

The thermal impacts of beach nourishment across a regionally important loggerhead sea turtle (*Caretta caretta*) rookery

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Abstract. Beach nourishment is a common coastal management practice used to protect and maintain infrastructure, tourist revenue, and sandy beach habitats. Coastal erosion and increased development along the coast of North Carolina, USA, have resulted in increased use of beach nourishment as an environmentally friendly alternative to hard structures, such as groins and jetties. Despite its advantages, beach nourishment can alter the thermal properties of a beach, potentially impacting the incubation environment of species that utilize this habitat during reproduction. Importantly, in organisms with temperature-dependent sex determination, the incubation environment plays a key role in determining offspring sex ratios, hatchling survival, and fitness. Here we investigate how beach nourishment influences thermal properties and sand characteristics of eight beaches in the high-density loggerhead sea turtle (*Caretta caretta*) nesting region of North Carolina. We find that, despite considerable spatial and temporal variation, nourishment is a significant predictor of mean monthly sand temperatures in both univariate and multivariable predictive models. Across a season, nourished beach sections are, on average, 0.4°C (range 0.3–0.8°C) warmer than their unnourished counterparts. Nourishment is also a significant predictor of the mean and variance of sand grain size. Furthermore, variation in mean grain size, the relative percent of small, medium and large grain sizes and albedo are mainly responsible for differences in mean monthly sand temperatures. As such, the coarser and darker sand often used in nourishment projects may exacerbate climate driven increases in surface temperature.

Key words: beach erosion; climate change; nesting beach; sand grain characteristics; sand temperature; sea turtle.

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INTRODUCTION

The impacts of climate change, primarily increased land and ocean surface temperatures (Hansen et al. 2010), sea level rise (Spencer et al. 2016, Schuerch et al. 2018) and increased severity and occurrence of precipitation events (Trenberth 2011, Emanuel 2013, Hanse et al. 2016) threaten coastal environments on a global scale. Given

current and future projected concentrations of atmospheric greenhouse gases and indicators such as ocean acidity and ice mass coverage in the poles, the warming trend is expected to continue throughout the next century (IPCC 2014). With global mean sea level expected to rise by 0.3–0.8 m over this time (IPCC 2014), sandy, low-lying coastal and island beaches are at special risk (Feagin et al. 2005, Baker et al. 2006,

FitzGerald et al. 2008, Hinkel et al. 2013), particularly when landward retreat is restricted by human infrastructure and development (Galbraith et al. 2002, Fish et al. 2008, Noss 2011). Moreover, likely increases in the occurrence of major storm events as a result of increased ocean surface temperatures (Goldenberg et al. 2001, Trenberth 2011, IPCC 2014) further threaten these ecosystems as well as the species that rely on them (Reid and Trexler 1992, Sala et al. 2000, Coombes et al. 2008, Van Houtan and Halley 2011, Schooler et al. 2019).

Coastal management practices utilize a variety of techniques to protect infrastructure, tourist dollars, and natural habitat from the impacts of global climate change (Phillips and Jones 2006, Fish et al. 2008). In the United States, beach nourishment has emerged as a potentially environmentally friendly solution to combat coastal erosion and is currently the main approach used in such projects (Valverde et al. 1999, Dean 2005, Speybroeck et al. 2006). Obvious advantages and benefits of beach nourishment include increasing or restoring habitat for endangered and threatened dune plants, shorebirds and sea turtles (Greene 2002, Dean 2005). However, there are concerns regarding the quality of material used in nourishment events and its effects on the wildlife that rely on sandy beach ecosystems (Crain et al. 1995, Milton et al. 1997, Rumbold et al. 2001, Peterson and Bishop 2005). For example, nourishment often creates steeper beach profiles and scarps at the shoreline (Greene 2002). Sand characteristics can also be altered with respect to color (Hawkes et al. 2005, Peterson and Bishop 2005, Peterson et al. 2014), grain shape, size, and porosity (Roman-Sierra et al. 2014), as well as sediment mineralogy, density, and compaction (Speybroeck et al. 2006). Maintaining proper sedimentary characteristics on beaches is especially important for species such as sea turtles, since the nest incubation environment directly impacts critical offspring characteristics (Packard and Packard 1988, Naro-Maciel et al. 1999, Carthy et al. 2003) such as offspring sex ratios (Yntema and Mrosovsky 1982, Mrosovsky 1988), hatchling size (Atkinson 1994), and locomotor performance (Glen et al. 2003, Witt et al. 2010, reviewed in Booth 2017).

All sea turtles exhibit temperature-dependent sex determination (TSD), where temperatures determine offspring sex during the thermosensitive period in the middle third of incubation (Yntema and Mrosovsky 1982, Mrosovsky et al. 1984). Female offspring are produced at higher temperatures and males at lower temperatures within a thermal tolerance range of 25–35°C (Ackerman 1997). The pivotal temperature, which results in a 1:1 ratio of male to female hatchlings, is 29°C for loggerheads (*Caretta caretta*) in the USA (Mrosovsky 1988) and is bounded by a narrow 2–3°C window known as the transitional range of temperatures in which both sexes are produced (Pieau and Mrosovsky 1991). This sensitivity leaves sea turtles vulnerable to sub-lethal temperature shifts in the incubation environment (Booth 2017). Specifically, increasing sand temperatures could produce female-biased primary sex ratios, contribute to decreased survivorship of clutches, alter nesting phenology and impact hatchling characteristics, performance and fitness (Poloczanska et al. 2009, Hamann et al. 2010, Hays et al. 2017).

North Carolina is the third most nourished state in the United States and has completed over 300 nourishment projects along the coast since 1939 (National Beach Nourishment Database 2019). North Carolina also represents a regionally important loggerhead rookery within the Northwest Atlantic Ocean Distinct Population Segment (DPS), which encompasses nesting beaches along the Atlantic coast of Florida through southern Virginia and is responsible for about 40% of all loggerhead nests laid annually (68,000–90,000 nests; NOAA Fisheries). Here, we provide a comprehensive analysis of changes in sand temperature and grain size of eight beaches along the coast of North Carolina, USA, to investigate how beach nourishment influences thermal properties and sand characteristics of loggerhead sea turtle nests. We use univariate and multivariable models to determine whether nourishment is a significant predictor of sand temperatures, in addition to other spatial and temporal variables. We also explore whether differences in sand grain size, composition, and albedo directly influence sand temperature and whether these variables are significantly altered by nourishment events.

METHODS

Study sites

We collected data on sand composition and temperature from eight beaches spanning the North Carolina coast: Pea Island National Wildlife Reserve (NWR), Cape Hatteras National Seashore (CHNS) located in the town of Buxton (hereafter, Buxton), Emerald Isle Beach, Topsail Island Beach, Wrightsville Beach, Bald Head Island, Holden Beach, and Ocean Isle Beach (Fig. 1). The northernmost beach was Pea Island National Wildlife Reserve (NWR), located approximately 400 kilometers from Ocean Isle Beach, the southernmost beach. We selected beaches with a history of loggerhead sea turtle nesting activity and recent nourishment (i.e., within 3 yr of data collection; Table 1). All beaches were monitored for sea turtle nesting activity. Between 2014 and 2018, beaches had an average of 39 ± 33.8 loggerhead nests/yr laid collectively on all 8 study beaches (minimum Wrightsville,

6.4 ± 5.9 nest/yr; maximum Topsail Island, 86.4 ± 47.1 nests/yr).

Data collection

Sand temperature.—We collected sand temperature data in two different years: Pea Island NWR, Emerald Isle Beach, Topsail Beach, Bald Head Island, and Ocean Isle Beach in 2015 and Wrightsville Beach, Holden Beach, and Buxton in 2018. At each beach, we placed HOBO Pendant Temperature data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA) along four transects. These loggers have a guaranteed accuracy of $\pm 0.2^\circ\text{C}$ from 0° to 50°C and a resolution of 0.1°C at 25°C . Two transects were located in areas that had been nourished within the last two years, and the other two transects were placed in areas that had not received nourished sand within the last three years (hereafter, natural). The distance between the two furthest transects varied across beaches, but the average midpoint distance between these transects was

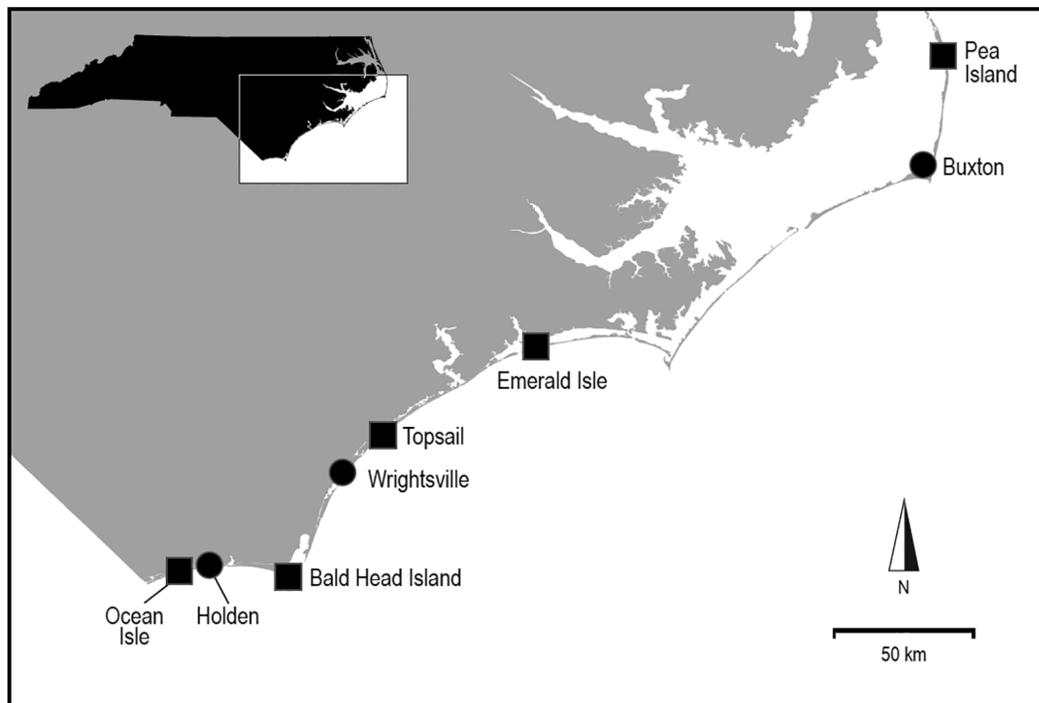


Fig. 1. Sampling sites for loggerhead sea turtle (*Caretta caretta*) nesting beaches along the coast of North Carolina, USA. Sites indicated by a square were sampled in 2015, and those indicated by a circle were sampled in 2018.

Table 1. Description of key parameters of the most recent nourishment event and past nourishment events on all eight sea turtle nesting beaches in North Carolina.

Beach	Lat.	Long.	Most recent nourishment event					All nourishment events (as of 2018)			
			Total length of beach (km)	Most recent event (yr)	Volume of sand (m ³)	Length of beach (km)	Cost (\$US)	No. events	Volume of sand (m ³)	Length of beach (km)	Total cost (\$US)
PI NWR	35.723	-75.496	20.9	2013	444,149	1.77	7,222,368	19	7,383,922	27.8	56,154,185
BUX	35.267	-75.542	11.26	2018	1,987,842	4.67	22,000,000	1	1,987,842	4.67	22,000,000
EIB	34.666	-77.013	20.9	2013	38,227	0.61	623,660	19	3,992,098	49	44,500,219
TOP	34.370	-77.625	41.8	2015	638,497	0.73	10,347,748	14	2,856,826	23	41,069,545
WB	34.211	-77.798	6	2018	583,355	2.44	10,500,000	28	13,133,473	51.3	61,334,290
BHI	33.867	-78.006	7.72	2015	1,017,414	3.43	12,700,000	15	9,806,033	42.2	114,200,661
HB	33.915	-78.286	13	2017	1,001,566	6.46	15,000,000	29	3,646,063	32.35	32,433,725
OIB	33.887	-78.436	11.26	2014	586,728	2.44	8,569,514	20	3,927,633	19	28,024,183

Note: Abbreviations represent the following beaches: Pea Island National Wildlife Reserve (PINWR), Cape Hatteras National Seashore in Buxton (BUX), Emerald Isle Beach (EIB), Topsail Beach (TOP), Wrightsville Beach (WB), Bald Head Island (BHI), Holden Beach (HB), Ocean Isle Beach (OIB).

4 km. Each transect contained one temperature logger placed at mean mid-nest depth (45 cm for loggerheads) in the vegetated landward zone and one logger placed in the open beach. We deployed a total of 64 loggers ($n = 8$ per beach) set to record hourly sand temperatures from May until October. The arrival of Hurricane Florence on September 14, 2018 resulted in the 2018 data loggers being collected early, on September 9 and September 11. We used GPS coordinates obtained when loggers were deployed to aid in recovery. We recovered a total of 46 data loggers across the two years. Comparisons were made from temperatures recorded between June and September, except for Buxton for which temperature data collection began in July. Mean seasonal temperatures were calculated by averaging mean daily temperatures throughout the months of July, August, and September.

Sand characteristics

1. *Sand grain size.*—In June of the 2015 and 2018 loggerhead nesting seasons, we collected two sand samples within a 1 m radius of the temperature logger sites: at a depth of 45 cm and from the surface. Prior to analysis, 100 g of each sample was dried in a Shake n' Bake Rocking Hybridization Laboratory Oven (Boekel Scientific, Feasterville, Pennsylvania, USA) at 60°C for 48 h or until the weight no longer changed. Dried samples taken from 45 cm were poured through a set of 8 mesh sieves (4 mm, 2 mm, 1 mm, 710 μ m,

500 μ m, 250 μ m, 125 μ m, and 63 μ m) on a Ro-Tap sieve shaker (W.S. Tyler, Mentor, Ohio, USA) for 10 min. All particles remaining in the bottom bin were categorized as <63 μ m. We weighed the contents of each weight class to the nearest one-hundredth gram on a portable electronic balance (VWR International, Radnor, Pennsylvania, USA). The percentage of each size class with respect to the total sample was then calculated. Following Folk (1980), data were standardized to units of μ m to calculate the arithmetic mean, midpoint deviation, and standard deviation of the mean grain size. We further categorized sand samples into the following size classes: extra small <63–63 μ m, small 125–250 μ m, medium 500–710 μ m, large 1–2 mm, and extra-large 4 mm. The percentage of each size class was calculated relative to the rest of the sample.

2. *Albedo.*—We obtained albedo measurements for each surface sand sample. Albedo is a unitless quantification of the amount of solar energy a surface reflects or an inverse indication of the amount of solar energy a substance absorbs (Hays et al. 2001). Lighter, more reflective surfaces will have high albedo whereas darker surfaces will have low albedo. In 2015, we measured albedo in the field using a Liemaster Pro L-478D (Sekonic, Tokyo, Japan). We recorded the amount of incoming solar radiation (RAD_{INC}) and the amount of light reflecting off the sand (RAD_{SAND}) in lux. We calculated albedo ($p_{350-800}$) as the fraction of solar radiation reflected relative

to the incoming radiation and multiplied by 100 to convert to a percentage of solar radiation. ($p_{350-800} = (\text{RAD}_{\text{SAND}}/\text{RAD}_{\text{INC}}) \times 100$). In 2018, surface sand samples were collected and brought back to UNCW's Center for Marine Science for analysis to minimize variation in the amount of incoming solar radiation from daily and monthly weather patterns. Referencing the validation in methodology for collecting albedo in field and laboratory environments published by Hays et al. (2001), our approach combined aspects of both field and laboratory protocols to produce data that could be compared with 2015 measurements. We took all albedo measurements on the same day under natural light conditions with the Litemaster Pro L-478D. We calculated albedo using following the equation provided by Hays et al. (2001) to calculate albedo as.

$$p_{350-800} = (L_S/L_G) \times 18\%$$

where L_S the amount of light (lux) reflecting off the surface sand sample, and (L_G) was the amount of reflected light off of a photographic gray card with a known albedo of 18%. We repeated measurements of reflectance from the sand and gray card three times; albedo values we report represent the mean of the three repeated measurements. Before each set of reflectance values were recorded, the amount of incoming solar radiation was observed to ensure consistency of measurements across beaches. Across all beaches, the average incoming solar radiation value observed throughout the 2018 albedo data collection was $75,120 \pm 3,650$ (range 70,000–80,000 lux).

Data analysis

We focused our analyses on mean daily and monthly sand temperatures as current literature on reproductive success in sea turtles most often uses mean incubation temperature as a predictor of incubation duration, and therefore offspring sex ratio (Mrosovsky et al. 1999). Using mean daily temperatures from each data logger, we calculated the mean, standard deviation, and coefficient of variation (CV) of monthly sand temperatures. We also calculated mean seasonal temperatures for each beach using mean daily temperatures from July through September, as June temperatures in Buxton were not recorded.

Monthly and seasonal mean temperatures within and among beaches were calculated for natural and nourished areas as well. We performed one- and two-way ANOVA to determine whether significant spatial (beach) or temporal (month) variation existed among beaches and areas. Finally, for each beach, we tabulated the number of days where the daily average temperatures reached or exceeded the pivotal temperature for loggerhead sea turtles regionally (29°C) and compared values among natural and nourished areas within beaches.

We calculated the mean difference between mean daily temperatures at nourished and natural sites for each zone within each beach. This was done monthly and seasonally for each zone separately and for the overall beach (except for Wrightsville and Topsail for which we did not have open beach zone temperatures). We performed a one-tailed *t*-test between mean daily temperatures on natural and nourished areas and a regression analysis to evaluate the effect of latitude on temperatures. We ran univariate fixed-effects models with mean and CV of monthly temperature as well as mean and CV of grain size as the response variables and BEACH, MONTH, ZONE (open vs. vegetated), and AREA (natural vs. nourished) as the predictor variables. Before performing univariate fixed-effects analyses, we logit transformed the relative percent of each size class as well as albedo measurements. We analyzed models with mean and CV of monthly temperature as the response variables and mean grain size (MGS), CV of grain size (CVGS), individual grain size classes (%XL, %L, %M, %S, %XS), and albedo as the predictor variables. Finally, we built fixed-effect multivariable models from the predictors used in our univariate models. We performed all analyses using JMP Pro, Version 13 (SAS Institute, Cary, North Carolina, USA).

RESULTS

Sand temperature

We found significant spatial variation in mean seasonal temperatures across all eight study sites (ANOVA $F_{7,3,123} = 59.26$, $P < 0.0001$). Bald Head Island was the warmest beach ($30.1^\circ \pm 1.2^\circ\text{C}$) which was 1.4°C warmer than the coolest (Topsail Beach $28.7^\circ \pm 1.2^\circ\text{C}$). There was also significant

spatial variation in seasonal temperatures among both natural (ANOVA $F_{7,1,398} = 51.39$, $P < 0.0001$) and nourished (ANOVA $F_{7,1,717} = 21.84$, $P < 0.0001$) areas. In the univariate analysis, BEACH was a significant predictor of the mean and CV of monthly temperatures ($P < 0.0001$ and $P = 0.001$, respectively). There was no correlation between mean or CV of monthly temperature and latitude ($r^2 = 0.12$, $P = 0.4$; $r^2 = 0.02$, $P = 0.7$, respectively).

When beaches were combined, we found significant temporal variation in mean monthly temperatures (ANOVA $F_{2,3,128} = 18.21$, $P < 0.0001$). July was the warmest month ($29.6^\circ \pm 1.4^\circ\text{C}$) while September was the coolest ($29.2^\circ \pm 1.5^\circ\text{C}$). There was also significant temporal variation in temperature among both natural (ANOVA $F_{7,53} = 5.13$, $P = 0.0002$) and nourished (ANOVA $F_{7,65} = 2.91$, $P = 0.01$) areas. In the univariate analysis, MONTH was also a significant predictor of mean and CV of monthly temperatures ($P < 0.0001$ and $P < 0.0001$, respectively).

Despite significant spatial and temporal variation among beaches, beach nourishment

significantly influenced both seasonal and monthly mean temperatures. Overall, Emerald Isle Beach had the largest difference ($1.6^\circ \pm 0.4^\circ\text{C}$) in mean daily sand temperature between natural and nourished areas. We observed the smallest difference between areas in Buxton ($0.2^\circ \pm 0.3^\circ\text{C}$). Nourished areas were consistently warmer on all beaches except for Holden Beach where the seasonal mean difference was -0.5°C . This pattern was mirrored in the differences between mean monthly temperatures (Fig. 2). In the univariate analysis, AREA was also a significant predictor of the mean but not the CV of monthly temperatures ($P = 0.03$ and $P = 0.79$, respectively). Overall, we found a significant difference between the mean daily temperatures of natural and nourished areas ($29.3^\circ \pm 1.4^\circ\text{C}$ and $29.7^\circ \pm 1.2^\circ\text{C}$, respectively; t -test $t_{1,2800} = 9.01$, $P < 0.0001$). Nourished areas were significantly warmer than natural on six out of the eight beaches (Fig. 3a).

The number of days above the pivotal temperature varied within and among beaches (Fig. 4).

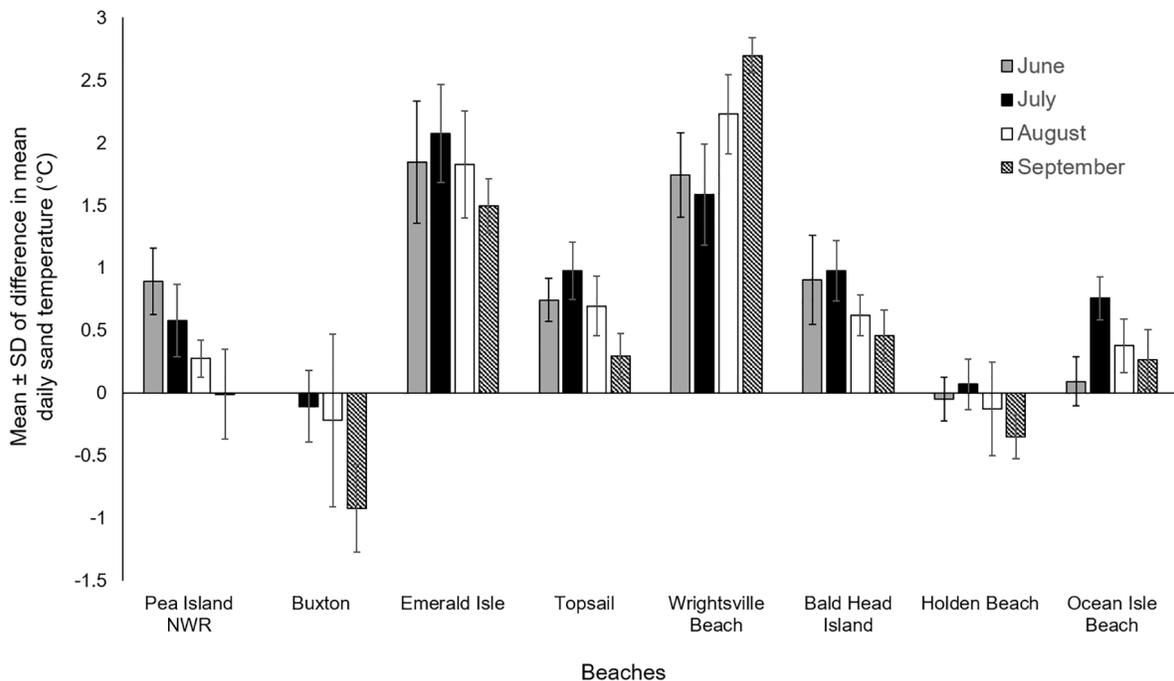


Fig. 2. Mean \pm SD of the difference in mean daily sand temperatures ($^\circ\text{C}$) between natural and nourished beach areas between June and September. Positive values indicate that nourished areas are warmer; negative values indicate that natural areas are warmer.

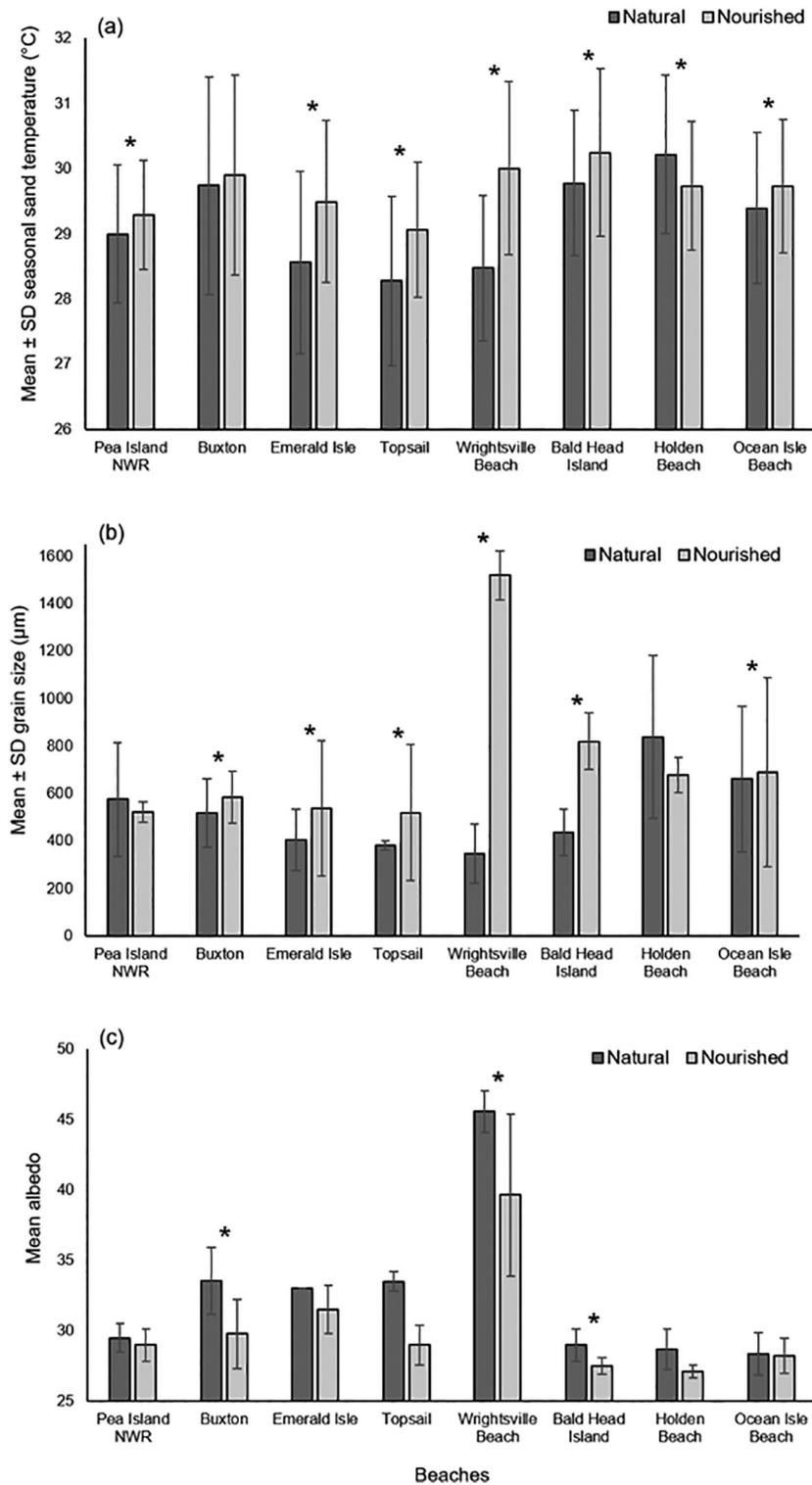


Fig. 3. Comparisons between natural and nourished beach areas in (a) mean seasonal sand temperatures ($^{\circ}$ C), (b) mean grain size (μ m), and (c) albedo. * indicate significant differences between values.

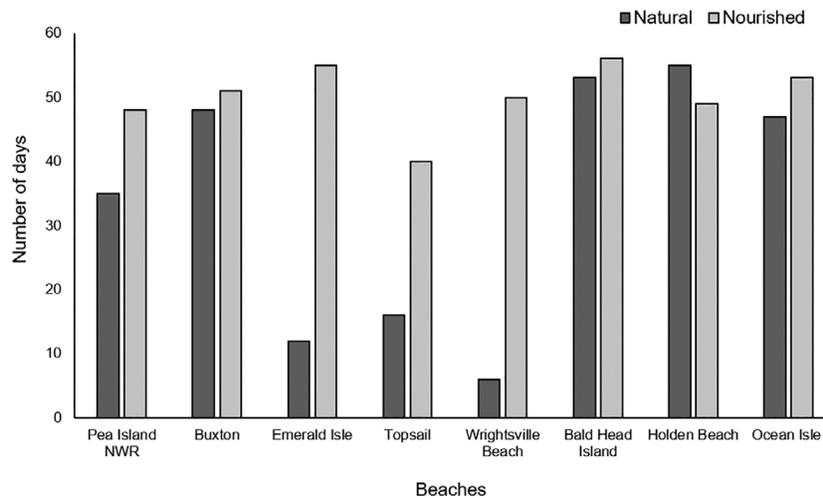


Fig. 4. Number of days observed throughout the season where daily sand temperatures were above the pivotal temperature (29°C) of loggerhead turtles for natural and nourished areas on all eight beaches.

Among beaches, natural areas exceeded 29°C for an average of 33 d. Among nourished areas, sand temperatures exceeded the pivotal temperature for an average of 50 d. The largest difference in the number of days above the pivotal was observed on Wrightsville Beach. In the natural area, we documented only six days above 29°C. However, within nourished areas we recorded 50 d above the pivotal temperature. We observed the smallest difference between areas in the number of days above the pivotal in Buxton, where we observed 48 and 51 d, respectively.

Sand characteristics

Mean grain sizes were not significantly different among beaches (ANOVA $F_{7,51} = 1.92$, $P = 0.08$). Among natural areas, there were no significant differences in mean grain size (ANOVA $F_{7,21} = 2.38$, $P = 0.06$). However, among nourished areas, we observed significant differences in mean grain size ($F_{7,22} = 10.14$, $P < 0.0001$), with the largest and smallest mean grain sizes on Wrightsville Beach ($1519.6 \pm 103.2 \mu\text{m}$) and Topsail Beach ($519.3 \pm 287.2 \mu\text{m}$), respectively (Table 2). Mean grain size was larger in nourished areas on six out of eight beaches; however, only two of these comparisons were significant (Fig. 3b). Holden Beach and Pea Island NWR both had larger mean grain sizes on natural areas as opposed to nourished, though the differences were not significant. In the

univariate analyses, AREA as well as BEACH and ZONE were significant predictors of mean grain size (Table 3). AREA was the second-best predictor, explaining 13% of the variation in mean grain size.

The distribution of grain size classes largely mirrored the patterns of mean grain size, with significant differences between natural and nourished areas. Overall, nourished areas had a greater proportion of extra-large and large size classes, and natural areas had a greater proportion of small and extra small size classes (see Appendix S1: Fig. S1 for overall grain size class distribution and grain size classes broken down for each beach). Indeed, when classes were considered separately, AREA was a significant predictor of grain size in all univariate analyses (data not shown). With the exception of the extra-large grain size class, in which every beach we sampled had more %XL grain sizes on nourished areas than natural, we consistently found the opposite patterns in grain size distribution (less of the larger/medium and more of the smaller grain sizes) in nourished areas than natural on Holden and Ocean Isle beaches (Table 2). In the univariate analyses, BEACH and AREA were significant predictors for CV of grain size ($P < 0.0001$, $P = 0.01$, respectively; Table 3). Nourished areas also had lower albedo than natural areas, though only three of the eight comparisons were significant (Fig. 3c).

Table 2. Descriptive statistics of temperature and sand variables across all eight sea turtle nesting beaches in North Carolina.

Variable	Beach type	Pea Island NWR	Buxton (CHNS)	Emerald Isle Beach	Topsail Beach	Wrightsville Beach	Bald Head Island	Holden Beach	Ocean Isle Beach
Mean seasonal temp (°C)	Natural	29.0 ± 1.1	29.7 ± 1.7	28.6 ± 1.4	28.3 ± 1.3	28.5 ± 1.1	29.8 ± 1.1	30.2 ± 1.2	29.4 ± 1.2
	Nourished	29.3 ± 0.8	29.9 ± 1.5	29.5 ± 1.5	29.1 ± 1.0	30.0 ± 1.3	30.2 ± 1.3	29.3 ± 1.2	29.7 ± 1.0
CV seasonal temp	Natural	0.04	0.06	0.05	0.05	0.04	0.04	0.04	0.04
	Nourished	0.03	0.05	0.04	0.04	0.04	0.04	0.03	0.03
Mean grain size (µm)	Natural	574.9 ± 238.7	446.8 ± 79.2	403.8 ± 129.9	381.6 ± 18.1	347.0 ± 125.7	436.0 ± 99.1	837.8 ± 342.0	660.7 ± 307.2
	Nourished	520.9 ± 43.9	552.5 ± 38.5	536.7 ± 285.5	519.3 ± 287.1	1519.6 ± 103.2	819.2 ± 119.9	678.1 ± 73.3	689.2 ± 399.2
CV grain size	Natural	0.42	0.16	0.32	0.05	0.36	0.23	0.41	0.46
	Nourished	0.08	0.07	0.53	0.55	0.07	0.15	0.11	0.58
%XS grain size (µm)	Natural	0.004 ± 0.004	0.002 ± 0.003	0.004 ± 0.002	0.007 ± 0.006	0.014 ± 0.006	0.004 ± 0.001	0.005 ± 0.007	0.008 ± 0.004
	Nourished	0.001 ± 0.00	0.002 ± 0.001	0.006 ± 0.003	0.015 ± 0.001	0.004 ± 0.003	0.004 ± 0.005	0.013 ± 0.007	0.004 ± 0.002
%S grain size (µm)	Natural	0.57 ± 0.31	0.61 ± 0.30	0.88 ± 0.16	0.92 ± 0.02	0.94 ± 0.05	0.80 ± 0.2	0.45 ± 0.15	0.63 ± 0.16
	Nourished	0.49 ± 0.06	0.44 ± 0.19	0.80 ± 0.15	0.83 ± 0.18	0.28 ± 0.14	0.32 ± 0.20	0.59 ± 0.06	0.67 ± 0.18
%M grain size (µm)	Natural	0.32 ± 0.28	0.35 ± 0.26	0.10 ± 0.12	0.05 ± 0.01	0.01 ± 0.01	0.17 ± 0.17	0.31 ± 0.20	0.27 ± 0.08
	Nourished	0.49 ± 0.05	0.49 ± 0.16	0.14 ± 0.08	0.07 ± 0.07	0.21 ± 0.08	0.50 ± 0.17	0.27 ± 0.05	0.23 ± 0.09
%L grain size (µm)	Natural	0.10 ± 0.14	0.04 ± 0.04	0.02 ± 0.04	0.01 ± 0.00	0.02 ± 0.03	0.02 ± 0.02	0.22 ± 0.20	0.07 ± 0.06
	Nourished	0.02 ± 0.01	0.07 ± 0.05	0.04 ± 0.05	0.07 ± 0.08	0.39 ± 0.11	0.16 ± 0.06	0.11 ± 0.02	0.06 ± 0.05
%XL grain size (µm)	Natural	0.001 ± 0.001	0.002 ± 0.002	0.003 ± 0.006	0.004 ± 0.004	0.015 ± 0.024	0.004 ± 0.004	0.012 ± 0.010	0.031 ± 0.046
	Nourished	0.002 ± 0.002	0	0.019 ± 0.038	0.017 ± 0.022	0.115 ± 0.046	0.018 ± 0.006	0.021 ± 0.009	0.046 ± 0.074
Albedo	Natural	29.5 ± 1.0	33.6 ± 2.4	33.0 ± 1.0	33.5 ± 0.7	45.6 ± 1.5	29.0 ± 1.2	28.7 ± 1.5	28.3 ± 1.5
	Nourished	29.0 ± 1.2	29.8 ± 2.4	31.5 ± 1.7	29.0 ± 1.4	39.7 ± 5.7	27.5 ± 0.6	27.1 ± 0.5	28.3 ± 1.3

Table 3. Univariate analysis of the relationship between temperature and sand characteristics and various spatial and temporal variables.

Variable	Mean monthly temperature (°C)		CV mean monthly temperature		Mean grain size (µm)		CV mean grain size		Albedo	
	<i>P</i>	<i>r</i> ²	<i>P</i>	<i>r</i> ²	<i>P</i>	<i>r</i> ²	<i>P</i>	<i>r</i> ²	<i>P</i>	<i>r</i> ²
Month	<0.0001	0.14	<0.0001	0.27	0.73	0.01	0.35	0.03	<0.0001	0.36
Beach	<0.0001	0.25	0.001	0.13	0.01	0.14	<0.0001	0.31	<0.0001	0.90
Area	0.03	0.03	0.99	3.42E-07	<0.0001	0.13	0.01	0.05	0.2	0.01
Zone	0.53	0.002	0.97	9.62E-06	0.02	0.04	0.89	2.00E-04	0.26	0.01

Note: Significant values are bolded, and the predictor variable with the highest *r*² value is italicized.

Mixed-effect models

We ran a mixed-effect model controlling for the natural spatial and temporal variation by including BEACH and MONTH as random effects. AREA was a significant predictor of mean monthly sand temperatures (*r*² = 0.4, *P* = 0.02), but not of CV. Moreover, the best multivariable model for mean monthly temperature included AREA (Appendix S1: Table S1). AREA was also included as a term in the best multivariable model explaining 30% and 36% of variation in the mean and CV of grain size, respectively (Appendix S1: Table S1). In the univariate analyses, albedo, the relative percentage of small, medium, and large grain size classes and mean grain size were also significant predictors of mean monthly temperature (Table 4). The multivariable

model that explained the most variation in mean monthly temperature included mean grain size, CV of mean grain size, and the three size classes identified as significant predictors in univariate analyses (*r*² = 0.21, *P* = 0.004; Appendix S1: Table S2).

DISCUSSION

Coastal ecosystems are estimated to contribute approximately 25% (\$28 trillion/yr) to the total \$125 trillion/yr provided by global ecosystem services (Costanza et al. 2014). In the United States alone, beaches generate approximately \$225 billion/yr for the national economy (Houston 2013). Since the 1920s there have been approximately 3400 nourishment events that

Table 4. Univariate analysis of the relationship between temperature and sand characteristics.

Variable	Mean monthly temperature		CV mean monthly temperature	
	<i>P</i>	<i>r</i> ²	<i>P</i>	<i>r</i> ²
Mean grain size	0.04	0.06	0.85	5.00E-04
CV grain size	0.84	6.00E-04	0.89	2.00E-04
%XL	0.49	0.01	0.45	0.01
%L	0.02	0.07	0.99	8.00E-07
%M	0.0004	0.15	0.84	6.00E-04
%S	0.0004	0.15	0.67	2.00E-03
%XS	0.15	0.03	0.88	3.00E-04
Albedo	0.001	0.14	<0.0001	<i>0.30</i>

Note: Significant values are bolded, and the predictor variable with the highest *r*² value is italicized.

have placed nearly one trillion cubic yards of sand over 1500 km of coastline, costing over \$7 trillion (National Beach Nourishment Database 2019) to protect these economically and ecologically valuable habitats. However, even under the most stringent scenario limiting greenhouse gas emissions, the global mean sea level is expected to rise for centuries to come (IPCC 2014). By the end of the 21st century, 70% of global coastlines will experience a change in mean sea level within 20% of the global mean (IPCC 2014). Climate warming is thus one of the most significant hazards to endangered sea turtles (Rees et al. 2016, Nalovic et al. 2019), which critically rely on the availability of nesting habitat. Currently, beach nourishment is among the most common coastal management tools used to protect these habitats (Greene 2002, Peterson and Bishop 2005, Speybroeck et al. 2006). It is a practice that inherently requires continued maintenance and replenishment events and therefore is likely to persist, if not increase, on a global scale (Dean 2003). Though effective, beach nourishment potentially operates at a cost to the reproductive output of nesting females.

We found a significant effect of beach nourishment on sand temperature in at least one month throughout the season of every beach we studied, with differences most frequently observed in July and August. We observed significantly warmer mean seasonal sand temperatures in nourished areas on six of the eight beaches we studied. We also found that temperature differences resulted from differences in sand characteristics between the borrowed sand used in

nourishment projects and the sand that naturally accumulates on the beach. On most beaches, nourished sand was characterized by considerable amounts of extra-large and large grain sizes and a distinct lack of small grain sizes. Sedimentary features such as grain size, distribution, and albedo can exert influence over thermal conductivity as well as water and gas diffusion processes within the incubation environment of sea turtles (Ackerman 1997), indirectly influencing incubation duration and hatchling success (Fadini et al. 2011, Ditmer and Stapleton 2012).

Previous work has reported significant effects of nourishment on the thermal properties of nesting beaches. In the Delaware Bay, a combination of darker, finer, borrowed sand increased sand temperatures, and oxygen limitation, leading to a lower habitat suitability index with respect to horseshoe crab nesting areas (Avisar 2006). These results highlighted the need to match the fill sediment to the natural grain size and color of the original sand, in order to minimize adverse impacts on horseshoe crab nests. Similarly, Milton et al. (1997) found that the aragonite sand imported from the Bahamas Banks (Sealy 1994) and deposited on Fisher Island, Florida was significantly cooler than the native silicate sand. In fact, nests laid in aragonite sand incubated at temperatures as much as 3°C cooler than nests laid in silica sand (Milton et al. 1997). While temperatures increased in both sand types as the season progressed, the slope of the increase in aragonite was 66% that of the silicate sand, indicating a lower thermal capacity for the Bahamian sand. As such, changes in the thermal regime are clearly dependent on the characteristics of dredged material used and the natural morphodynamic and sand grain properties found on each nourished beach, emphasizing the ecologically and biologically relevant impacts of beach nourishment (Peterson and Bishop 2005). Further, monitoring the morphological changes of nesting habitat is a key factor in assessing the impact of climate change on sea turtles, as discussed in several reviews highlighting management and conservation priorities (Hamann et al. 2010, Rees et al. 2016).

Differences in sand temperature on nesting beaches raises concerns about the future production of male hatchlings from regionally and globally important rookeries (Hays et al. 2014). The

observed differences between the number of days that exceeded the pivotal temperature among areas within beaches strongly indicate that beach nourishment can directly influence the incubation environment and therefore critical fitness characteristics as well as primary sex ratios of loggerhead sea turtle hatchlings. Nourished areas within beaches had a greater number of days above the pivotal temperature on each beach we observed except for Holden Beach (Fig. 4). These data suggest that nests were more likely to produce female-biased primary sex ratios on nourished compared to natural areas. The incubation duration of loggerhead nests has already decreased an average of seven days over the past 25 yr at an important North Carolina loggerhead rookery, which has led to a concomitant increase in the estimated percentage of female hatchlings produced, from a mean of 55% in 1991 to a mean of 88% in 2015 (Reneker and Kamel 2016a).

This pattern of extreme female bias in the primary sex ratios of loggerheads is extensive (see Fig. 3 in Hays et al. 2014). Potential mitigation techniques such as the relocation, shading, and watering of nests have been investigated in several sea turtle populations. For example, shading sand with fence mesh in Playa Grande, Costa Rica, resulted in about a 2°C decrease in temperature and was more effective than watering (Hill et al. 2015). Decreases of similar magnitude were also reported when sand was sprinkled with water or shaded in an experimental setting in Australia (Jourdan and Fuentes 2015). More recently, a combination of relocation and shading with palm trees was predicted to reduce primary sex ratios from a current range of 97–100% female to 60–90% female (Esteban et al. 2018). This low-cost, low technology method might therefore be useful to mitigate the immediate effects of warming due to beach nourishment. A decision science approach would be a useful tool to identify the most cost-effective, feasible and beneficial management interventions relevant to North Carolina's sea turtle populations (Klein et al. 2017).

Whether these long-lived species have the potential to adapt to global climate change via shifts in nesting phenology or nest-site selection behaviors is still unknown (Hawkes et al. 2007, Schwanz and Janzen 2008, Refsnider et al. 2013,

Reneker and Kamel 2016b). However, we have shown that beach nourishment can cause significant changes to the thermal profile of loggerhead nesting beaches and we support a directed effort to incorporate these impacts into species assessments. Moreover, it is critical to take a regional approach to not only assess temperature at all rookeries and identify male-producing beaches for protection, but also to identify beaches where nourishment projects may be exacerbating sex ratio distortions and thus require additional intervention (Klein et al. 2017, Esteban et al. 2018).

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