Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Forty Years of Monitoring Increasing Sea Turtle Abundance in the Gulf of Mexico

Jacob Lasala (jlasala@mote.org)
Mote Marine Laboratory
Melissa C Macksey
Mote Marine Laboratory
Kristen T Mazzarella
Mote Marine Laboratory
Kevan L Main
Mote Marine Laboratory
Jerris J Foote
Parks Recreation and Natural Resources, Sarasota County
Anton D Tucker
Marine Science Program, Biodiversity and Conservation Science, Department of Biodiversity, Conservation and Attractions

Article

Keywords: trend monitoring, citizen science, fishery bycatch, direct harvest, recovery, climate change, Caretta, Chelonia

Posted Date: June 27th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3040773/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on October 11th, 2023. See the published version at https://doi.org/10.1038/s41598-023-43651-4.

Abstract

Longitudinal data sets for population abundance are essential for studies of imperiled organisms with long life spans or migratory movements, such as marine turtles. Population status trends are crucial for conservation managers to assess recovery effectiveness. A direct assessment of population growth is the enumeration of nesting numbers and quantifying nest attempts (successful nests / unsuccessful attempts) and emergence success (number of hatchlings leaving the nest) because of the substantial annual variations due to nest placement, predation, and storm activity. We documented over 133,000 sea turtle crawls for 50.9 km (31.5 miles) of Florida Gulf of Mexico coastline from 1982–2021 for a large loggerhead turtle nesting aggregation and a recovering remnant population of green sea turtles. Nest counts and hatchling production for both species have significantly increased, but emergence success has not. Sea level rise and coastal developments undoubtedly influence habitats in the long-term, impacting nest site selection and potential recruitment from the loss of emerged hatchlings. However, the present indications for steady Gulf of Mexico recovery of loggerhead and green sea turtles and range expansions of Kemp's ridley and leatherback turtles parallel findings of the Florida Atlantic coasts. This study indicates that effective conservation practices can be detected within time scales of 1–2 turtle generations.

INTRODUCTION

Longitudinal data sets and analyses are essential to long term conservation plans of a species[1–3]. In ideal situations, observations of behavior can be combined with census counts of individuals[4, 5] thus allowing researchers to quantify how populations change over time. For many species, especially those that are threatened or endangered, these changes may be difficult to observe[6, 7] and proxies for direct observation must be used instead. This is especially true for animals that migrate from foraging grounds to breeding grounds[8–10] and might not be easily accessible year-round, such as marine turtles.

Marine turtles are one of the few reptiles that migrate long-distances between foraging areas and breeding areas[11, 12]. Observational data linked with mark-recapture histories indicate that migration cycles are resource driven and food availability can affect the time-frame between breeding seasons[13–15]. Remigration cycle shifts may influence recruitment rates, possibly impacting a population's growth over time. Some demographic studies of marine turtles occur in-water through mark-recapture techniques[16–18], but most estimates of population size are made during the breeding season from evidence of female tracks at nesting beaches. Females, their nests, and the resulting hatchlings are accessible on the beach during the nesting season and provide a baseline for population trends[19–21]. Marine turtles reach sexual maturity later than other reptiles and have a long lifespan [22–25] reducing the likelihood that changes within a population are immediately apparent. Long term beach monitoring data can provide a reference point for the health of that breeding population[26–28] and by coupling nest counts with reproductive success data researchers can predict future issues stemming from population fitness changes[29].

The prevailing theory of marine turtle population structure suggests that data from one beach may not be enough to see the full picture of a breeding population[30]. Marine turtle genetic population structure is driven by female natal philopatry[31] and gene flow occurs throughout the region as males travel along the coast toward their breeding areas[32, 33]. More recent studies propose that population subdivision creates pockets of subpopulations[30, 34, 35]. It is therefore critical to document monitoring for more than a decade of contiguous nesting beaches to assay a region's population trend[36, 37].

Marine turtles are threatened globally. In some regions they are hunted for their meat and shells, their eggs are poached, and turtles can be caught as bycatch[38–40]. Pollution in the ocean increases the likelihood of plastic ingestion or death and boat strikes are prevalent near populated areas[41, 42]. Their nesting beaches are at risk from armoring/sand nourishment techniques, their nests are at risk of predation, and hatchling disorientation/misorientation from artificial lighting[43–45]. However, abundance research provides conservation managers with tools to better protect these animals. The loggerhead sea turtle (*Caretta caretta)* nesting aggregation on the Northwest Atlantic Ocean is the largest in the world[46], and 90% of these nests are laid in Florida[47, 48]. Green sea turtle (*Chelonia mydas*) nesting populations have been rapidly increasing in Florida since 1998[49, 50]; these increases have resulted in the down-listing of this species from “endangered” to “threatened” [51]. Much of the research on these and other species of marine turtles occurs on the East coast of Florida, where nesting density is high[52–54]. Few studies have focused on Florida’s Gulf of Mexico coastline[28, 55, 56], despite the growing nesting populations in this region. Programs that have monitored marine turtle nesting over time are invaluable to identifying trends of how populations have changed through time [27,57.58].

The primary goal of this project was to determine how nesting counts and hatchling production have changed over time and to quantify how nesting turtles on these beaches are contributing to the greater Gulf of Mexico marine turtle populations. The secondary goal was to assess how the different beaches contribute to the population and to identify regions that are more or less productive to inform regional conservation managers of these trends.

METHODS

Study sites

Since 1982, the Mote Marine Laboratory Sea Turtle Conservation and Research Program (MML STCRP) has standardized annual monitoring for 50.9 km (31.5 miles) of nesting habitat across six beaches in Sarasota County, Florida. With 40 years of continuous data, STCRP is uniquely placed to identify trends in the growing population and to estimate how this population’s breeding behavior has changed over time. Sarasota County hosts the largest nesting aggregation of loggerheads within the Gulf of Mexico and is an excellent representation of the growth of nesting in the region[59, 60].

During the nesting season (April-October), MML STCRP staff and volunteers monitor sea turtle nesting during morning patrols on six beaches in Sarasota County. The majority of these barrier islands are considered to be critically eroded[61] and residents of these coastal communities have attempted to safeguard their beaches through beach nourishment and/or implementing coastal armoring techniques. These activities can negatively impact sea turtle nesting behavior[62–65]. Each beach varies in length, sand color and sand grain, armoring, nourishment, and profile (Table 1, Fig. 1).

Table 1
Six beaches in Sarasota County, Florida, USA that STCRP monitors annually (mapped in Fig. 1). Each beach is unique in length, sand color/albedo/grain size, beach profile, nourishment, and armoring methods.

Beach	Length km (mi)	Sand Color	Sand Grain	Beach Profile	Nourished? (# of times)	Armoring
Longboat Key	17.1 (10.6)	White - Brown	Fine - Medium	Moderate	Yes (18)	seawalls, groins, rock revetments
Lido Key	5.3 (3.3)	White	Fine	Flat - Moderate	Yes (10)	groins, rock revetments
North Siesta Key	5.2 (3.2)	White - Brown	Very Fine	Flat	No	outfalls, groins, rock revetments
South Siesta Key	4.1 (2.5)	Dark	Coarse	Dynamic	Yes (2)	rock revetments
Casey Key	11.8 (7.3)	Brown	Medium	Flat - Moderate	No	seawalls, groins, rock revetments, pilings, jetty, sandbags, stepped revetments, geotextile container
Venice	7.4 (4.6)	Dark	Coarse	Dynamic	Yes (5)	outfalls, rock revetments, jetty

Coordinated citizen science nesting surveys

All beaches monitored by MML STCRP fall under the Statewide Nesting Beach Survey (SNBS) program under the Florida Fish and Wildlife Conservation Commission (FWC). Siesta Key is also part of a standardized data collection program called the Index Nesting Beach Survey (INBS). These two programs are designed to assess the distribution and abundance of sea turtle nesting across Florida to inform beach managers of coastal development issues and promote the recovery of sea turtles[57, 66]. Survey data are collected through permit holders, but the core of the data could not be collected without the help of trained volunteers who patrol the beaches to identify and document sea turtle ocean emergences. One such volunteer group: Longboat Key Turtle Watch started quantifying nesting activity in 1969 and was a pioneering example for other long-term projects in the region. Since 2005, volunteers log an average 19,000 + hours every nesting season.

Annual daily monitoring was conducted from April 15 (May 1st prior to 2016) through October 31, or three days after the final nest hatched. Permitted personnel traveled the shoreline at dawn above the mean high-water line to document turtle nesting activity. Using Florida Fish and Wildlife's marine turtle guidelines[67], each activity was classified as a nest or a non-nesting emergence (also known as a false crawl) and the species was identified via crawl pattern. A nest was defined as a turtle emergence from the surf that resulted in the turtle successfully depositing eggs in the sand. A non-nesting emergence was defined as an emergence that did not result in egg deposition. *Nesting success* was calculated as the proportion of emergences that resulted in a nest and served as an indicator of a beach's nesting suitability:

$$NestingSuccess = \frac{\#nests}{\#nests + \#falsecrawls} \quad (1)$$

Nesting density is an index of nest distribution and is used as a metric for conservation success when assessed over time:

$$NestingDensity = \frac{\#nests}{distance\,(km)}$$

(2)

Most nests were left in situ, but nests laid during active nourishment projects were relocated by 9 AM the morning after deposition – eggs were transported to a location higher on the beach and placed into an artificially produced nest chamber that closely resembled the original nest chamber in shape, size, and depth. Additionally, regulations reflecting the potential negative impacts of nest relocations were not set prior to 1987 and many nests were relocated to protective “hatcheries.”

Turtle crawl locations were documented in relation to the nearest Florida Department of Environmental Protection (FDEP) range monument to the north and, beginning in 2004, with global positioning system (GPS). Starting in 1997, personnel measured the distance from the nest or false crawl apex to the closest upland vegetation/barrier and from the nest or false crawl apex to the day’s mean high-water line. By adding these two values together, total *beach width* was estimated. These measurements were used to assess nest site selection in relation to the lower, middle, or upper thirds of the beach, regardless of beach width.

Prior to 2013, all nests were monitored, eggs verified, marked with stakes and checked daily for depredation, disorientation/misorientation, wash-overs/inundation, wash outs and hatchling emergences. By 2013, the nesting population had grown too large to monitor and stake every nest. Following communication with FWC, MML STCRP shifted to a new sampling protocol based on turtle species and beach nesting density. On moderate to high density non-nourished beaches all loggerhead nests laid on Wednesdays were verified and monitored; all nests on low density beaches, all rare species (green, Kemp’s ridley, leatherback) nests, research nests, relocated nests, and all nests in nourishment areas were monitored.

Nest depredation occurs when a native or non-native organism preys on incubating sea turtle eggs and hatchlings. In Sarasota County, depredation occurs from native predators (raccoons, armadillos, ghost crabs, coyote) and from introduced predators (fire ants). Depredation events include predators digging into a nest and removing or damaging nest contents, subsequently impacting hatchling production. From 1982–2020, to mitigate depredation, all verified rare species nests and some loggerhead nests in high depredation areas had self-releasing cages and/or screens installed.

After a monitored nest hatched and the hatchlings emerged, MML STCRP determined whether the hatchlings disoriented/misoriented en route to the Gulf. When a hatchling becomes disoriented, their tracks don’t lead to a specific location (often tracks loop as they work out where to go). When a hatchling is misoriented their tracks lead towards an incorrect location (i.e. not the ocean). Disorientation or misorientation events can be caused by natural and artificial lighting[68]. MML STCRP documents every disorientation/misorientation event, but their impact on hatchling survival is not fully described here.

Incubation duration was assessed by subtracting the date the nest emerged by the date the nest was laid. MML STCRP staff excavated the nest three days following an observed emergence. If an emergence was not noted, excavations occurred after 70 days of incubation (80 days on North Siesta Key, where cooler sand temperature extends the incubation duration, and for all leatherback nests). During an excavation, nest contents were classified by counting hatched eggshells, hatchlings, and remaining unhatched eggs. These counts were used to determine the *emergence*

success of the nest. *Emergence success* quantified how many hatchlings exited the nest chamber and made it to the surface.

$$(3) Emergence Success = \frac{\#hatched eggs - (live hatchlings in nest chamber + dead hatchlings in nest chamber)}{total clutch size}$$

Emergence success was calculated for all nests from 1982–2012, but only for monitored nests from 2013–2021 (see above). To remove potential bias from relocations, only *in situ* nests were included in the hatch and emergence success calculations. Partial depredations and partial washouts were removed from overall success calculations, because we cannot ascertain how many eggs were lost. Full depredations and full washouts were included as zero (0) success because the entire nest was removed from productivity. By compiling these data, the *annual hatchling production* was assessed using regression analysis by beach and year (a further explanation can be found in Supplementary Information A). Two values are provided here: 1) a minimum number of hatchlings confirmed from all excavations from 1982–2021 and 2) a high estimated number of hatchlings if MML STCRP had monitored and excavated every nest post-2013.

Data standardization and analysis

All data were assessed and analyzed from 1982–2021. All analyses were performed on loggerhead and green data sets. MML STCRP also identified nests and false crawls from Kemp's ridleys, leatherbacks and loggerhead/hawksbill hybrids (confirmed by genetics, B. Shamblin *pers comm.*), but the total number of these rare sea turtles nesting in the region remains too low to make inferences about overall nesting behavior. Further, adjustments were made to the beach protocol over time (see above); thus, not all parameters could be compared and analyzed throughout the timeframe. Nest counts, nesting density, nesting success, and incubation duration were all compared for the full 40-year monitoring timeframe (emergence success for 35 years). Nest location placement was only compared from 1997–2021. A separate data set removing beaches by the year that they were nourished is analyzed and the results are presented in Supplemental Information B.

All analyses were run in Program R[69] and all maps were made using QGIS 3.16[70]. All data were tested for normality (Shapiro-Wilk or Kolmogorov-Smirnov tests) and homoscedasticity (Levene's test). Most data were non-normal and most tests were non-parametric. To identify if there were differences in nest counts, nesting density via beach or year, generalized linear models were assessed and post-hoc Dunn tests were performed. Siegel nonparametric linear regression was used to determine if first and last nest dates had changed over the course of the study for both species and for analysis of incubation duration and emergence success over time (unless parametric linear regression could be used). Both nesting success and hatch/emergence success are proportions that range between values of 0 and 1 and modified beta regression models were run to explore whether nesting success or emergence success were affected by abiotic factors including Year, Beach Width, Date of Activity and Latitude (proxied by FDEP monument)[71]. Finally, Kruskal-Wallis tests were used to compare nest site selection in relation to the spatial placement on the beach.

RESULTS

With the help of up to 300 annual volunteers, interns, and the Longboat Key Turtle Watch, MML STCRP documented 133,835 marine turtle crawls over the course of the study; 48.7% of these crawls resulted in nests (65,233). Of those nests, 98.5% (64,269) were laid by loggerheads. There were 608 green sea turtle nests, ten Kemp's ridley nests, five leatherback nests and two known loggerhead/hawksbill hybrid nests.

Nesting counts for loggerheads and *rare species* increased since monitoring began (Fig. 2). The nest count data for both loggerheads and green sea turtles were not normally distributed (Shapiro-Wilk: loggerheads: $W = 0.71$, $p < 0.001$;

green sea turtles: W = 0.42, p < 0.001) and all tests run were therefore non-parametric. No other species data were analyzed due to small sample size. For loggerheads, there were significant differences in nest counts due to year and by beach (χ^2 = 84.59, df = 39, p < 0.001; χ^2 = 142.83, df = 5, p < 0.001 respectively). Post-hoc tests revealed that Casey Key had significantly higher nest counts than the other beaches and Lido Key and North Siesta Key had significantly fewer nests than the other beaches. For green sea turtles, even though the nesting population was growing there was no significant difference in nest counts due to year (χ^2 = 28.03, df = 26, p = 0.36). However, green sea turtle nesting counts were significantly higher on Casey Key than on all of the other beaches (χ^2 = 16.91, df = 5, p < 0.001).

Species seasonal phenology, density, and success

The earliest loggerhead nest was laid on April 20 and the latest was laid on September 30, and for green sea turtles: May 21 and September 19, respectively. Nest dates have significantly shifted earlier in the year for both loggerheads (V = 37, df = 38, p < 0.001) and for green sea turtles (V = 76.5, df = 22, p = 0.037; Fig. 3). Last nest dates have not significantly shifted later for loggerheads (V = 437, df = 38, p = 0.104), but they have shifted significantly later for green sea turtles (V = 298, df = 22, p < 0.001).

Nesting density for both loggerheads and green sea turtles were not normally distributed (W = 0.79, p < 0.001; W = 0.49, p < 0.001). For loggerheads, nesting density ($\bar{x}$: 30.7 nests/km) significantly increased over time and was significantly different between beaches (χ^2 = 96.12, df = 39, p < 0.001; χ^2 = 129.54, df = 5, p < 0.001; Fig. 4). Loggerhead nesting density was highest on Casey Key and lowest on North Siesta Key. For green sea turtles, nesting density ($\bar{x}$: 0.822 nests/km) increased over time – but not significantly (χ^2 = 30.43, df = 25, p = 0.21); but there were significant differences by beach (χ^2 = 16.36, df = 5, p = 0.01). Post-hoc tests determined that green sea turtles prefer to nest on Casey Key and South Siesta Key, and have never nested on North Siesta Key.

Nesting success for both species were not normally distributed (loggerheads: W = 0.97, p < 0.001; green sea turtles: W = 0.91, p < 0.001). Loggerhead nesting success declined over time, but not significantly ($\bar{x}$: 0.49 ± 0.14; χ^2 = 51.57, df = 39, p = 0.09). Loggerhead nesting success significantly varied between beaches (χ^2 = 68.39, df = 5, p < 0.001) – nesting success was highest on South Siesta Key (0.57) and lowest on North Siesta Key (0.38). Nesting success for green sea turtles varied widely ($\bar{x}$: 0.53 ± 0.33), but it did not significantly vary by year (χ^2 = 30.967, df = 30, p = 0.42), nor by beach (χ^2 = 4.577, df = 5, p = 0.47, despite the lack of nesting on North Siesta Key).

Species incubation and emergence success

The average incubation duration and emergence success for loggerheads across all beaches (derived from 34,194 nests) was 58.9 days and 52.1%, respectively. Over the course of the project, incubation duration was not normally distributed (W = 0.919, p = 0.008), but emergence success was (W = 0.962, p = 0.193). Incubation duration has significantly increased over the course of the study (V = 741, df = 37, p < 0.001) and it significantly varied between beaches (χ^2 = 114.87, df = 5, p < 0.001). The longest average incubation duration was on North Siesta Key (77.6 days in 2015) and the shortest average on Venice (50.9 days in 1994). There was no significant difference in emergence success over time ($F_{1,38}$ = 0.251, p = 0.619), but it was significantly different between beaches ($F_{5,216}$ = 13.54, p < 0.001). Over all years Casey Key had the highest average emergence success (61.1%) and North Siesta Key the lowest (28.3%). From 1982–2021, the minimum number of loggerhead hatchlings that emerged from these nests was 2,180,700, but using multiple regression models outlined in Supplementary Information, we estimate a higher value of 3,078,811. Casey Key produces the most hatchlings annually ($\bar{x}$: 24,000–33,500 per year, see Fig. 5).

Of the 608 green sea turtle nests that were laid, 484 nests emerged (79.6%), resulting in 40,580 hatchlings. The average incubation duration was 58.4 days and the average emergence success was 63.7%. Over the course of the study, both

were normally distributed (emergence success: W = 0.959, p = 0.479; incubation duration: W = 0.953, p = 0.331). Incubation duration has not significantly changed over the course of the study ($F_{1,20}$ = 2.524, p = 0.128), but it did significantly differ between beaches ($F_{4,47}$ =5.446, p = 0.001) – Lido Key has significantly higher incubation duration than both South Siesta Key and Venice. There was a significant decline in emergence success over time ($F_{1,21}$ = 12.03, p = 0.002) and there was no significant difference in emergence success between beaches ($F_{4,49}$ = 0.503, p = 0.734). There were 320 Kemp's ridley hatchlings that emerged from nests (incubation $\bar{x}$: 63.8 days, emergence success $\bar{x}$: 27.3%) and 165 loggerhead/hawksbill hybrid hatchlings (incubation $\bar{x}$: 54 days, emergence success $\bar{x}$: 50%). None of the five leatherback nests hatched.

Effects of nest site selection on nest success

Only statistically significant values are explained below, full model breakdowns are in Supplementary Information.

For loggerheads, nesting success significantly increased from north to south (z = -7.75, p < 0.001) and significantly decreased as the beach widened (z = -12.84, p < 0.001). Nesting success was also significantly different when these terms interact (z = 7.28, p < 0.001). For green sea turtles: nesting success significantly decreased from north to south (z = -2.41, p = 0.02) and significantly decreased as the beach widened (z = -1.99, p = 0.046, Fig. 6). Emergence success for loggerheads significantly increased from north to south (z = 2.68, p = 0.007). Emergence success significantly decreased over the course of the nesting season (z = -2.45, p = 0.014) and significantly decreased over the course of the study (z = -2.69, p = 0.007). For green sea turtles, emergence success significantly increased over the course of the study (z = 2.45, p = 0.014); significantly increased from north to south (z = 2.05, p = 0.04), as the beach widened (z = 3.92, p < 0.001), and significantly decreased over the course of the season (z = -2.71, p = 0.007).

For both species, nest site selection differed between the upper, middle, and lower portions of the beach (by width, Table 2). Loggerheads significantly preferred to nest in the upper portion of the beach – nearer to the dune (χ^2 = 962.92, df = 2, p < 0.001), but they were significantly more successful at nesting in the middle (χ^2 = 419.05, df = 2, p < 0.001). Loggerheads had a significantly higher emergence success in the upper portion of the beach (χ^2 = 208.62, df = 2, p < 0.001), and a significantly lower incubation duration in the lower part of the beach (χ^2 = 101.72, df = 2, p < 0.001). Green sea turtles significantly prefer to nest in the upper part of the beach near or in the dune (χ^2 = 58.64, df = 2, p < 0.001), are significantly more successful at nesting in the upper portion (χ^2 = 9.02, df = 2, p = 0.01), and have significantly lower emergence success in the lower portion (χ^2 = 11.65, df = 2, p < 0.001). There was a significant difference in incubation duration in relation to location on the beach (χ^2 = 6.06, df = 2, p = 0.048), nests laid in the upper portion of the beach had a higher average incubation duration.

Table 2
Nest site selection, nesting success, emergence success, and incubation duration within three spatial "thirds" of the beach width. Significantly different values are described in the text but are **bolded** in the table.

	Loggerheads				**Greens**			
	Nest Placement	Nesting Success	Emergence Success	Incubation	Nest Placement	Nesting Success	Emergence Success	Incubation
Lower	**16.7%**	**38.0%**	**40.6%**	**58.4**	**3.8%**	**38.3%**	**30.5%**	58.8
Middle	**28.2%**	**55.7%**	**48.6%**	59.6	**11.2%**	**44.7%**	**58.8%**	57.4
Upper	**55.1%**	**48.3%**	**58.2%**	59.3	**85.0%**	**51.4%**	**65.9%**	59.1

During some years, storm activity and high surf can effectively remove the lower and middle portions of the beach over the course of the season. To account for this spatial difference, separate models were run to determine if nest placement, nesting success, emergence success, and incubation duration were impacted by the continuous variable of distance to the upper barrier or dune. For loggerheads, nest placement was significantly more likely to be closer to the upland barrier ($t = -18.77$, $df = 9786$, $p < 0.001$), nesting success was significantly greater closer to the upland barrier ($z = -28.33$, $df = 9787$, $p < 0.001$); emergence success significantly declined further from the upland barrier ($z = -12.72$, $df = 5628$, $p < 0.001$, Fig. 7), and incubation duration significantly increased further from the upland barrier ($t = 5.29$, $df = 4935$, $p < 0.001$). For green sea turtles, nest placement was significantly more likely closer to the upland barrier ($t = -7.03$, $df = 466$, $p < 0.001$), but nesting success did not differ ($z = -1.28$, $df = 466$, $p = 0.20$); emergence success significantly declined farther from the upland barrier ($z = -1.99$, $df = 235$, $p = 0.473$), and incubation duration significantly declined farther from the upland barrier ($t = -2.75$, $df = 223$, $p = 0.006$).

DISCUSSION

Although loggerhead nesting counts have increased across Florida beaches[59], there has not been a significant increase in the overall number of breeding females in the past 30 years[66] hampering a strong recovery of the overall population. In contrast, little information has been published about the slow recovery of green sea turtle in the Gulf of Mexico following the overharvesting of the species in the 1800's[72, 73]. Beaches to the north in the panhandle have seen a reduction in the number of nests[74]. To the south on Keewaydin Island, although nest counts have increased, their hatchling production has declined[28]. However, the data presented in this paper shows that nest counts in Sarasota County have rapidly grown for both species, as has hatchling production. These factors encourage the likelihood of recovery in the Gulf of Mexico region for both loggerheads and green sea turtles.

One of the contributing factors of increased growth may be due to the implementation of turtle excluder devices (TEDs) on shrimp trawling vessels in the 1990's. Reducing bycatch invariably expands the number of sea turtles reaching sexual maturity – loggerheads: 27–38 years[13, 24]; green turtles: 19–44 years[22, 75, 76], and increases the number of potential nesters for future generations. There was an estimated 60% reduction in bycatch of all species of sea turtles in the Atlantic following the TED regulation (mortality: 94% reduction[77]). Remaining high rates of sea turtle bycatch from shrimp trawlers[78], which may be higher in the Gulf of Mexico than in the southeastern Atlantic fishery could hinder recovery. Beaches in Florida have partnered with FWC for their SNBS program since 1979 and the INBS program since 1989. For over 40 years, citizen scientists have provided data for the management of these beaches. The usage of TEDs and the increased awareness in the region have provided nearly two generations worth of potential nesters to aid in recruitment and growth of the population. Additionally, these increased recruitment rates could be due to ocean currents in the Gulf of Mexico.

Recruitment to sea turtle nesting aggregations is strongly influenced by proximity to the Gulf Stream System (GSS), which affects overall population structure[79]. This model accounted for 90% of the spatial variation in regional nesting density and may explain why rookeries on the east coast will continue to dramatically increase in recruitment. In the Gulf of Mexico, the Loop Current passes near the western coast of Florida before joining the GSS[80], and may explain increased nesting in the Sarasota County region in relation to the rest of the Florida rookeries on the Gulf of Mexico. From 2016–2021, loggerhead nesting counts in Sarasota County (which includes beaches monitored by MML STCRP and the Coastal Wildlife Club) accounted for 44.4% of all nesting on Florida beaches on the Gulf of Mexico and 50.1% for greens[59, 60]. Genetically, the loggerhead population nesting in the region is distinct from management units to the north (St. Georges Island, Florida) and to the south (Keewaydin Island, Florida)[81] and the central west region is one of

the fastest growing nesting populations in Florida[66]. While biogeography may help explain the overall population shifts, individual assessments could explain the finer differences by beach.

Loggerheads and green sea turtles prefer to nest on beaches with less artificial light and on shorelines that are less developed[82–84]. Comparable to previous observations[73, 85], both species in the Sarasota region also prefer to nest closer to the upland barrier. Nesting success has significantly declined over the course of the study – likely due to increased coastal housing density and construction near the beach[49, 86]. Increases in coastal development result in more obstructions on the beach deterring nesters[87, 88], more lighting issues that discourage nesters[89, 90], and more nourishment or beach armoring that can prevent nesters from approaching the beach[43, 65, 91]. Two of the beaches with the lowest nesting success and nesting density beaches (Lido Key, and Longboat Key) are also the beaches that have been (re)nourished the most in the county. Casey Key is the least developed, and it has the highest nesting density. Unfortunately, modeling of nesting beach inundation into the future, suggests that sea level rise could cover 5–32% of suitable nesting beach widths by the year 2100[92–94]. A recent report from NOAA estimates that by 2050 sea levels will rise on average between 0.25–0.30 meters, increasing the likelihood of coastal flooding, storm surge impact, and coastal erosion[95]. Nesting density has continued to increase in line with the nest counts, which could be an exacerbating factor if the suitable nesting areas decline due to sea level rise and coastal development.

Nesting females may increase their fitness by laying nests in varied locations over the course of the season and by varying the number of eggs per clutch[96]. Loggerhead nests laid later in the season had a much lower emergence success rate – partially due to the typically increased level of tropical storms and the increase in predation over the course of the season. These “adaptations” may help explain why females are laying nests earlier. However it is more likely that regional temperature increases at foraging areas are influencing sea turtle nesting phenology[97–99]. Longer lived females consistently lay more clutches over the course of the season[100], increasing future population growth and many of our best estimates of population size derives from nest counts[101]. Capture-mark-recapture studies provide a ground truthing to how individuals vary over time[15, 102] and satellite tagging data can explain elusive or low fidelity turtles[103]. One such telemetry study in the region determined that loggerhead females lay at least five nests per season (capture-mark-recapture efforts only saw two), suggesting that population stock quantities are lower than previously estimated[104]. Further modeling of how clutch frequency and clutch size has changed over time in relation to rising sea levels should be prioritized for the Sarasota region.

Throughout Florida, air temperature rises over the course of the nesting season, but different abiotic factors influence how nest temperatures fluctuate. Increased temperature influences embryo mortality[105], but nests in the Sarasota region typically get more rainfall than nests on the east coast of Florida at similar latitudes and thus tend to be cooler (Lolavar & Wyneken *pers. comm*). The six beaches have different sand particle size and reflectance (albedo) that affect incubation temperature and duration (e.g. nest incubation duration is shorter on the dark, coarse sand of Venice than on the white, silty sand of north Siesta). An assessment is needed for the region to determine how physical characteristics (sand type, slope, albedo, etc.) influence nest temperatures. For green turtles, emergence success increased over the course of the season, possibly due to preferred nest site selection. Green turtles tend to lay deep nests, that are placed closer to the upper barrier resulting in few green turtle nests that washout (barring a hurricane). On the Gulf coast of Florida, green sea turtles are considered to be a rare species and most of their nests were caged to prevent depredation and increase potential recruitment. Caging is a likely factor of the discrepancy in emergence success between the two species[106]. However, the green nesting population is recovering and since 2021, MML STCRP has stopped caging all green nests.

Following emergence, both species encounter predators on the beach and can become disoriented from nearby lighting, reducing potential recruitment. Along Florida's east coast, 7.6% of hatchlings do not survive to the water after emergence[107]. On the west coast, the rate declines (6.1% on Anna Maria Island and Naples), but this difference was not significant[108]. In heavily developed areas, the primary cause of hatchling mortality was directly due to sky glow and artificial lighting sources that collectively lead hatchlings towards the dune and increase the likelihood of depredation or exhaustion. The Longboat Key Turtle Watch helped to enact one of Florida's first lighting ordinances in 1997, but from 2018–2021 disorientation events in Sarasota County make up 9% of all disorientation events in the state of Florida[109]. Models that assessed which conservation measures had the greatest effect on nesting success, determined that by increasing hatchling recruitment even at a single site, would increase the overall hatchling production from entire nesting aggregations[110]. Future projects should assess lighting issues in relation to disorientation events and hatchling mortality in the Sarasota region.

The data presented here documented the expanding nesting population for Sarasota County region. Although total nesting counts in the Gulf of Mexico annually accounts for only 7% of all loggerhead nesting in Florida, these beaches have a significant hatchling production annually reinforcing recovery. Primary, adult, and breeding sex ratios should be assessed to quantify the population age structure and determine if there is any risk of a sex ratio skew that other rookeries are experiencing[111]. Projects should model how ocean level increases will decrease suitable nesting habitat and how coastal development exacerbates the issue[93, 95]. When suitable nesting area decreases, will there be an effect on carrying capacity or will nesters migrate to less suitable beaches? Recruitment is critical to lasting recovery, and protection measures are needed to maintain population growth.

Declarations

Acknowledgements

Data were collected under the guidance and permitting of the Florida Fish and Wildlife Conservation Commission's (FWC) Marine Turtle Permits: 027, 028, 048, 054, 070, and RP #915. This paper would not have been possible without the help from hundreds of interns, volunteers and MML staff. Thanks in particular to E. Argo, J. Beggs, B. Bendel, P. Block, E. Briner, C. Brinton-Perz, J. Budzynkiewicz, K. Carter, P. Clark, K. Cochran, S. Condran, J. Cormany, J. Coulter, M. Crocker, J. Drenth, R. Edman, V. Erb, A. Ferrera, H. Fitzgerald, J. Flint, S. Gaillard, S. Gofman, J. Grimes, A. Hallbach, M. Hansen, A. Harper, A. Hays, M. Herron, S. Hirsch, C. Homer, S. Hoover, L. Kabat, K. Klaustermeier, K. Klingensmith, D. Lytwynec, C. Marshall, B. McIntyre, S. Morello, M. Mota, T. Muller, J. Neill, K. Noiseux, C. Olsen, N. Parks, M. Robinson, R. Romanowski, K. Schanzle S. Shaw, J. Sobin, P. Solomon, R. Warren, R. Welsh, S. Whitebread, and V. Wiese.

Author contributions statement:

JAL, MCM, and KTM conceived the idea of project and compiled the data; JAL drafted the original manuscript; all other authors contributed to collecting the data, writing and editing the manuscript.

Data availability:

The data sets generated during and/or analyzed during the current study will be available by request. Please contact the corresponding author at jlasala@mote.org for information.

Additional Information:

Competing Interests

The authors declare no competing interests.

References

1. Magurran, A.E. *et al*. Long-term datasets in biodiversity research and monitoring: Assessing change in ecological communities through time. Trends in Ecology & Evolution, 25(10): 574–82 (2010). https://doi.org/10.1016/j.tree.2010.06.016
2. Ahumada, J.A., Hurtado, J., & Lizcano, D. Monitoring the status and trends of tropical forest terrestrial vertebrate communities from camera trap data: A tool for conservation. PLoS ONE 8(9) (2013). https://doi.org/10.1371/journal.pone.0073707
3. Leslie, S.C., Blackett, F.C., Stalio, M., and Black, S.A. Systems behavior charts for longitudinal data inform marine conservation management. Journal of Aquaculture & Marine Biology 6(5): 00171 (2017).
4. Trillmich, F.*et al.* On the challenge of interpreting census data: insights from a study of an endangered pinniped. PLoS ONE, 11(5) (2016). https://doi.org/10.1371/journal.pone.0154588
5. Waterhouse, L. *et al.* Recovery of critically endangered Nassau grouper E*epinephelus striatus*) in the Cayman Islands following targeted conservation actions. PNAS, 117(3): 1587–1595 (2020). https://doi.org/10.5281/zenodo.3585864
6. Gray, M.E., Dickson, B.G., Nussear, K.E., Esque, T.C., and Chang, T. A range-wide model of contemporary, omnidirectional connectivity for the threatened Mojave desert tortoise. Ecosphere, 10(9) (2019). https://doi.org/10.1002/ecs2.2847
7. Beranek, C., Colyvas, K., Clulow, J., and Mahony, M. Novel use of statistics to determine precise relationship assignment to estimate breeding output of a threatened amphibian with tadpole genotypes. Authorea (2020). https://doi.org/10.22541/au.160611302.24625206/v1
8. Acevedo, J. *et al.* Migratory preferences of humpback whales between feeding and breeding grounds in the eastern south pacific. Marine Mammal Science 33(4): 1035–52 (2017). https://doi.org/10.1111/mms.12423
9. Paxton, K.L., and Moore, F.R. Connecting the dots: stopover strategies of an intercontinental migratory songbird in the context of the annual cycle. Ecology and Evolution, 7(17): 6716–6728 (2017). https://doi.org/10.1002/ece3.3227
10. Howard, C., Stephens, P.A., Pearce-Higgins, J.W., Gregory, R.D., Butchart, S.H.M., and Willis, S.G. Disentangling the relative roles of climate and land cover change in driving the long-term population trends of European migratory birds. Diversity and Distributions, 26(11): 1442–55 (2020). https://doi.org/10.1111/ddi.13144
11. Plotkin, P.T., Owens, D., Byles, R.A., and Patterson, R. Departure of male olive ridley turtles (*Lepidochelys olivacea*) from a nearshore breeding ground. Herpetologica, 52: 1–7 (1996).
12. National Research Council (NRC). Assessment of Sea Turtle Status and Trends: Integrating Demography and Abundance. The National Academies Press, Washington, DC. 162 pp. (2010)
13. Bjorndal, K.A., Bolten, A.B., and Chaloupka, M.Y. Green turtle somatic growth model: evidence for density dependence. Ecological Applications, 10: 269–282 (2000).
14. Chaloupka, M., Kamezaki, N., and Limpus, C. Is climate change affecting the population dynamics of the endangered pacific loggerhead sea turtle? Journal of Experimental Marine Biology and Ecology, 356: 136–143 (2008). https://doi.org/10.1016/j.jembe.2007.12.009
15. Phillips, K.P., Mortimer, J.A., Jolliffe, K.G., Jorgensen, T.H., and Richardson, D.S. Molecular techniques reveal cryptic life history and demographic processes of a critically endangered marine turtle. Journal of Experimental Marine Biology and Ecology, 455: 29–37 (2014). https://doi.org/10.1016/j.jembe.2014.02.012

16. Casale, P., Mazaris, A.D., Freggi, D., Basso, R., and Argano, R. Survival probabilities of loggerhead sea turtles (Caretta caretta) estimated from capture-mark-recapture data in the Mediterranean sea. Scientia Marina, 71(2): 365–372 (2007).
17. Ehrhart, L.M., Redfoot, W.E., and Bagley, D.A. Marine turtles of the central region of the Indian River Lagoon system. Florida Scientist, 70(4): 415–34 (2007). http://www.jstor.org/stable/24321669
18. Siegwalt, F. *et al*. High fidelity of sea turtles to their foraging grounds revealed by satellite tracking and capture-mark-recapture: new insights for the establishment of key marine conservation areas. Biological Conservation, 20: 108742 (2020). https://doi.org/10.1016/j.biocon.2020.108742
19. Addison, D.S. Mean annual nest frequency for renesting loggerhead turtles (Caretta caretta) on the southwest coast of Florida. Marine Turtle Newsletter 75: 13–15 (1996).
20. Conant, T.A. *et al.* Loggerhead sea turtle (Caretta caretta) 2009 Status Review Under the U.S. Endangered Species Act. Loggerhead Biological Review Team. (2009).
21. Lasala, J.A., Hughes, C.R., and Wyneken, J. Breeding sex ratio and population size of loggerhead turtles from southwestern Florida. PLoS ONE, 13(1) (2018). https://doi.org/10.1371/journal.pone.0191615
22. Bjorndal, K., and Zug, G. Growth and age of sea turtles. In *Biology and Conservation of Sea Turtles*. (1995).
23. Scott, R., Marsh, R., Hays, G.C. Life in the really slow lane: loggerhead sea turtles mature late relative to other reptiles. Functional Ecology, 26: 227–235 (2011).
24. Chasco, B.E. *et al.* Integrated mixed-effect growth models for species with incomplete ageing histories: a case study for the loggerhead sea turtle Caretta caretta. Marine Ecology Progress Series, 636: 221–234 (2020). https://doi.org/10.3354/meps13222.
25. Girondot, M., Mourrain, B., Chevallier, D., and Godfrey, M.H. Maturity of a giant: age and size reaction norm for sexual maturity for Atlantic leatherback turtles. Marine Ecology, 42(5) (2021). https://doi.org/10.1111/maec.12631
26. Derville, S., Jean, C., Dalleau, M., le Gall, J.Y., Ciccione, S., and Bourjea, J. Long-term monitoring of green turtle nesting on Tromelin Island demonstrates stable reproduction and population parameters. Chelonian Conservation and Biology, 14: 11–20 (2015). https://doi.org/10.2744/ccab-14-01-11-20.1
27. Garner, J.A., MacKenzie, D.S., and Gatlin, D. Reproductive biology of Atlantic leatherback sea turtles at Sandy Point, St. Croix: the first 30 years. Chelonian Conservation and Biology 16: 29–43 (2017). https://doi.org/10.2744/CCB-1224.1
28. Hoover, S.R. Long-term analyses (1986–2018) of the loggerhead sea turtle (Caretta caretta) nesting data from Keewaydin Island, Florida. Florida Atlantic University. (2019).
29. Le Gouvello, D.Z.M., Girondot, M., Bachoo, S., and Nel, R. the good and bad news of long-term monitoring: an increase in abundance but decreased body size suggests reduced potential fitness in nesting sea turtles. Marine Biology, 167(8) (2020). https://doi.org/10.1007/s00227-020-03736-4
30. Shamblin, B.M. *et al.* Genetic structure of the southeastern united states loggerhead turtle nesting aggregation: evidence of additional structure within the peninsular Florida recovery unit. Marine Biology, 158(3): 571–587 (2011). https://doi.org/10.1007/s00227-010-1582-6
31. Bowen, B.W. *et al.* Natal homing in juvenile loggerhead turtles (Caretta caretta). Molecular Ecology, 13(12): 3797–3808 (2004). https://doi.org/10.1111/j.1365-294X.2004.02356.x
32. Arendt, M.D. *et al*. Migration, distribution, and diving behavior of adult male loggerhead sea turtles (Caretta caretta) following dispersal from a major breeding aggregation in the western North Atlantic." Marine Biology 159: 113–25 (2012). https://doi.org/10.1007/s00227-011-1826-0

33. Wright, L.I. *et al.* Turtle mating patterns buffer against disruptive effects of climate change. *Proceedings of the Royal Society B: Biological Sciences*, 279(1736): 2122–2127 (2012). https://doi.org/10.1098/rspb.2011.2285
34. Shamblin, B.M. *et al.* Mitogenomic sequences better resolve stock structure of southern greater Caribbean green turtle rookeries. Molecular Ecology, 21(10): 2330–2340 (2012). https://doi.org/10.1111/j.1365-294X.2012.05530.x
35. Shamblin, B.M. *et al.* Green turtles nesting at their northern range limit in the United States represent a distinct subpopulation. Chelonian Conservation and Biology, 17(2): 314–319 (2018). https://doi.org/10.2744/CCB-1332.1
36. Girondot, M. Estimating density of animals during migratory waves: a new model applied to marine turtles at nesting sites. Endangered Species Research, 12: 95–105 (2010).
37. Whiting, A.U., Chaloupka, M., Pilcher, N., Basintal, P., Limpus, C.J. Sampling nesting sea turtles: optimizing survey design to minimize error. *MEPS*, 674:257–270 (2021).
38. Joseph, J., Nishizawa, H., Alin, J.M., Othman, R., Jolis, G., Isnain, I., Nais, J. Mass sea turtle slaughter at Pulau Tiga, Malaysia: Genetic studies indicate poaching locations and its potential effects. Global Ecology and Conservation, 17: e00586 (2019).
39. Mejías-Balsalobre, C., Restrepo, J., Borges, G., García, R., Rojas-Canizales, Barrios-Garrido, H., Valverde, R.A. Local community perceptions of sea turtle egg use in Tortuguero, Costa Rica. Ocean and Coastal Management, 201: 105423 (2021).
40. Putman, N.F., Richards, P.M., Dufault, S.G., Scott-Dention, E., McCarthy, K., Beyea, R.T., Caillouet Jr., C.W., Herman, W.D., Seney, E.E., Mansfield, K.L., Gallaway, B.J. Modeling juvenile sea turtle bycatch risk in commercial and recreational fisheries. iScience, 26: 105977 (2023).
41. López-Martinez, S., Morales-Caselles, C., Kadar, J., Rivas, M.L. Overview of global status of plastic presence in marine vertebrates. Global Change Biology, 27(4): 728–737 (2020).
42. Foley, A.M., Stacy, B.A., Hardy, R.F., Shea, C.P., Minch K.E., Schroeder, B.A. Characterizing Watercraft-Related Mortality of Sea Turtles in Florida. The Journal of Wildlife Management, 83(5): 1057–1072 (2019).
43. Rumbold, D.G., Davis, P.W., and Perretta, C. Estimating the effect of beach nourishment on *Caretta caretta* (loggerhead sea turtle) nesting. Restoration Ecology, 9(3): 304–10 (2001). https://doi.org/10.1046/j.1526-100X.2001.009003304.x
44. Butler, Z.P., Wenger, S.J., Pfaller, J.B., Dodd, M.G., Ondich, B.L., Coleman, S., Gaskin, J.L., Hickey, N., Kitchens-Hayes, K., Vance, R.K., Williams, K.L. Predation of loggerhead sea turtle eggs across Georgia's barrier islands. Global Ecology and Conservation, 23: e01139 (2020).
45. Price, J.T., Drye, B., Domangue, R.J., Paladino, F.V. Exploring the role of artificial lighting in loggerhead turtle (*Caretta caretta*) nest-site selection and hatchling disorientation. Herpetological Conservation and Biology, 13(2): 415–422 (2018).
46. Casale, P., and T Tucker. Caretta caretta. The IUCN Red List of Threatened Species. (2017).
47. Encalada, S.E. *et al.* Population structure of loggerhead turtle (Caretta caretta) nesting colonies in the Atlantic and Mediterranean as inferred from mitochondrial DNA control region sequences. Marine Biology, 130: 567–575 (1998).
48. Turtle Expert Working Group (TEWG). An assessment of the Kemp's ridley (L*epidochelys kempii*) and loggerhead (C*aretta caretta*) sea turtle populations in the western north Atlantic. *NOAA Technical Memorandum NMFS-SEFSC-409* (1998).
49. Fuentes, M.M.P.B. *et al.* Conservation hotspots for marine turtle nesting in the united states based on coastal development. Ecological Applications, 26(8): 2708–2719 (2016).

50. Sella, K.A.N. & Fuentes, M.M.P.B. Exposure of marine turtle nesting grounds to coastal modifications: implications for management. Ocean and Coastal Management, 169 (March): 182–190 (2019). https://doi.org/10.1016/j.ocecoaman.2018.12.011
51. Seminoff, J.A. Marine turtle specialist group *Chelonia mydas* assessment. *IUCN Marine Turtle Specialist Group*, pp. 34 (2004).
52. Lindborg, R. *et al.* An ethogram describing the nesting behavior of green sea turtles (*Chelonia mydas*). Herpetologica, 75 (2): 114–122 (2019). https://doi.org/10.1655/D-18-00015
53. Page-Karjian, A. *et al.* Comprehensive health assessment of green turtles *Chelonia mydas* nesting in southeastern Florida, USA." Endangered Species Research, 42: 21–35 (2020). https://doi.org/10.3354/ESR01036
54. Reusche, M.R. Genetic structure of green sea turtle (Chelonia mydas) foraging aggregations on the east coast of Florida. Orlando, FL, USA: University of Central Florida (2020). https://stars.library.ucf.edu/honorstheses/750
55. Nielsen, J.T. Population structure and the mating system of loggerhead turtles (*Caretta caretta*). Coral Gables, FL, USA: University of Miami (2010).
56. Lasala, J.A., Hughes, C.R., and Wyneken, J. Female loggerhead sea turtles (*Caretta caretta* L.) rarely remate during nesting season. Ecology and Evolution, 10: 163–174 (2020). https://doi.org/10.1002/ece3.5869
57. Witherington, B.E., Kubilis, P., Brost, B., Meylan, A. Decreasing annual nest counts in a globally important loggerhead sea turtle population. Ecological Applications, 19: 30–54 (2009).
58. Ceriani, S.A., Brost, B., Meylan, A.B., Meylan, P.A., Casale, P. Bias in sea turtle productivity estimates: error and factors involved. Marine Biology, 168: 41 (2021).
59. FWC Florida Fish and Wildlife Research Institute (a). Statewide nesting beach survey program loggerhead nesting data 2016–2021. (2021). Retrieved from: https://myfwc.com/media/23244/loggerheadnestingdata5years.pdf
60. FWC Florida Fish and Wildlife Research Institute (b). Statewide nesting beach survey program green nesting data 2016–2021. (2022). Retrieved from: https://myfwc.com/media/23245/greenturtlenestingdata5years.pdf
61. Florida Department of Environmental Protection (FDEP). Critically eroded beaches in Florida. (2021). Retrieved from: https://floridadep.gov/sites/default/files/FDEP-Critically-Eroded-Beaches-07-2021_0_1.pdf
62. Mosier, A.E. The impact of coastal armoring structures on sea turtle nesting behavior at three beaches on the east coast of Florida. St. Petersburg, FL, USA (1998).
63. Steinitz, M.J., Salmon, M., and Wyneken, J. Beach renourishment and loggerhead turtle reproduction: a seven-year study at Jupiter Island, Florida. Journal of Coastal Research, 14(3): 1000–1013 (1998).
64. Mosier, A.E., and Witherington, B. Documented Effects of Coastal Armoring Structures on Sea Turtle Nesting Behavior. In *20th Annual Sea Turtle Symposium*, 304–305 (2000).
65. Rizkalla, C.E., and Savage, A. Impact of seawalls on loggerhead sea turtle (*Caretta caretta*) nesting and hatching success. Journal of Coastal Research, 27: 166–173 (2011).
66. Ceriani, S.A., Casale, P., Brost, M., Leone, E.H., and Witherington, B. Conservation implications of sea turtle nesting trends: Elusive recovery of a globally important loggerhead population. Ecosphere 10 (11) (2019). https://doi.org/10.1002/ecs2.2936.
67. Florida Fish Wildlife Conservation Commission. Marine Turtle Conservation Handbook. (2016). Retrieved from: https://myfwc.com/media/3133/fwc-mtconservationhandbook.pdf.
68. Dimitriadis, C., Fournari – Konstantinidou, I., Sourbès, L., Koutsoubas, D., and Mazaris, A.D. Reduction of sea turtle population recruitment caused by nightlight: Evidence from the mediterranean region. Ocean & Coastal Management, 153 (March): 108–15 (2018). https://doi.org/10.1016/j.ocecoaman.2017.12.013

69. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. (2020).
70. QGIS.org. QGIS Geographic Information System. QGIS Association. (2022). http://www.qgis.org
71. Cribari-Neto, F. and Zeileis, A. Beta Regression in R. Journal of Statistical Software, 34(2):1–24 (2010). https://doi.org/10.18637/jss.v034.i02
72. Shamblin, B.M. *et al.* Genetic structure of Florida green turtle rookeries as indicated by mitochondrial DNA control region sequences. Conservation Genetics, 16(3): 673–85 (2015). https://doi.org/10.1007/s10592-014-0692-y
73. Valverde, R.A., and Holzwart, K.R. Sea turtles of the Gulf of Mexico. In *Habitats and Biota of the Gulf of Mexico: Before the Deepwater Horizon Oil Spill*, edited by C.H. Ward, 1189–1352 (2017). Houston, Texas: Rice University.
74. Fujisaki, I., Lamont, M., and Carthy, R. Temporal shift of sea turtle nest sites in an eroding barrier island beach. Ocean & Coastal Management, 155: 24–29 (2018).
75. Goshe, L.R., Avens, L., Scharf, F.S., and Southwood, S.L. Estimation of age at maturation and growth of Atlantic green turtles (*Chelonia mydas*) using skeletochronology. Marine Biology, 157(8): 1725–1740 (2010). https://doi.org/10.1007/s00227-010-1446-0
76. Avens, L. *et al.* Population characteristics, age structure, and growth dynamics of neritic juvenile green turtles in the northeastern Gulf of Mexico. Marine Ecology Progress Series, 458 (July): 213–29 (2012). https://doi.org/10.3354/meps09720
77. Finkbeiner, E.M., Wallace, B.P., Moore, J.E., Lewison, R.L., Crowder, L.B., and Read, A.J. Cumulative estimates of sea turtle bycatch and mortality in USA fisheries between 1990 and 2007. Biological Conservation, 144 (11): 2719–27 (2011). https://doi.org/10.1016/j.biocon.2011.07.033
78. Babcock, E.A. *et al.* Integrated Bayesian Models to Estimate Bycatch of Sea Turtles in the Gulf of Mexico and Southeastern U.S. Atlantic Coast Shrimp Otter Trawl Fishery. NOAA TECHNICAL MEMORANDUM NMFS-SEFSC-721. (2018).
79. Putman, N.F., Bane, J.M., and Lohmann, K.J. 2010. Sea turtle nesting distributions and oceanographic constraints on hatchling migration. *Proceedings of the Royal Society B: Biological Sciences*, 277: 3631–3637. https://doi.org/10.1098/rspb.2010.1088
80. Shanmugam, G. Slides, slumps, debris flows, turbidity currents, and bottom currents: Implications . In *Encyclopedia of Ocean Sciences (Third Edition)*, Volume 4. Elsevier. Pages: 228–257 (2019). https://doi.org/10.1016/b978-0-12-409548-9.04380-3
81. Shamblin B.M. *et al.* Geographic patterns of genetic variation in a broadly distributed marine vertebrate: new insights into loggerhead turtle stock structure from expanded mitochondrial DNA sequences. PLoS One, 9: e85956 (2014). https://doi.org/10.1371/journal.pone.0085956
82. Kikukawa, A., Kamezaki, N., and Otal, H. Factors affecting nesting beach selection by loggerhead turtles (*Caretta caretta*); a multiple regression approach. Journal of Zoology, 249(4): 447–454 (1999).
83. Weishampel, J.F., Bagley, D.A., Ehrhart, L.M. and Rodenbeck, B.L. Spatiotemporal patterns of annual sea turtle nesting behaviors along an east central Florida beach. Biological Conservation, 110(2): 295–303 (2003).
84. Weishampel, Z.A., Cheng, W.H. and Weishampel, J.F. Sea turtle nesting patterns in Florida vis-à-vis satellite-derived measures of artificial lighting. Remote Sensing in Ecology and Conservation, 2(1): 59–72 (2016). https://doi.org/10.1002/rse2.12
85. Garmestani, A.S., Percival, H.F., Portier, K.M., and Rice, K.G. Nest-site selection by the loggerhead sea turtle in Florida's ten thousand islands. Journal of Herpetology, 34(4): 504–510 (2000).

86. Kaska, Y. *et al.* Natural and anthropogenic factors affecting the nest-site selection of loggerhead turtles, *Caretta caretta*, on Dalaman-Sarıgerme beach in south-west Turkey." Zoology in the Middle East, 50: 47–58 (2010). https://doi.org/10.1080/09397140.2010.10638411
87. Oliver de la Esperanza, A., Martínez, A.A., Tuz, M.T., and Pérez-Collazos, E. Are anthropogenic factors affecting nesting habitat of sea turtles? the case of Kanzul Beach, Riviera Maya-Tulum (Mexico)." Journal of Coastal Conservation, 21: 85–93 (2017). https://doi.org/10.1007/s11852-016-0473-5
88. Ware, M. and Fuentes, M.M.P.B. Leave no trace ordinances for coastal species management: influences on sea turtle nesting success. Endangered Species Research, 41: 197–207 (2020). https://doi.org/10.3354/ESR01020
89. Witherington, B.E. Behavioral responses of nesting sea turtles to artificial lighting. Herpetologica, 48: 31–39 (1992). https://www.jstor.org/stable/3892916
90. Price, J.T., Drye, B., Domangue, R.J., and Paladino, F. Exploring the role of artificial lighting in loggerhead turtle (*Caretta caretta*) nest-site selection and hatchling disorientation. Herpetological Conservation and Biology, 13(2): 415–422 (2018).
91. Hirsch, S.E., Kedzuf, S., and Perrault, J.R. Impacts of a geotextile container dune core on marine turtle nesting in Juno Beach, Florida, United States. Restoration Ecology, 27(2): 431–39 (2019). https://doi.org/10.1111/rec.12878
92. Fish, M.R., Côté, I.M., Horrocks, J.A., Mulligan, B., Watkinson, A.R., and Jones, A.P. Construction setback regulations and sea-level rise: mitigating sea turtle nesting beach loss. Ocean and Coastal Management, 51(4): 330–41 (2008). https://doi.org/10.1016/j.ocecoaman.2007.09.002
93. Fuentes, M.M.P.B., Limpus, C.J., Hamann, M., and Dawson, J. Potential impacts of projected sea-level rise on sea turtle rookeries. Aquatic Conservation: Marine and Freshwater Ecosystems, 20(2): 132–39 (2010). https://doi.org/10.1002/aqc.1088
94. Lyons, M.P., von Holle, B., Caffrey, M.A., and Weishampel, J.F. Quantifying the impacts of future sea level rise on nesting sea turtles in the southeastern United States. Ecological Applications, 30(5): e02100 (2020). https://doi.org/10.1002/eap.2100
95. Sweet, W.V. *et al.* Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along U.S. coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. (2022). https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf
96. Cassill, D.L. Multiple maternal risk-management adaptations in the loggerhead sea turtle (*Caretta caretta*) mitigate clutch failure caused by catastrophic storms and predators. Scientific Reports, 11: 2491 (2021).
97. Mazaris, A.D., Kallimanis, A.S., Tzanopoulos, J., Sgardelis, S.P., and Pantis, J.D. Sea surface temperature variations in core foraging grounds drive nesting trends and phenology of loggerhead turtles in the Mediterranean Sea. Journal of Experimental Marine Biology and Ecology, 379: 23–27 (2009).
98. Neeman, N., Robinson, N.J., Paladino, F.V., Spotila, J.R., and O'Connor, M.P. Phenology shifts in leatherback turtles (*Dermochelys coriacea*) due to changes in sea surface temperature. Journal of Experimental Marine Biology and Ecology, 462: 113–120 (2015).
99. Monsingjon, J., Lopez-Mendilaharsu, M., Lara, P., Santos, A., dei Marcovaldi, M.A.G., Girondot, M., Fuentes, M.M.P.B. Effects of temperature and demography on the phenology of loggerhead sea turtles in Brazil. *Marine Ecology Progress Series*, 623: 209–219 (2019).
100. Frazer, N.B. A model for assessing mean age-specific fecundity in sea turtle populations. Herpetologica, 40(3): 281–291 (1984). https://www.jstor.org/stable/3892296.
101. Mazaris, A., Kramer-Schadt, S., Tzanopoulos, J., Johst, K., Matsinos, G., and Pantis, J. Assessing the relative importance of conservation measures applied on sea turtles: Comparison of measures focusing on nesting

success and hatching recruitment success. Amphibia-Reptilia, 30(2): 221–231 (2009). https://doi.org/10.1163/156853809788201180

102. Kendall, W.L. & Bjorkland, R. Using open robust design models to estimate temporary emigration from capture-recapture data. Biometrics, 57: 1113–1122 (2001).
103. Pfaller, J.B. *et al.* One beach amongst many: how weak fidelity to a focal nesting site can bias demographic rates in marine turtles. Marine Biology, 169(8) (2021). https://doi.org/10.1007/s00227-021-03991-z
104. Tucker, A.D. Nest site fidelity and clutch frequency of loggerhead turtles are better elucidated by satellite telemetry than by nocturnal tagging efforts: Implications for stock estimation. Journal of Experimental Marine Biology and Ecology, 383: 48–55 (2010).
105. Bladow, R.A., and Milton, S.L. Embryonic Mortality in Green (Chelonia Mydas) and Loggerhead (Caretta Caretta) Sea Turtle Nests Increases with Cumulative Exposure to Elevated Temperatures. Journal of Experimental Marine Biology and Ecology 518 (September): 151180 (2019). https://doi.org/10.1016/j.jembe.2019.151180
106. Brost, B., Witherington, B., Meylan, A., Leone, E., Ehrhart, L., and Bagley, D. Sea turtle hatchling production from Florida (USA) beaches, 2002–2012, with recommendations for analyzing hatching success. Endangered Species Research 27: 53–68 (2015). https://doi.org/10.3354/esr00653.
107. Erb, V. & Wyneken, J. Nest-to-surf mortality of loggerhead sea turtle (*Caretta caretta*) hatchlings on Florida's east coast. Frontiers in Marine Science, 6 (May) (2019). https://doi.org/10.3389/fmars.2019.00271
108. Villegas Vindiola, B. Measuring nest-to-surf mortality of Florida's east and west coast loggerhead sea turtle (*Caretta caretta*) hatchlings. Boca Raton, FL USA: Florida Atlantic University. (2019)
109. FWC Florida Fish and Wildlife Research Institute (c). FWC Sea Turtle Disorientation Survey 2018–2021. (2021). Retrieved from: https://myfwc.maps.arcgis.com/apps/dashboards/53699c9690024c079ed60aaa74a763c8
110. Mazaris, A.D., Schofield, G., Gkazinou, C., Almpanidou, V., and Hays, G. Global sea turtle conservation successes. Science Advances, 3(9): e1600730 (2017).
111. 111. Jensen, M.P., *et al*. Environmental warming and feminization of one of the largest sea turtle populations in the world. Current Biology, 28: 154–159.e4 (2018). https://doi.org/10.1016/j.cub.2017.11.057
112. Tuttle, J. and Rostal, D. Effects of nest relocation on nest temperature and embryonic development of loggerhead sea turtles (*Caretta caretta*). Chelonian Conservation and Biology, 9:1–7 (2010).

Figures

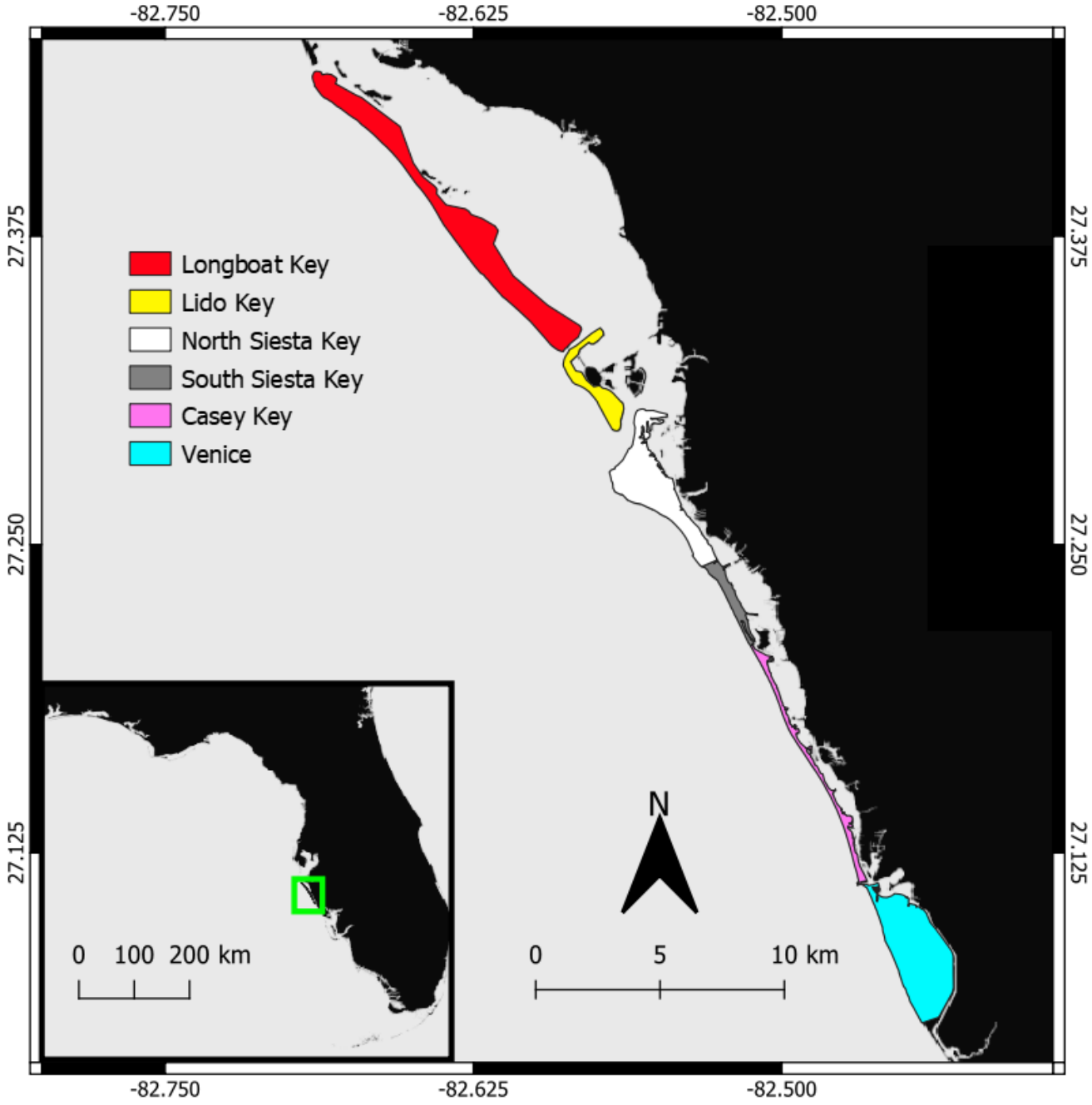


Figure 1

Nesting beaches monitored by MML STCRP in Sarasota Florida. North to South they are: Longboat Key, Lido Key, Siesta Key (North and South), Casey Key and Venice. Beaches vary in physical parameters (sand type, nourishment, obstructions, armoring) and these differences are highlighted in Table 1.

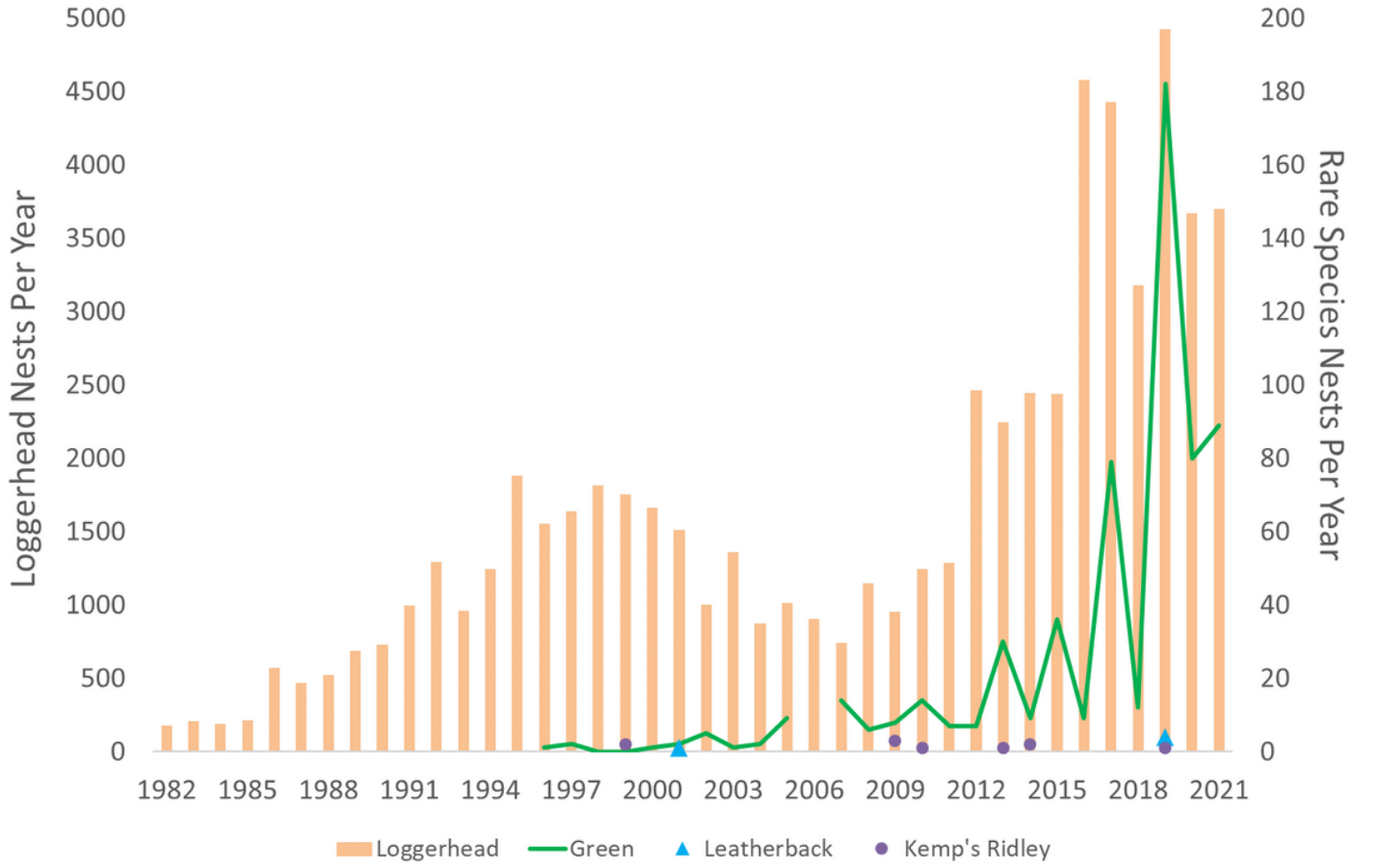


Figure 2

Nest counts from 1982 – 2021 from all beaches monitored by MML STCRP. Rare species include green sea turtles, leatherbacks, and Kemp's ridley turtles. Turtle excluder devices were mandatory federally for shrimp trawlers starting in 1989 and their use has likely encouraged the nesting count increases.

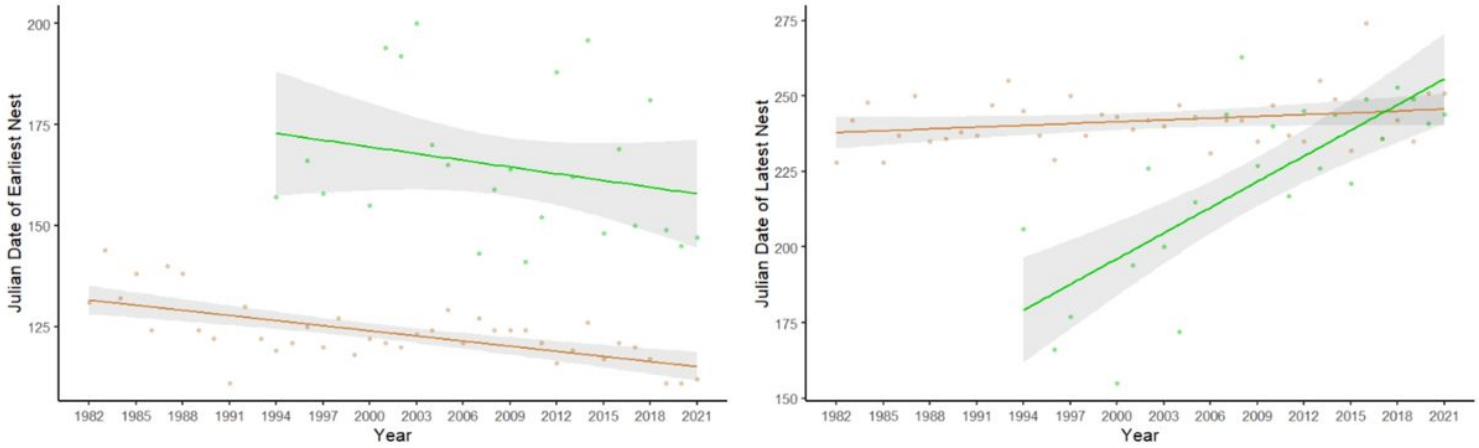


Figure 3

Julian date of earliest (**a**) and latest (**b**) laid nests for loggerheads (tan) and green sea turtles (green) from 1982-2021. Grey bands are 95% confidence intervals. Both species are significantly laying their nests earlier over the 40-year

timeframe and greens are significantly laying their last nests later.

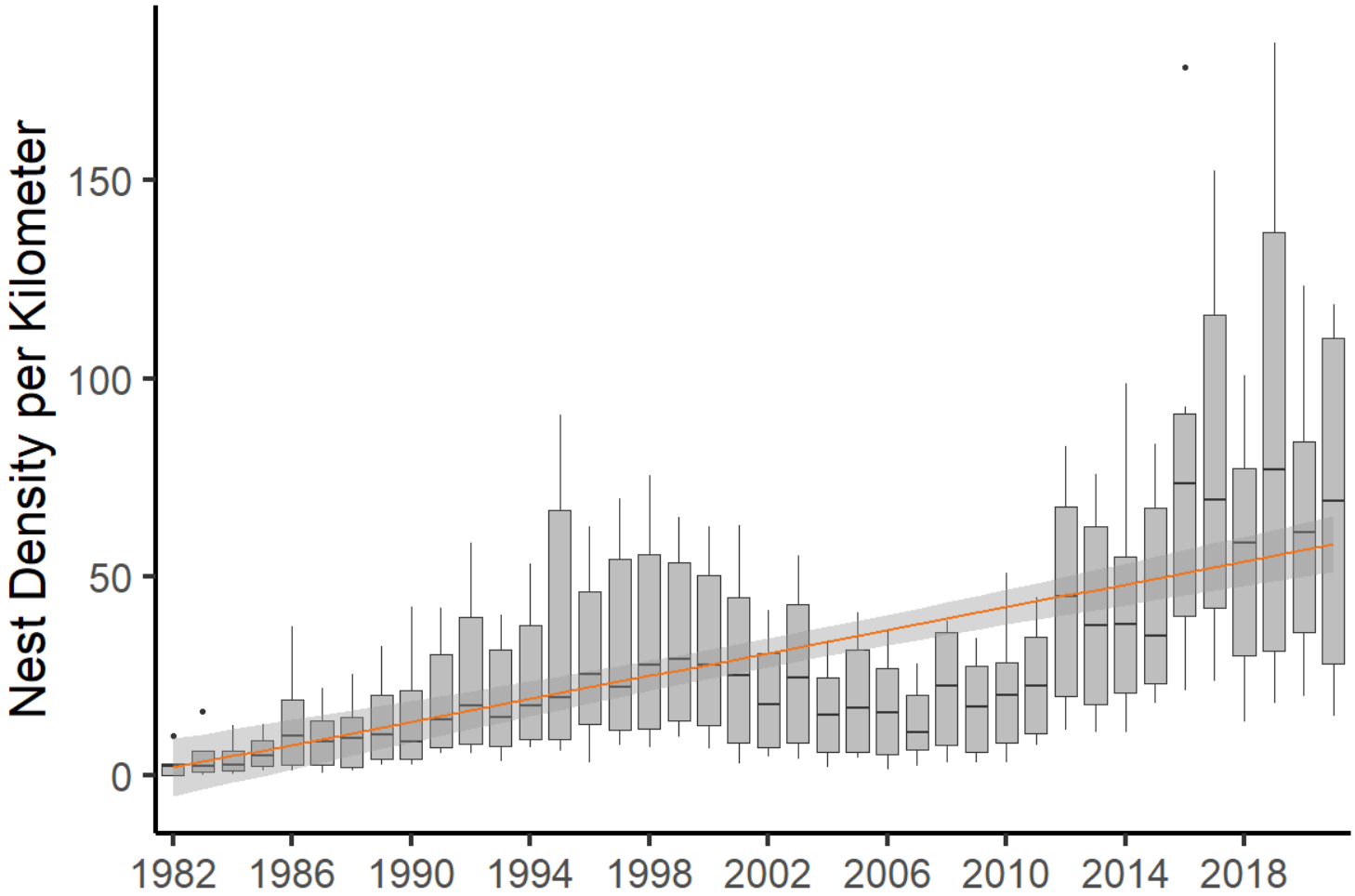


Figure 4

Loggerhead nesting density per km over time 1982-2021 – there was a significant trend over time (grey band is the 95% confidence interval). Grey dots represent outliers from those years. More southern beaches had higher densities than northern beaches, resulting in high variation between the beaches from year to year.

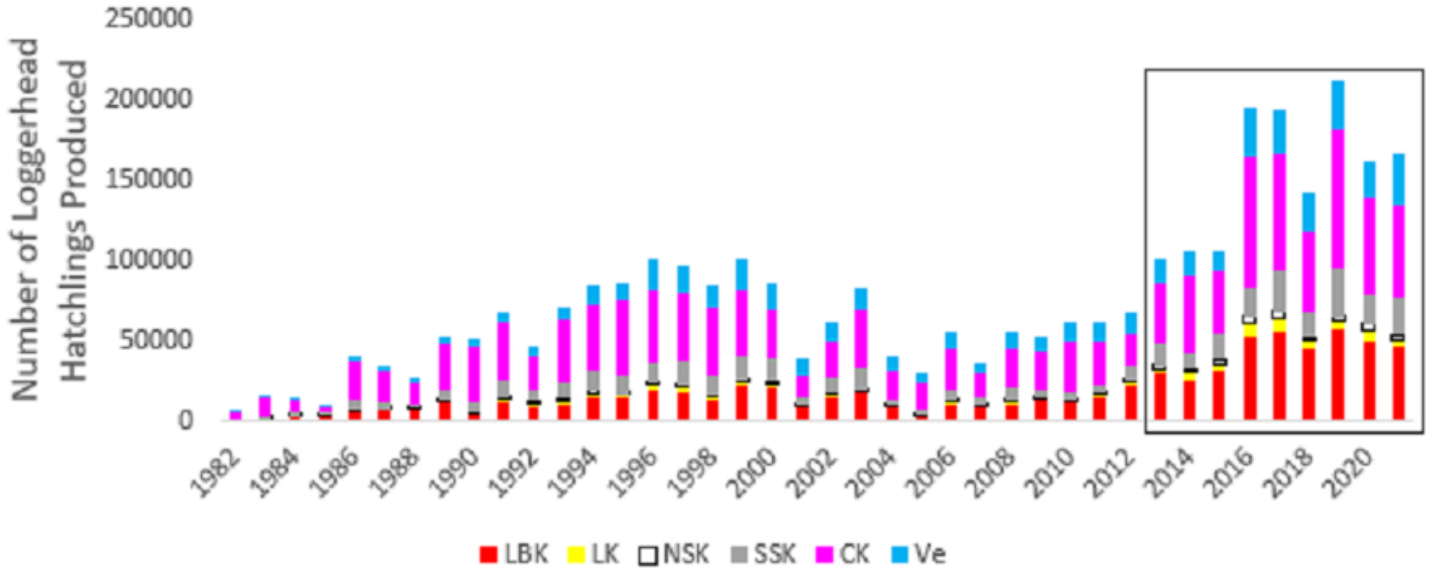


Figure 5

Estimated number of loggerhead hatchlings produced by year. Prior to the black box, all nests were excavated and the hatchling numbers are confirmed – the black box includes estimated number of hatchlings based on regression analysis (Supplementary Information).

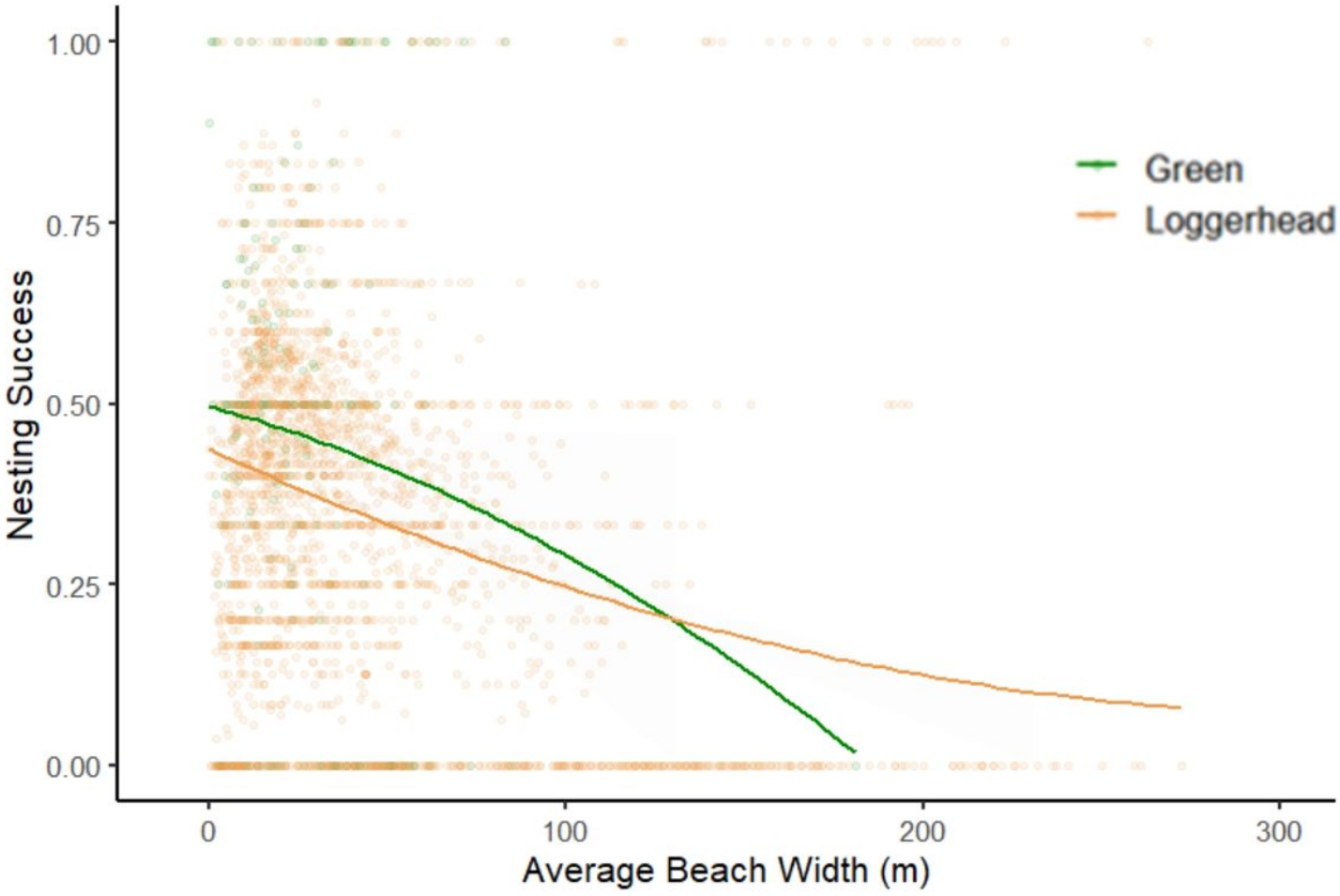


Figure 6

Loggerhead and green sea turtle nesting success in relation to average beach width (m). Nesting success was calculated as the proportion of sea turtle emergences that resulted in a nest.Greens rarely nest successfully on wide beaches, but loggerheads will travel long distances.

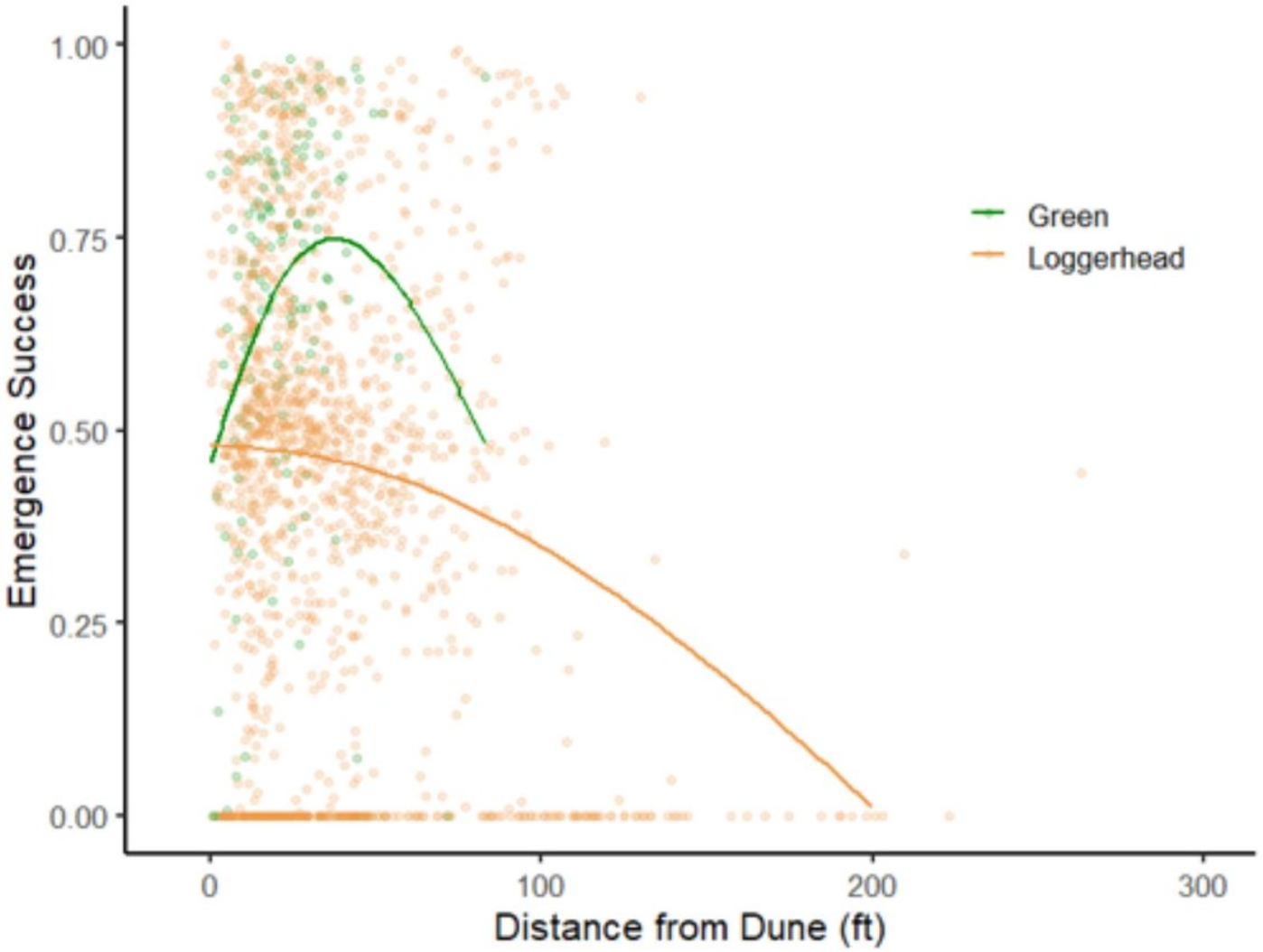


Figure 7

Emergence success in relation to the distance from the upper barrier (the dune). Loggerhead nests laid closer to the dune tend to have a higher emergence rate. Few green turtles lay their nests away from the dune and tend to have a higher success rate near, but not in the vegetation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 40yearSupplementaryInfoAppeal.docx