was categorized by the R zone and beach location as well as the cleaning method which correlates with that R zone.

Permission to use the following data was granted through Broward County and the Florida Fish and Wildlife Conservation Committee (FWC) on current marine turtle permit MTP-16-214.

Calculation of nesting success on beaches with or without mechanical beach cleaning

The start date for this study corresponded with the introduction of mechanical beach cleaning in 1997 on all beaches during sea turtle nesting season. Nesting success (NS) was defined as the successful deposition of eggs from a female and was calculated using eq. 1 where #Nest is the number of successful nests and #FC is the number of false crawls (Miller 1999).

$$NS\ (\%) = \frac{\#Nest}{\#Nest + \#FC} x100 \qquad (1)$$

Calculation of hatching and emergence success on beaches with or without mechanical beach cleaning

To determine the impact of mechanical beach cleaning on loggerhead and green sea turtle hatching and emergence success, excavation and hatching data was acquired from the BCSTCP. Hatching success (HS) refers to the number of hatchlings that hatch out of their shell and was calculated using eq. 2 where #hatched is the successful number of hatched eggs and ∑Total is the sum of hatched, VD, NVD, LPIP, DPIP (Miller 1999).

$$HS\ (\%) = \frac{\#hatched}{\sum Total} x100 \qquad (2)$$

Emergence success (ES) refers to the number of hatchlings that reach the surface of the beach and was calculated using eq. 3 where #L is the number of live hatchlings and #D is the number of dead hatchlings found in the nest (Miller 1999).

$$ES(\%) = \frac{\#hatched - (\#L + \#D)}{\sum Total} x100 \qquad (3)$$

Analysis

The effects of cleaning activity and beach on annual success rates were examined using Generalized Linear Mixed Models (GLMM) in R Studio (R Core Team 2016) using the packages: arm (Gelman and Su 2016), car (Fox and Weisberg 2011), glmm (Knudson 2016), lme4 (Bates et al 2015), and multcomp (Hothorn 2008). A GLMM is an extension of the General Linear model (logistic regression that handles non-normal data) that includes both fixed and random effects (Hedeker 2005, Bolker et al. 2008). The factors included in candidate models included: cleaning method, beach, year, R zone, and index. Index is an observation-level random effect to account for over dispersion of the data (Harrison 2015). A cursory examination of the data suggested that success rates may differ along the Broward County coastline, therefore the beaches were grouped based on the locations of natural barriers (i.e. inlets). This resulted in the following groups Hillsboro, Fort Lauderdale/Pompano, MJSP and Hollywood/Hallandale beaches. MJSP was chosen to be a separate beach because it was never cleaned by mechanical beach cleaning, even though there was no natural barrier dividing it from Hollywood/Hallandale beach. Various candidate models were run with combinations of cleaning method (categorical variable with three levels) and beach (categorical variable with four levels) as fixed effects and the random effects year, R zone, and index (Table 1). Because the response variable (success rate (NS, HS, ES)) was a proportion, the binomial model (logit link) was used. The best fit model was chosen by selecting the lowest Akaike Information Criterion (AIC) Score. The AIC scores can be used to compare the quality of a set of statistical models to each other.

Table 1. Model variations of fixed and random effects for each success rate.

	Model Variations
null	$y = Success\ rate \sim 1$
Mod	$y = Success\ rate \sim method + beach + (year)$
Mod1	$y = Success\ rate \sim method * beach + (year)$
Mod2	$y = Success\ rate \sim method + (year)$
Mod3	$y = Success\ rate \sim beach + (year)$
Mod4	$y = Success\ rate \sim method + beach + (year) + (zone)$
Mod5	$y = Success\ rate \sim method + beach + (year) + (index)$
Mod6	$y = Success\ rate \sim method + beach + (year) + (beach/zone)$
Mod7	$y = Success\ rate \sim beach + (year) + (zone)$
Mod8	$y = Success\ rate \sim method + (year) + (zone)$
Mod9	$y = Success\ rate \sim method + beach + (year) + (beach/zone/index)$
Mod10	$y = Success\ rate \sim beach + (year) + (beach/zone/index)$
Mod11	$y = Success\ rate \sim beach + (year) + (beach/zone)$
Mod12	$y = Success\ rate \sim method + (year) + (beach/zone)$
Mod13	$y = Success\ rate \sim beach + (year) + (index)$
Mod14	$y = Success\ rate \sim method + (year) + (index)$
Mod15	$y = Success\ rate \sim method + (year) + (beach/zone/index)$
Mod16	$y = Success\ rate \sim method + beach + (year) + (beach/index)$
Mod17	$y = Success\ rate \sim method + beach + (index)$
Mod18	$y = Success\ rate \sim beach + (index)$
Mod19	$y = Success\ rate \sim beach + (zone)$
Mod20	$y = Success\ rate \sim method + (index)$
Mod21	$y = Success\ rate \sim method + (zone)$
Mod22	$y = Success\ rate \sim method + beach + (zone)$
Mod23	$y = Success\ rate \sim (year)$
Mod24	$y = Success\ rate \sim (zone)$
Mod25	$y = Success\ rate \sim (index)$
Mod26	$y = Success\ rate \sim beach + (year) + (index)$
Mod27	$y = Success\ rate \sim method + beach + (year) + (zone/index)$
Mod28	$y = Success\ rate \sim method + beach + (year) + (beach/zone)$
Mod29	$y = Success\ rate \sim method + beach + (year) + (beach/index)$

Results

Nest Success

Loggerhead Sea Turtles

For loggerhead sea turtle nest success comparing each cleaning method at FTL/P and HO/HA beaches, because all cleaning types occurred on those beaches, the best fit model included beach and method as the fixed effects and year, zone and index as random effects with index nested in zone (Table 2). The model predicted significantly higher nesting success values at FTL/P than HO/HA beaches (Tukey pair-wise comparison: p-value <0.05). The three cleaning types were not significantly different (Tukey pair-wise comparison: all p-values >0.05) (Figure 4).

Table 2. Top two models and which was selected for loggerhead sea turtle nesting success for each cleaning type.

Species	**Model**	**Model Variations**	**AIC Score**	**Selected?**
CC	Mod9	$y = NS \sim method + beach + (year) + beach/index/zone$	11893.08	N
CC	Mod27	$y = NS \sim method + beach + (year) + (zone/index)$	11704.22	Y

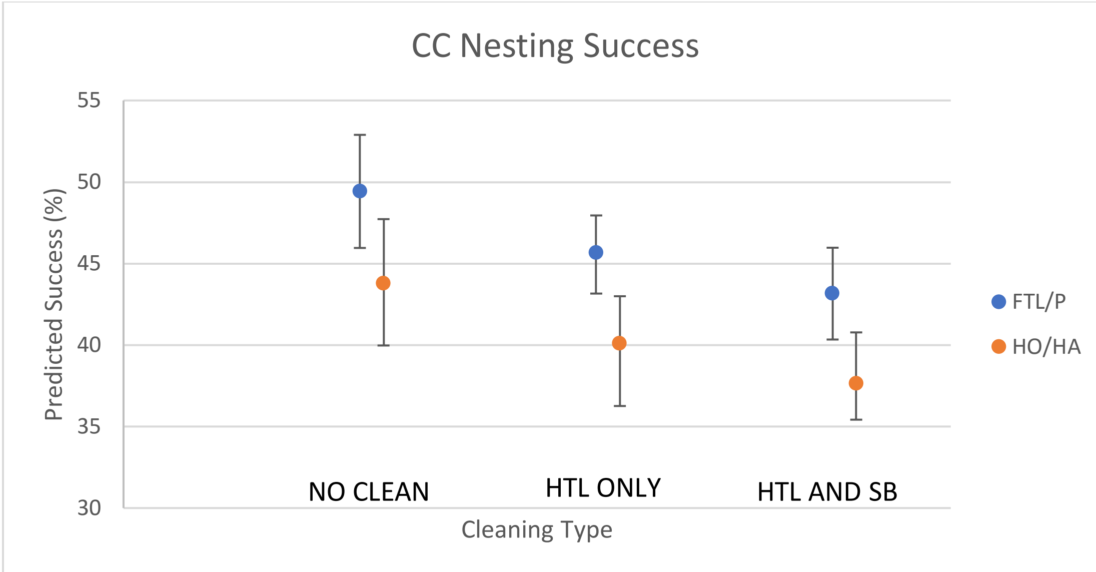

Figure 4. Loggerhead sea turtle nest success including comparing all cleaning type on FTL/P and HO/HA beaches. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test for cleaning method. Values with different letters are statistically different.

For loggerhead sea turtle nest success comparisons of no cleaning, including MJSP, the best fit model included beach and the random effects year, index and zone, where index was nested in zone nested in beach (Table 3). The model predicted significantly higher nesting success at Fort Lauderdale/Pompano than Hillsboro and MJSP, but Fort Lauderdale/Pompano had a similar success rate to HO/HA. There were no significant differences between Hillsboro, Hollywood/Hallandale and MJSP beaches (Tukey pair-wise comparisons: all p-values > 0.05) (Figure 5).

Table 3. Top two models and which was selected for loggerhead sea turtle nesting success for each cleaning type.

Species	Success Type	Cleaning Method	Model	AIC Score	Selected?
CC	NS	No Clean	$mod10: y = Success\ Rate \sim beach + (year) + (beach/zone/index)$	2099.238	Y
CC	NS	No Clean	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	2136.421	N
CC	NS	HTL only	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	6701.92	Y
CC	NS	HTL only	$mod6: y = Success\ Rate \sim beach + (year) + (beach/index)$	6703.92	N
CC	NS	HTL and SB	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	3020.182	Y
CC	NS	HTL and SB	$mod7: y = Success\ rate \sim beach + (year) + (zone)$	3036.650	N

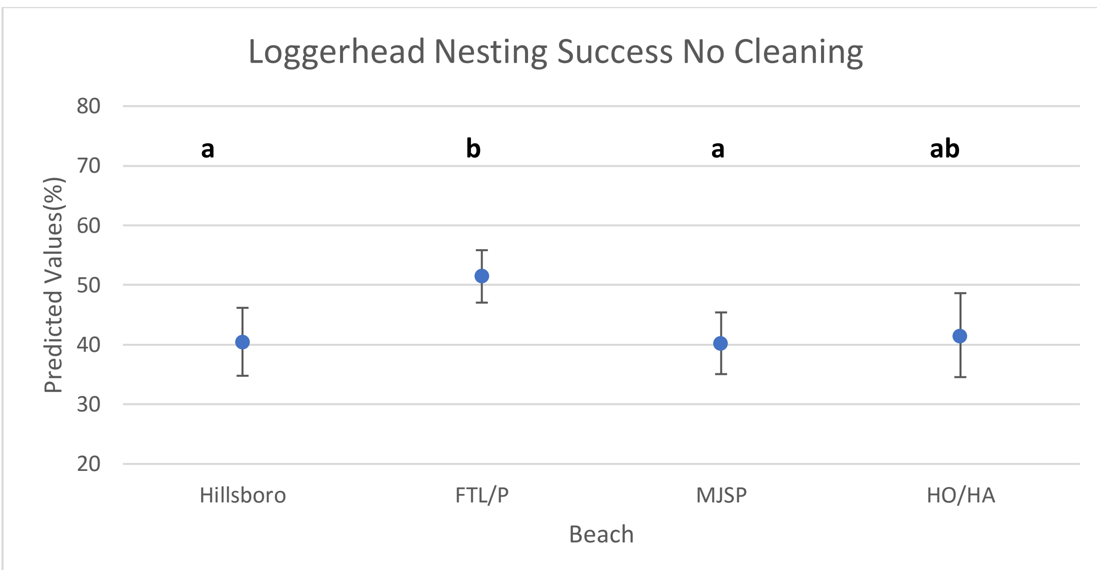

Figure 5. Loggerhead sea turtle nest success including MJSP. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Similarly, a model was run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach, year and index as random effects (Table 3). The model showed that Hillsboro, Fort Lauderdale/Pompano and Hollywood/Hallandale beaches are different from each other (Tukey pair-wise comparisons all p-values < 0.05). However, the model predicted higher nesting success at Hillsboro beach (Figure 6).

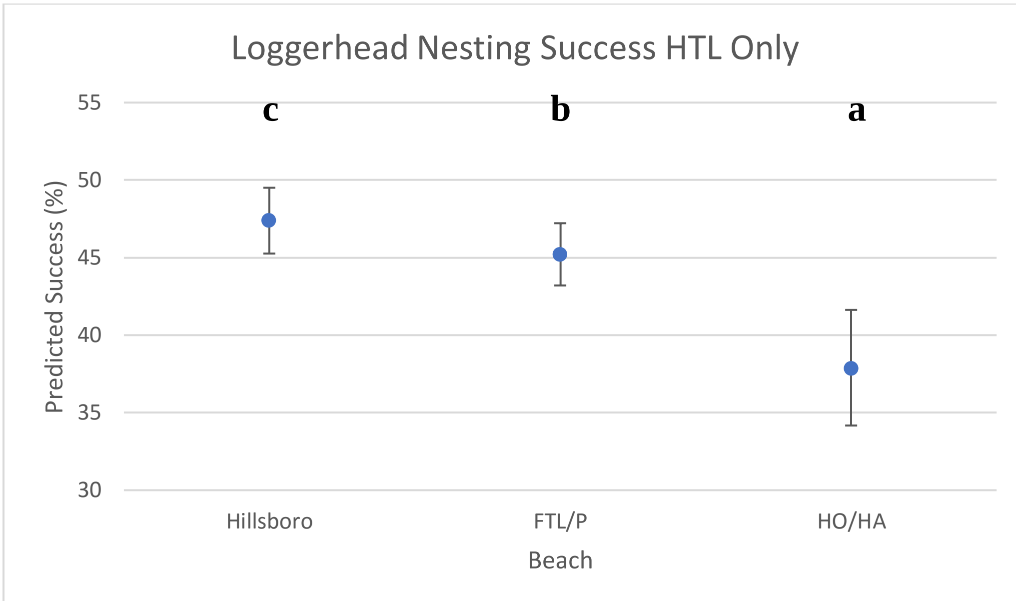

Figure 6. Loggerhead sea turtle nesting success HTL only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison for loggerhead sea turtle nesting success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included beach effect and the random effects year, index (Table 3). The model predicted significantly higher nesting success at Fort Lauderdale/Pompano and Hollywood/Hallandale (Tukey pair-wise comparison: $p < 0.05$) (Figure 7).

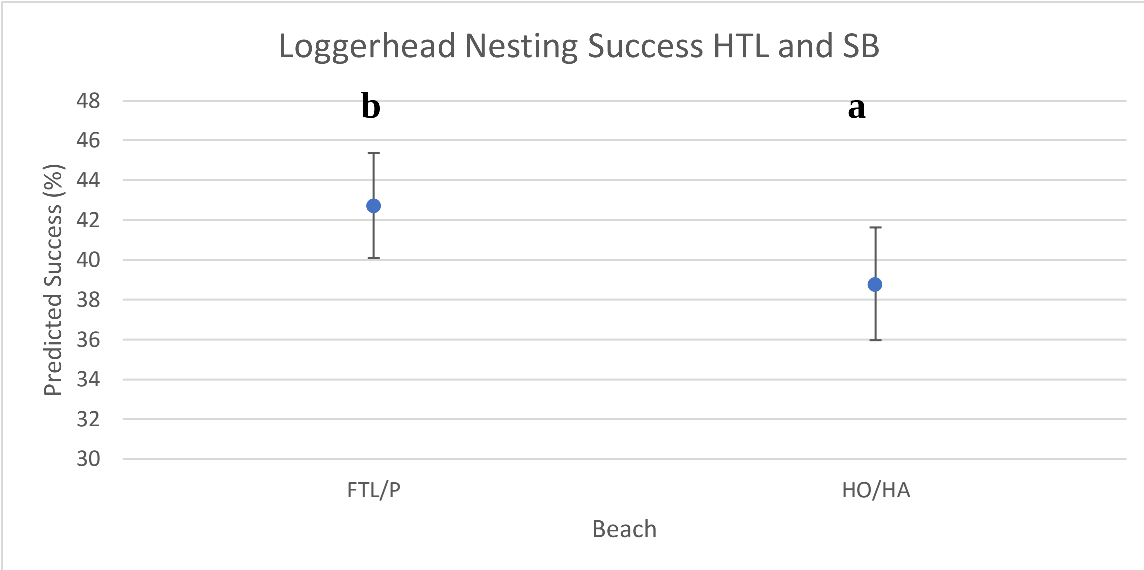

Figure 7. Loggerhead sea turtle nesting success with cleaning HTL and SB. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Green Sea Turtles

For green sea turtle nest success, the comparing of each cleaning method for FTL/P and HO/HA beaches, the best fit model included beach and method as the fixed effects and year, zone and index (with index nested in zone) as the random effects (Table 4). The model predicted significantly higher nesting success for FTL/P than HO/HA beaches. There were differences between any of the cleaning types (Tukey pair-wise comparison: all p-values < 0.05) (Figure 8).

Table 4. Top two models and which was selected for green sea turtle nesting success for each cleaning type.

Species		**Model Variations**	**AIC Score**	**Selected?**
CM	Mod9	$y = NS \sim method + beach + (year) + beach/index/zone$	2660.263	N
CM	Mod27	$y = NS \sim method + beach + (year) + (zone/index)$	2651.144	Y

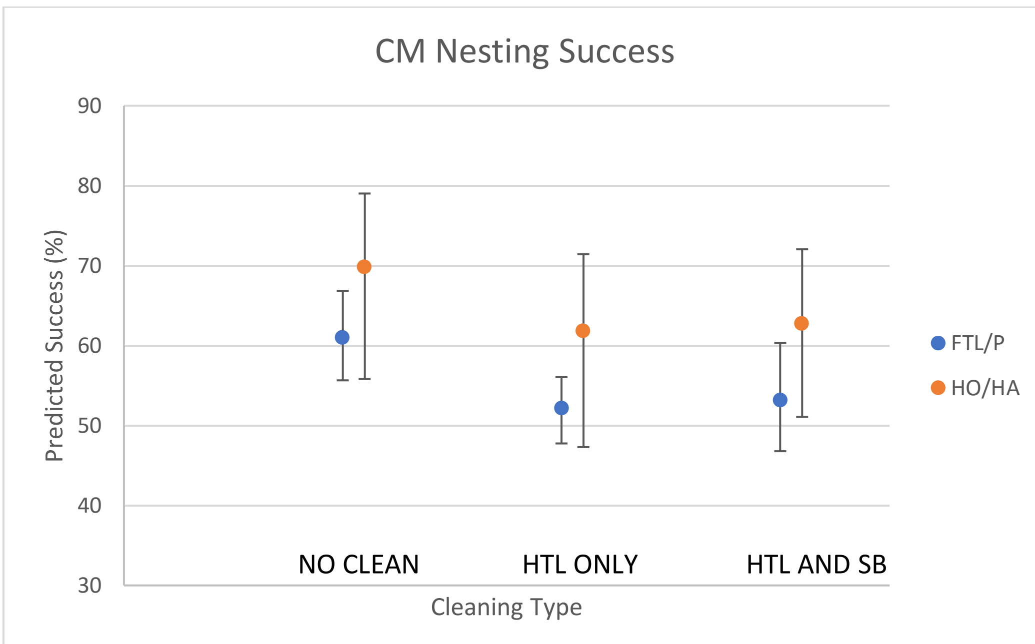

Figure 8. Green sea turtle nest success including comparing all cleaning type on FTL/P and HO/HA beaches. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test for cleaning method. Values with different letters are statistically different.

For green sea turtle nest comparing no cleaning among all beaches, including MJSP, the best fit included beach as the fixed factor and index as the random factor (Table 5). The model predicted similar success rates at Hillsboro, Fort

Lauderdale/Pompano and HO/HA beaches (Tukey pair-wise comparisons: all values p >0.05). The model also predicted there was a significant difference between Hillsboro and MSJP as well as Fort Lauderdale/Pompano and MJSP (Tukey pair-wise comparison: p <0.05) (Figure 9).

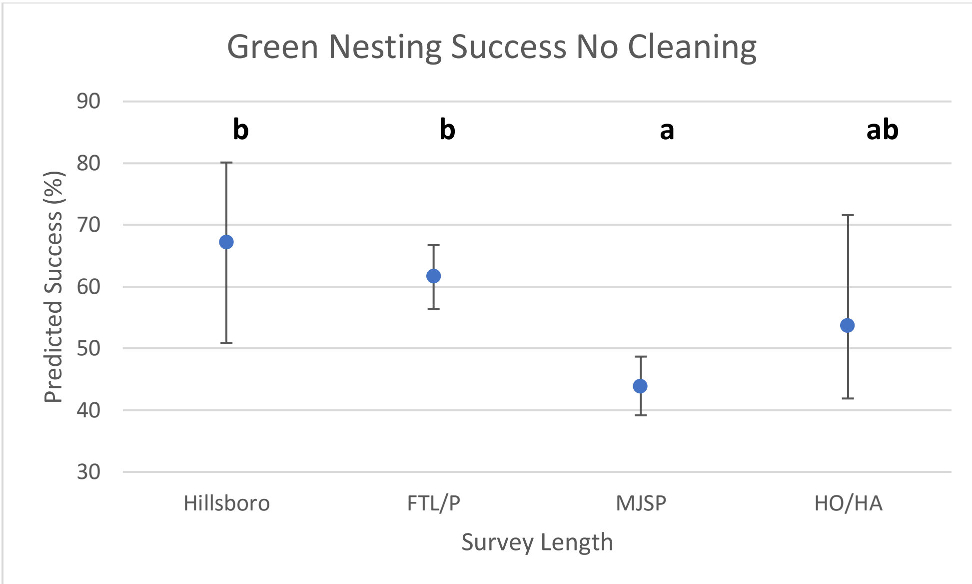

Figure 9. Green sea turtle nesting success, comparing no cleaning on all beaches (excluding MJSP). The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Table 5. Top two models and which was selected for green sea turtle nesting success for each cleaning type.

Species	**Success Type**	**Cleaning Method**	**Model**	**AIC Score**	**Selected?**
CM	NS	No Clean	$null: y = Success\ rate{\sim}1$	597.1683	N
CM	NS	No Clean	$mod18: y = Success\ Rate{\sim}\ beach + (index)$	559.0341	Y
CM	NS	HTL only	$mod7: y = Success\ Rate{\sim}\ beach + (year) + (zone)$	1906.81	Y
CM	NS	HTL only	$mod10: y = Success\ Rate{\sim}beach + (year))$ +(beach/zone)	1908.812	N
CM	NS	HTL and SB	$mod19: y = Success\ Rate{\sim}\ beach + (zone)$	193.96	Y
CM	NS	HTL and SB	$mod3: y = Success\ Rate{\sim}beach + (year)$	195.44	N

Similarly, a model was run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach and the random effects year and zone (Table 5). The model predicted similar nesting successes at all three beaches (Figure 10) (Tukey pair-wise comparisons: all $p > 0.05$).

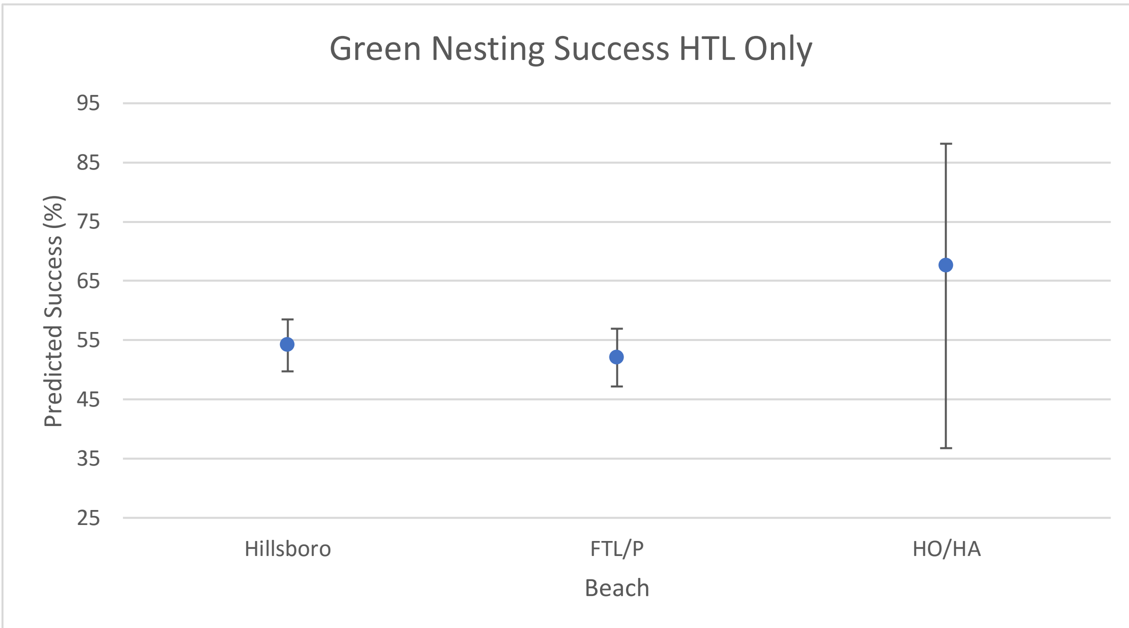

Figure 10. Green sea turtle nesting success, comparing HTL only on beaches (excluding MJSP). The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison for green sea turtle nesting success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included the fixed effect beach and the random effect, zone (Table 5). The model predicted significantly higher nesting success at Hollywood/Hallandale beach than Fort Lauderdale/Pompano Beach (Tukey pair-wise comparison: $p < 0.05$) (Figure 11).

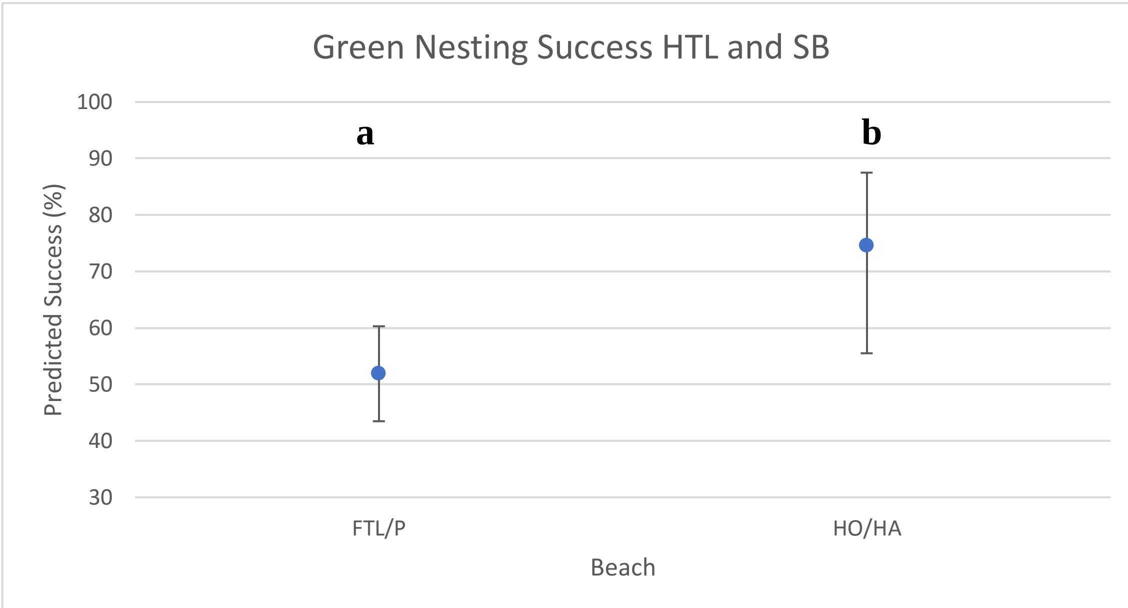

Figure 11. Green sea turtle nesting success comparing HTL and SB cleaning at Fort Lauderdale/Pompano and Hollywood/Hallandale beaches. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Hatch Success

Loggerhead Sea Turtles

When comparing FTL/P and HO/HA for each cleaning type, the best fit model did not include cleaning method, but did include beach in the best fit model. Therefore, each cleaning types were broken down to see the differences among the beaches.

For the dataset comparing no cleaning among all beaches, including MJSP, the best fit model included beach and the random effects year and index (Table 6). The model predicted similar hatch success at MJSP and HO/HA (Tukey pair-wise comparison: $p > 0.05$). The model predicted significantly higher hatch success on MJSP than Hillsboro and Fort Lauderdale/Pompano beaches ((Tukey pair-wise comparison: $p < 0.05$) (Figure 12).

Table 6. Top two models and which was selected for loggerhead sea turtle hatching success for each cleaning type.

Species	Success Type	Cleaning Method	Model	AIC Score	Selected ?
CC	HS	No Clean	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	488.3859	Y
CC	HS	No Clean	$mod18: y = Success\ rate \sim beach + (index)$	489.7275	N
CC	HS	HTL only	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	1694.029	Y
CC	HS	HTL only	$mod6: y = Success\ Rate \sim beach + (year) + (beach/index)$	1696.029	N
CC	HS	HTL and SB	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	155.0131	Y
CC	HS	HTL and SB	$mod18: y = Success\ rate \sim beach + (index)$	156.7098	N

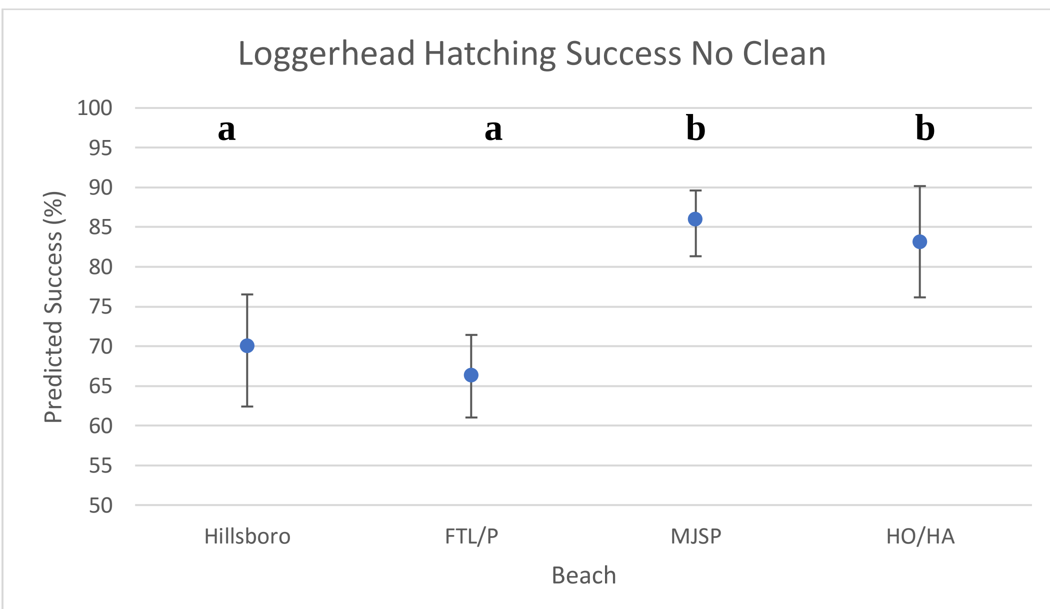

Figure 12. Loggerhead sea turtle hatch success for all beaches. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Similarly, the analysis was run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach as the fixed effect and year and index as the random effects (Table 6). The model showed that all beaches were different from each other (Tukey pair-wise comparisons: all p-values <0.05) (Figure 13). The model predicted a significantly higher hatch success at Hollywood/Hallandale beach.

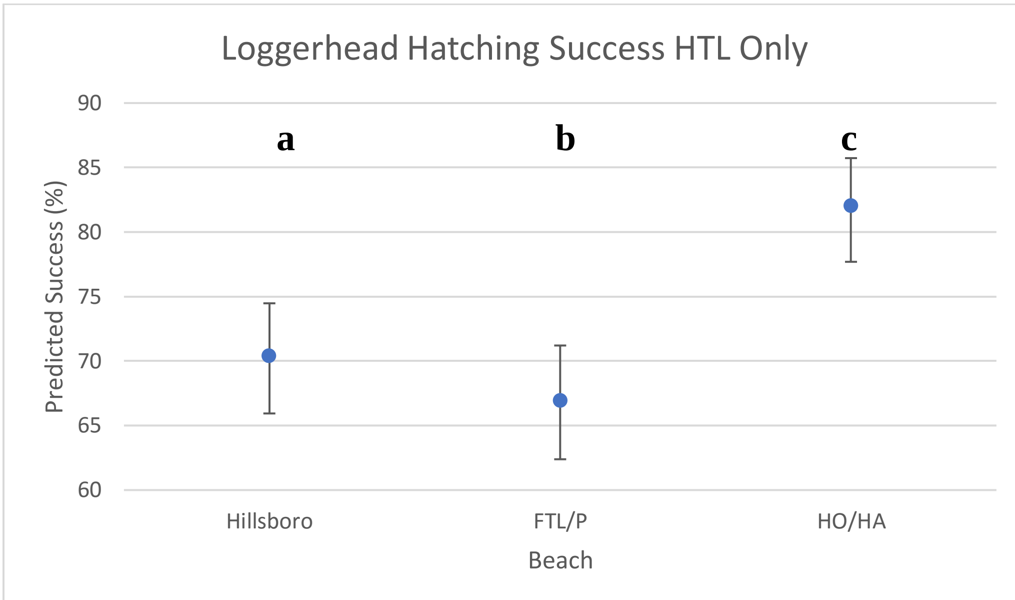

Figure 13. Loggerhead sea turtle hatch success excluding MJSP. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison for loggerhead sea turtle hatch success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included beach as the fixed effect and year and index as the random effects (Table 6). The model predicted significantly higher hatching success at Hollywood/Hallandale beach than Fort Lauderdale/Pompano Beach (Tukey pair-wise comparison: p-value<0.05) (Figure 14).

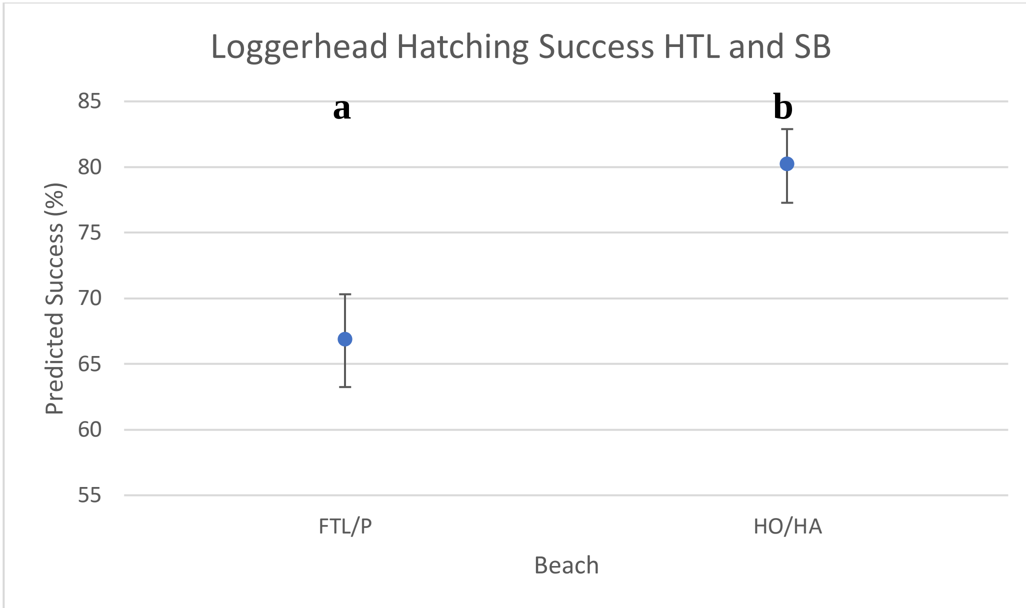

Figure 14. Loggerhead sea turtle hatching success where HTL and SB is the only cleaning method. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Green Sea Turtles

When comparing FTL/P and HO/HA for each cleaning type, the best fit model did not include cleaning method, but did include beach in the best fit model. Therefore, each cleaning types were broken down to see the differences among the beaches.

For the dataset comparing no cleaning, including MJSP, the best fit model included beach as the fixed effect and the random effects year and index (Table 7). The model showed that there was no significant difference between beaches (all p-values > 0.05) (Figure 15).

Table 7. Top two models and which was selected for green sea turtle hatching success for each cleaning type.

Species	Success Type	Cleaning Method	Model	AIC Score	Selected?
CM	HS	No Clean	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	1622.439	Y
CM	HS	No Clean	$mod6: y = Success\ Rate \sim beach + (year) + (beach/index)$	1624.439	N
CM	HS	HTL only	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	626.8885	Y
CM	HS	HTL only	$mod6: y = Success\ Rate \sim beach + (year) + (beach/index)$	628.8885	N
CM	HS	HTL and SB	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	9523.698	Y
CM	HS	HTL and SB	$mod6: y = Success\ Rate \sim beach + (year) + (beach/index)$	9525.698	N

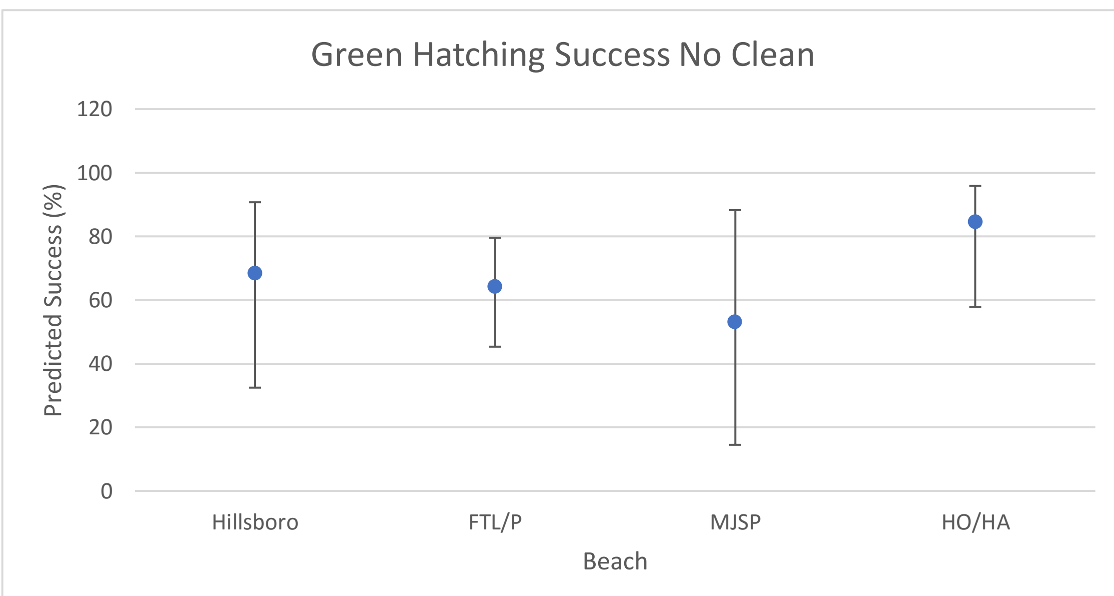

Figure 15. Green sea turtle hatch success where there is no cleaning. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Similarly, models were run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach as a fixed effect and year and index as the random effects (Table 7). The model predicted similar hatching success at Hollywood/Hallandale and Hillsboro as well as Hollywood/Hallandale and Fort Lauderdale/Pompano (Tukey pair-wise comparison: $p>0.05$). There was a significantly higher hatching success rate at Hillsboro than Fort Lauderdale/Pompano beaches (Tukey pair-wise comparison: $p<0.05$) (Figure 16).

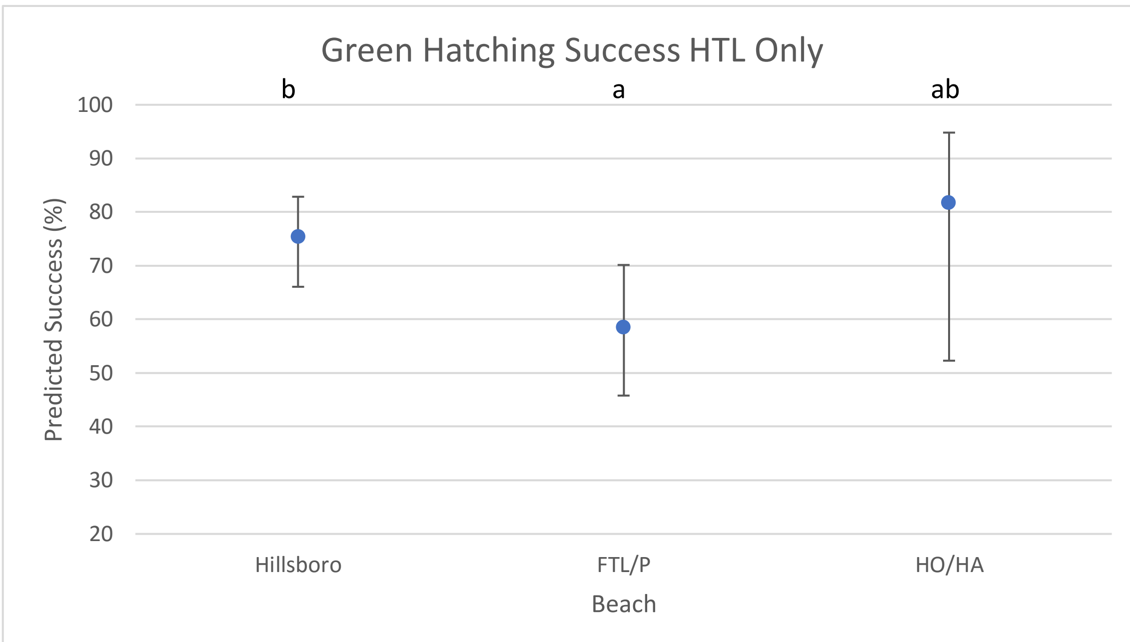

Figure 16. Green sea turtle hatch success where there is cleaning at HTL only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison for green sea turtle hatch success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included beach as the fixed effect and year and index as the random effects (Table 7). The model showed there was no significant difference between Fort Lauderdale/Pompano and Hollywood/Hallandale beaches (Tukey pair-wise comparison: $p >0.05$) (Figure 17).

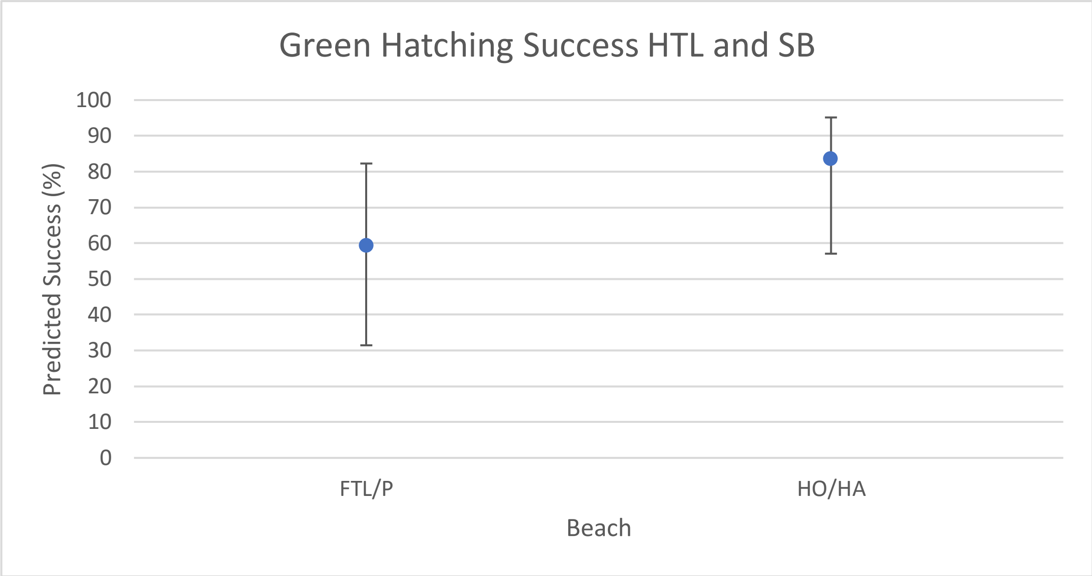

Figure 17. Green sea turtle hatching success where HTL and SB cleaning is present only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Emergence Success

Loggerhead Sea Turtles

When comparing FTL/P and HO/HA for each cleaning type, the best fit model did not include cleaning method, but did include beach in the best fit model. Therefore, each cleaning types were broken down to see the differences among the beaches.

For the dataset comparing no cleaning, including MJSP, the best fit model included beach as the fixed effect and index, and zone as the random effects. Index is nested in zone which is nested in beach (Table 8). The model predicted significantly higher emergence success at MJSP beach than Hollywood/Hallandale, Hillsboro and Fort Lauderdale/Pompano Beaches (Figure 18). Also, the model showed that Hollywood was greater than Hillsboro and Fort Lauderdale/ Pompano (Tukey pair-wise comparison: $p > 0.05$).

Table 8. Top two models and which was selected for loggerhead sea turtle emergence success for each cleaning type.

Species	Success Type	Cleaning Method	Model	AIC Score	Selected?
CC	ES	No Clean	$mod10: y = Success\ Rate \sim beach + (year) + (beach/zone/index)$	31597.31	Y
CC	ES	No Clean	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	31602.61	N
CC	ES	HTL only	$mod10: y = Success\ Rate \sim beach + (year) + (beach/zone/index)$	170112.0	N
CC	ES	HTL only	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	170110.0	Y
CC	ES	HTL and SB	$mod10: y = Success\ Rate \sim beach + (year) + (beach/zone/index)$	41266.95	N
CC	ES	HTL and SB	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	41267.57	Y

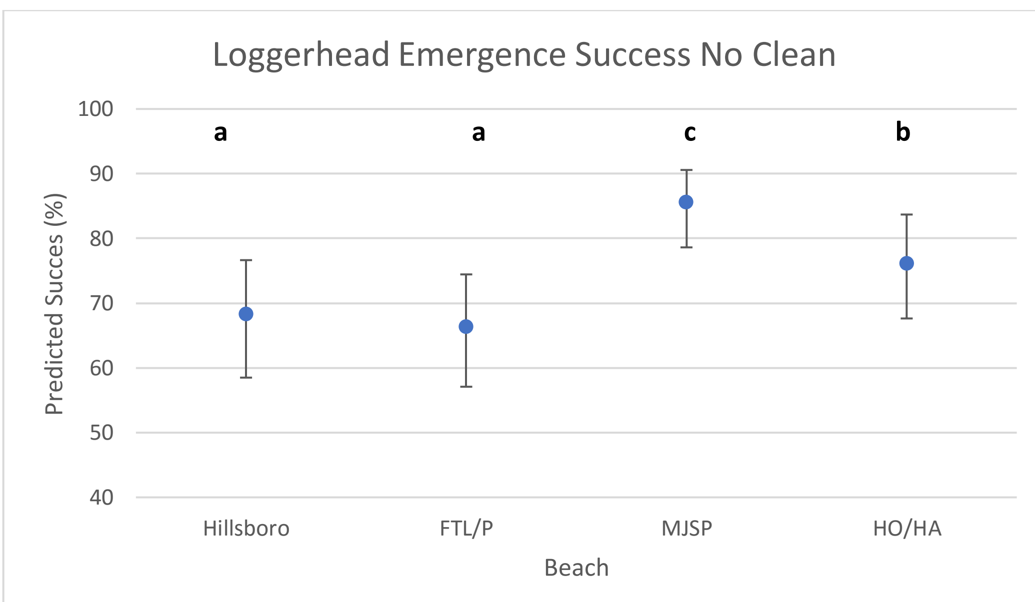

Figure 18. Loggerhead sea turtle emergence success including MJSP. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Similarly, models were run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach as the fixed effect and index, and zone as the random effects. Index is nested in zone which is nested in beach (Table 8). The model predicted a significantly higher emergence success at Hollywood/Hallandale than Hillsboro and Fort Lauderdale/Pompano beaches (Figure 19). The model showed that there were differences between Hollywood/Hallandale and Hillsboro and Hollywood/ Hallandale and Fort Lauderdale/Pompano beaches (Tukey pair-wise comparisons: $p<0.05$) and there was no significant difference between Hillsboro and Fort Lauderdale/Pompano beaches (Tukey pair-wise comparison: $p<0.05$).

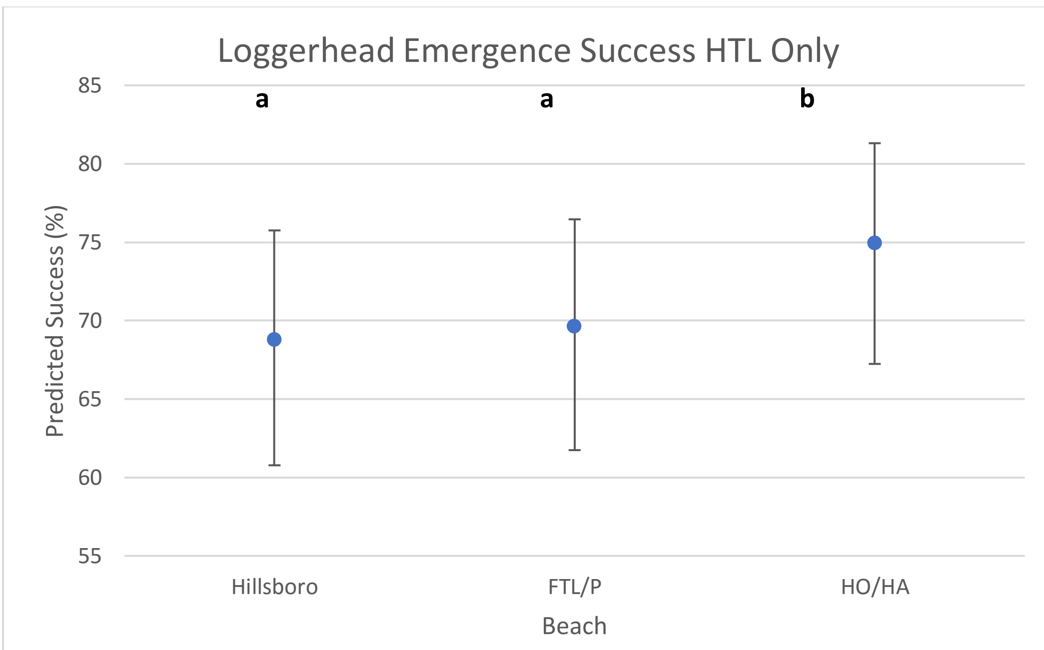

Figure 19. Loggerhead sea turtle emergence success where HTL only cleaning occurs (excluding MJSP). The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison for loggerhead sea turtle emergence success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included beach as the fixed effect and index and zone as the random effects, where index is nested in zone, which is nested in beach (Table 8). The model predicted significantly higher emergence success at Hollywood/Hallandale than Fort Lauderdale/Pompano (Tukey pair-wise comparison: $p <0.0001$) (Figure 20).

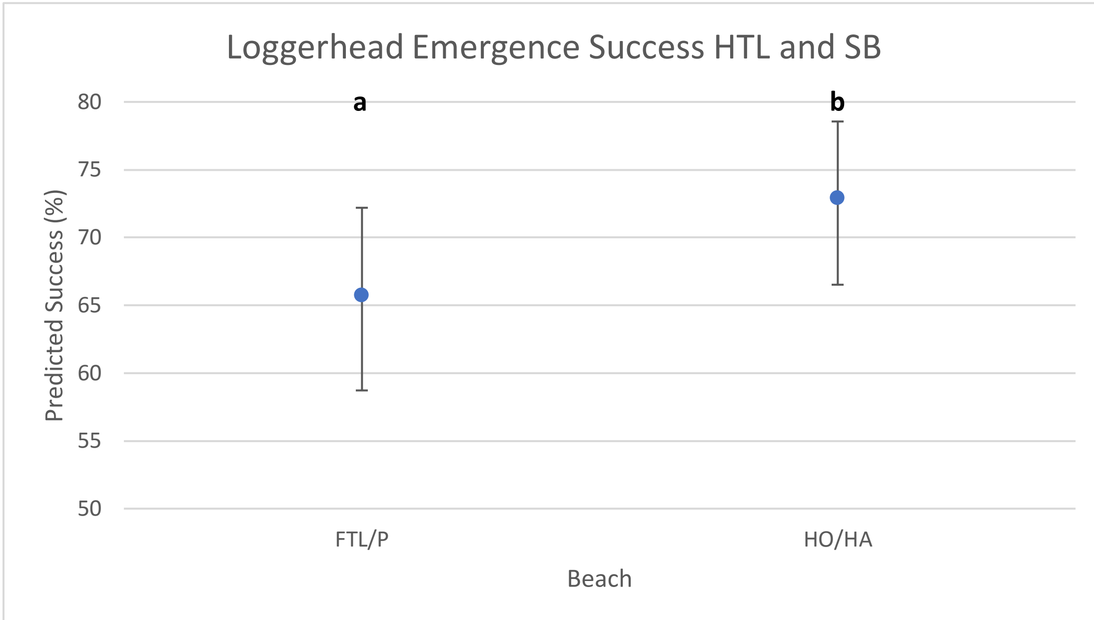

Figure 20. Loggerhead sea turtle emergence success where there is cleaning at HTL and SB only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Green Sea Turtles

When comparing FTL/P and HO/HA for each cleaning type, the best fit model did not include cleaning method, but did include beach in the best fit model. Therefore, each cleaning types were broken down to see the differences among the beaches.

For the dataset comparing no cleaning, including MJSP, the best fit model included beach as the fixed effect and year and index as the random effects (Table 9). The model predicted similar emergence success rates at all beaches (Tukey pair-wise comparison: $p>0.05$) (Figure 21).

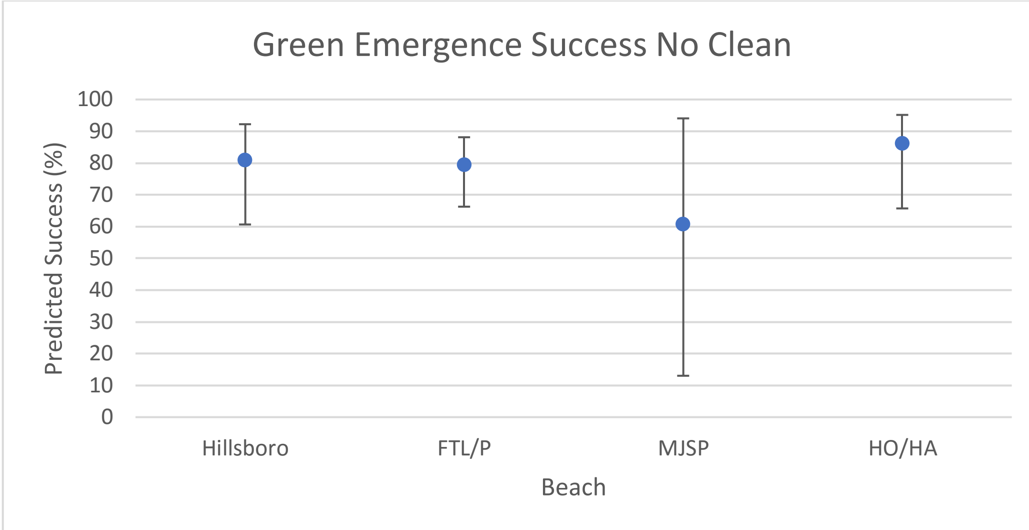

Figure 21. Green sea turtle emergence success among all beaches where no cleaning occurs. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Table 9. Top two models and which was selected for green sea turtle emergence success for each cleaning type.

Species	**Success Type**	**Cleaning Method**	**Model**	**AIC Score**	**Selected?**
CM	ES	No Clean	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	1622.44	Y
CM	ES	No Clean	$mod6: y = Success\ Rate \sim beach + (year) + (\text{beach/index})$	1624.44	N
CM	ES	HTL only	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	9523.70	Y
CM	ES	HTL only	$mod6: y = Success\ Rate \sim beach + (year) + (\text{beach/index})$	9525.70	N
CM	ES	HTL and SB	$mod13: y = Success\ Rate \sim beach + (year) + (index)$	626.89	Y
CM	ES	HTL and SB	$mod6: y = Success\ Rate \sim beach + (year) + (\text{beach/index})$	628.89	N

Similarly, models were run excluding MJSP to compare HTL only cleaning among the other three beaches. The best fit model included beach as the fixed effect and year and index as the random effects (Table 9). The model predicted significantly higher emergence success at Fort Lauderdale/Pompano than Hillsboro (Tukey pair-wise comparison: $p<0.05$) (Figure 22). Fort Lauderdale/Pompano had similar success rate to Hollywood/Hallandale (Tukey pair-wise comparison: $p>0.05$).

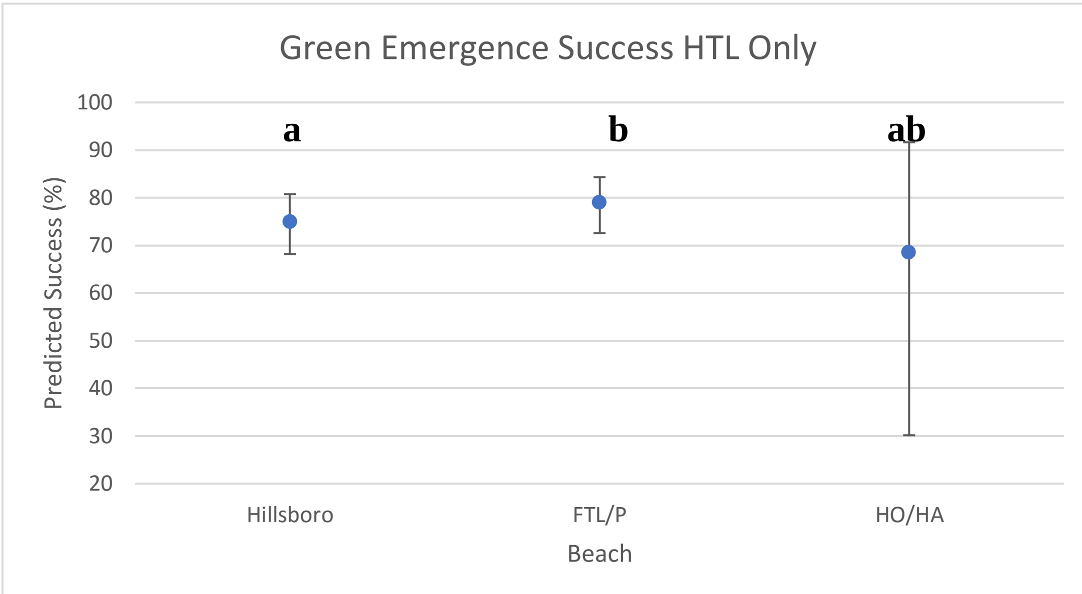

Figure 22. Green sea turtle emergence success where there is cleaning at HTL only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

A third comparison of green sea turtle emergence success was run comparing Fort Lauderdale/Pompano and Hollywood/Hallandale beaches with HTL and SB cleaning. The best fit model included beach as the fixed effect with year and index as the random effects (Table 9). The model showed there was no significant difference between Fort Lauderdale/Pompano and Hollywood/Hallandale beaches (Tukey pair-wise comparisons: all p-values >0.05) (Figure 23).

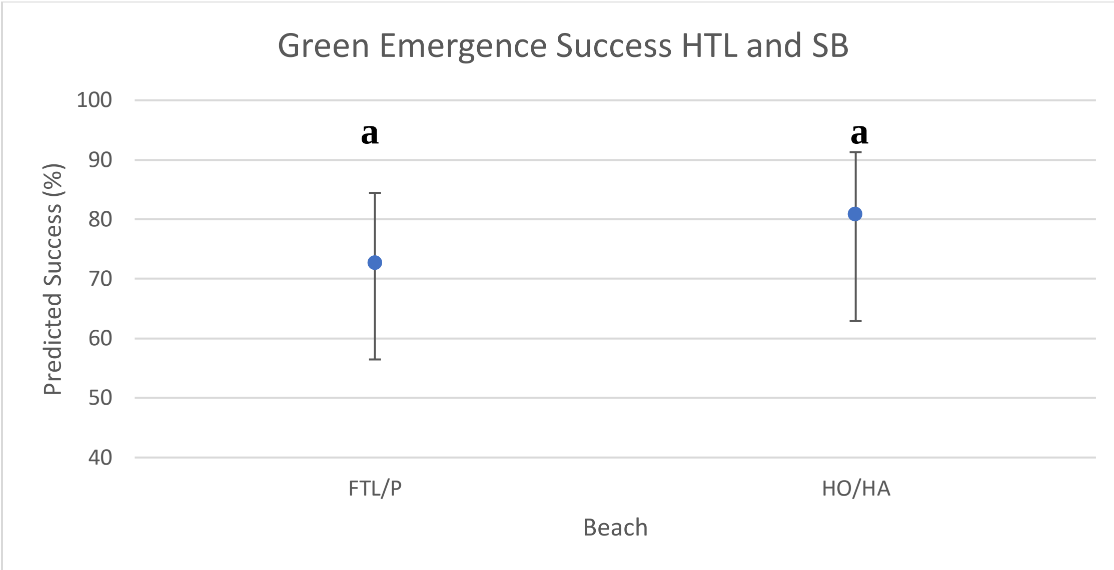

Figure 23. Green sea turtle emergence success where cleaning occurs at HTL and SB only. The letters above the figure are the results from the Tukey Pair-Wise Comparisons test. Values with different letters are statistically different.

Discussion

This study aimed to investigate the effects of mechanical beach cleaning on loggerhead and green sea turtle nesting, hatching, and emergence success. The results indicated that there was a significant impact of mechanical beach cleaning on nesting success only, but no significant impact on hatching and emergence success for both species.

Overall, there was no definitive pattern for mechanical beach cleaning impacts on any of the success rates for either species when comparing the different beaches. The success rates would be expected to be relatively similar across all beaches for each method if mechanical cleaning was the sole influence in nesting, hatching and emergence success. However, the results do not confirm this hypothesis and there are likely other factors that explain the variability in success rates. Most likely physical and environmental characteristics, which differ among beaches may explain different success rates. These differences can include biotic and abiotic factors, such as the physical composition of sand type, precipitation, light pollution, and predation risks.

Predation risks could potentially affect the nesting, hatching and emergence successes that were calculated in this study. Predation levels vary greatly at each beach in Broward County. Sea turtles face the risk of predation at every stage of their life cycle, but it is most prominent for the egg and hatchling stages. Prior to a nest hatching, foxes and raccoons can locate egg chambers and dig up the eggs and hatchlings inside, impacting the hatch and emergence success. Nesting females are also susceptible to harassment by predators, which may play a role in nesting success as a female may return to the ocean before egg laying can commence. For each cleaning type, beaches that had higher success rates were typically beaches with limited predation. MJSP and H experience more predation than FTL/P and HO/HA, however H is left more natural, whereas MJSP is controlled for via caging and eradicating of some predators. However, MJSP, had higher hatch success than H and FTL/P beaches and had higher emergence success than H, FTL/P and HO/HA beaches for loggerhead sea turtles. This could suggest that management practices that MJSP has in place are showing positive results. However, the success rates at Hillsboro beach when compared to MJSP, HO/HA and FTL/P varied for all success rates and each cleaning type. There was no definite pattern that H was worse due to predation, in some situations, H produced higher success rates. For example, for green sea turtle NS when there was no cleaning when compared to all other beaches. For loggerhead NS, H had the higher success rate when there was cleaning at the HTL only. Though, H does experience predation, the predators may not actually be affecting the nesting females in this area of Broward County.

Anthropogenic impacts vary among beaches as well. Humans could have similar impacts as predators on nesting successes. Increased human presence on the beach may cause a nesting female to false crawl rather than successfully nest. Humans inhabiting the coastlines contribute artificial light pollution. Sea turtles in Broward County face the risk of disorientation due to light pollution. Artificial light can hinder the female turtle's ability to find a suitable nesting location (Tuxbury and Salmon 2005). The turtle could be deterred from a suitable nesting beach and choose a suboptimal nesting beach where the survival of hatchlings could be compromised (Murphy 1985, Witherington and Martin 2000). The beaches of FTL/P and HO/HA are heavily populated in the evening hours due to tourist destinations such as restaurants on the beach front. It is unexpected that these areas would have higher nesting success. However, for loggerhead NS comparing the different cleaning types, FTL/P had the higher predicted success rates. This indicated that other factors, other than artificial lighting, are affecting the nesting success rates.

Beach renourishment projects are another example of an anthropogenic impact that occur at many beaches in Broward County. Beach renourishment involves the pumping of sand from different areas onto a beach to mitigate erosion. The renourishment of beaches can impact three abiotic factors necessary for the survival of eggs in a nest: temperature, gas diffusion and moisture content (Packard and Packard 1988). If any of these abiotic factors is compromised, embryo development can be inhibited (Prange and Ackerman 1974). Sand characteristics (i.e. size, type, and sorting of the grains) are also a large component to the success of a nest. If the sand is too compact, the female sea turtle can be deterred from nesting or the hatchlings can have a difficult time emerging from the nest (Grain et al. 1995). Each of the beaches in this study experienced beach renourishment within the years of 1997-2015. HO/HA was renourished in 2005 and has very compact sand compared to the other beaches in the county (pers. observation). This beach experiences more false crawls than nests for both species, however, my data showed that HO/HA had the highest success rates for green nesting success and loggerhead hatching and emergence success when there was cleaning at the HTL or HTL and SB, for green hatching success for all cleaning types, and for green emergence success when there was no cleaning or HTL and SB cleaning. It appears that once the female has dug the nest, breaking up the compact sand, to lay her eggs, the hatchlings are able to successfully exit the nest without sand compaction being an issue. Evidence has showed that the compaction of sand can negatively affect sea turtle nesting success (Kepplan 2013). The compact sand may have played a role in the nesting success of loggerheads, since HO/HA beach did not have the highest success rate for any cleaning type.

Precipitation is another factor that may impact sea turtle hatching and emergence success. When rain water reaches a nest, the hatching success decreases as the eggs become inundated (Foley et al. 2004). Excessive rainfall is another environmental factor that can lead to embryo mortality (Kraemer and Bell 1980). Too much rain can cause the sand to be saturated with water, thus adversely affecting the embryos at an early stage.

The embryos obtain their oxygen through gas diffusion with the egg and the surface of the nest (Ackerman and Prange 1972). Conversely, increased air and water temperatures and an absence of rain, can cause the egg chamber to reach a thermal threshold where it is too warm for embryo development leading (Laloë et al. 2016, Matsuzawa et al 2002).

Hillsboro and MJSP are not as wide as Hollywood/Hallandale or Fort Lauderdale/Pompano and are less disturbed by foot traffic. Because H and MJSP are not as wide, there is less surface area for the turtles to nest solely on the sandy beach and they tend to nest in the dunes or in vegetation. This allows for shading of the nests which can prolong incubation time and yield a higher success rate (Patino-Martinez et al 2012, Wood et al 2014). However, in this study, it was found that H and MJSP did not have the highest success rates for most of the cleaning types for each species. This could indicate that other factors are affecting the success rates.

Conclusion

These above environmental conditions play an instrumental role in the success of sea turtles. Increased knowledge of how these environmental conditions impact sea turtle nesting, hatching and emergence success is vital for our understanding of the threats that sea turtles face. Future work should be aimed at investigating which environmental factors are responsible for the differences between nesting, hatching and emergence successes determined at the individual beaches from this study. While this study found no significant effect of mechanical beach cleaning on hatching and emergence success, the use of this cleaning should not be overlooked.

In some R zones, several structures/locations are not inhabited by people and thus no cleaning takes place. However, since there was cleaning that took place in the R zone, that R zone was still classified into a cleaning type. The impact of mechanical beach cleaning may be different at other locations throughout Florida. Future studies should be conducted to examine the effects of mechanical beach cleaning where cleaning pressures and tourism are different from the beaches in this study (i.e., less populated and/ or not cleaned as frequently).

The null impact of mechanical beach cleaning as determined in this study should not be taken as fact for other counties throughout Florida. However, while the results of this study do not indicate a significant effect of mechanical beach cleaning on sea turtle hatch and emergence success, they do for nesting success. The management and conservation efforts are starting to show positive impacts with rising nesting numbers for both loggerhead and green sea turtles. The impact that mechanical beach cleaning has on nesting success should be considered for management and the oversight between the Broward County Sea Turtle Conservation Program and the mechanical beach cleaning groups should continue.

Funding

This study is made possible by my current employment with the Broward County Sea Turtle Conservation Program. This allows for continued data collection and use of the long-term data set from 1991-2015.

Acknowledgements

I would like to first thank my advisors, Dr. Derek Burkholder, Dr. Jeremy Vaudo and Dr. Kenneth Banks for their support and guidance of sea turtles, statistics and ecology throughout this process. With special thanks to Stephanie Kedzuf and Glenn Goodwin for their sea turtle expertise and knowledge. A large part of my success is due to my family and friends for their endless support throughout my time at Nova Southeastern University, for that I thank you all. Finally, I would like to thank FWC for allowing me to do this project and Broward County Sea Turtle Conservation Program for providing me with a fantastic opportunity working in the field and the use of their data for this project

Appendix

False Crawl Data Sheet

BEACH: ____________ DATE: ____________ SURVEYOR NAME(S) (PRINT): ____________

FC Number	Species	Trim?	Apex GPS Latitude	Apex GPS Longitude	R-Zone	Distance HTL (ft)	Distance Dune (ft)	Final Digging Activity?	ONA with Scarp?	Remarks
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						
				-80						

Appendix 1. False crawl data sheet.

In Situ Nesting Data Sheet

BEACH:___________ DATE: _______________________________________ SURVEYOR NAME(S) (PRINT): _________________________________

Nest Number	Species	Trim?	Egg Chamber GPS Latitude	Egg Chamber GPS Longitude	R-zone	Track Width (cm)	Distance HTL (ft)	Distance Dune (ft)	ONA with Scarp?
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				
				-80					
Address:					Remarks:				

Appendix 2. Nesting data sheet.

Hatch Data Sheet						BEACH: ___________
Nest Number	**R-Zone**	**Egg Chamber GPS Latitude**	**Egg Chamber GPS Longitude**	**Hatch Date**	**Initials (3)**	**Notes**
			-80			
			-80			
			-80			
			-80			
			-80			
			-80			
			-80			
			-80			
			-80			
			-80			
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			-80			
			-80			
			-80			
			-80			
			-80			
			-80			

Appendix 3. Hatch-out data sheet.

Excavation Data Sheet **YEAR: ________** **BEACH: ________**

Nest #	GPS Lat.	GPS Long.	Species	Hatch Date	Exc. Date	CD	LIN	LPIP	DIN	DPIP	VD	NVD	W	H Eggs	Remarks	Initials
		-80														
		-80														
		-80														
		-80														
		-80														
		-80														
		-80														
		-80														
		-80														
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		-80														
		-80														
		-80														
		-80														
		-80														
		-80														
		-80														

Appendix 4. Nest excavation data sheet. See text for details.

Pulled Nest Data Sheet | **BEACH:** _______

Nest Number	Date Pulled	GPS Latitude	GPS Longitude	Reason Pulled	Initials (3)
			-80		
			-80		
			-80		
			-80		
			-80		
			-80		
			-80		
			-80		
			-80		
			-80		
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			-80		
			-80		
			-80		
			-80		
			-80		

Appendix 5. Pulled nest data sheet.

References

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