Evaluation of Bird Nesting Use on Substrate Enhanced Beach Habitat: Final Report

A Report of the:

Barataria-Terrebonne National Estuary Program

Prepared by:

Delaina LeBlanc, BTNEP Migratory Birds Coordinator

Paul L. Leberg, University of Southwestern Louisiana

Emily Clark, BTNEP Coastal Bird Coordinator

Prepared for the:

Coastal Protection and Restoration Authority of Louisiana

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Contents

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Introduction

Background Information

Louisiana's barrier shoreline serves an important societal function through the protection of coastal communities and infrastructure by absorbing storm energy. It also provides necessary habitat for numerous species of wildlife. Millions of birds utilize these habitats each year for their wintering grounds, as a stopover site to refuel on long migratory journeys, or to breed and raise their young. In particular, the Caminada Headland in southeast Louisiana was identified by the Louisiana Coastal Area Ecosystem Restoration Study as essential habitat due to its role in the preservation and protection of gulf shoreline, inland wetlands and bays, as well as a significant and unique foraging and nesting area for threatened and endangered species (USACE 2004). Surveys conducted by the Barataria Terrebonne National Estuary Program (BTNEP) since 2005 have documented extensive breeding use along the Caminada Headland by Least Tern (*Sternula antillarum*) and other species. Least Tern are listed on the U.S. Fish and Wildlife Service (USFWS) Birds of Conservation Concern (2008), making it a vital area to focus coastal conservation efforts.

Over the last several decades, the Caminada Headland has experienced significant shoreline erosion and land loss due to anthropogenic impacts, storm over-wash, wind and wave induced erosion, sea level rise, and subsidence (CEC 2012). These factors, in conjunction with extensive development along the Gulf Coast, have drastically reduced the availability of prime foraging and nesting habitat for shorebirds (Johnson, 2016). To combat the issue of rapid land loss, Louisiana and the federal government have developed funding streams meant to help restore these important habitats. One such endeavor, The Caminada Headland Beach and Dune Restoration Project (BA-45), was designed to protect and preserve the structural integrity of the barrier shoreline and to restore hydrologic conditions, ecosystem processes, and habitats (CPRA 2015). Managed by the Coastal Protection and Restoration Authority of Louisiana (CPRA), construction of the project began in August of 2013 and was completed in January of 2015. One of the main goals of the project was to create approximately 303 acres of beach and dune habitat along the Caminada Headland through dredging and pumping sand from an offshore location at Ship Shoal (CPRA 2015).

Focal Species

The Least Tern is the smallest tern species in North America. It is a widely distributed colonial nesting seabird that breeds along major interior rivers as well as coastal beaches and islands. The Least Tern spends its winters on the marine coastlines of Central and South America (Thompson et al. 1997). Its preferred nesting sites are relatively open beaches or islands with little vegetation, including those found in southeast Louisiana.

Unfortunately, these riverine and coastal habitats are the same areas utilized by humans for recreation, residential development, and alteration by water diversion, which has led to a serious lack in suitable nesting habitat for the species and widespread population decline (Thompson et al. 1997). According to the North American Breeding Bird Survey, Least Tern populations have declined by about 88% between 1966 and

2015 (USGS 2015). The North American Waterbird Conservation Plan estimates a continental population of 60,000-100,000 breeding birds, and lists it as a Species of High Concern (Kushlan et al. 2002). Many historical breeding areas have been altered to the point that terns can no longer nest on them, or are subject to high rates of human disturbance and predation. The Least Tern is listed as a Species of Greatest Conservation Need in the Louisiana Wildlife Action Plan (Holcomb et al. 2015).

Research Justification

With increasing unavailability of natural habitats, Least Terns have been nesting on man-made dredge-spoil islands. Navigable waterways and channels are maintained in the U.S. to the proper depths through dredging, which removes the excess material and redeposits it elsewhere. This material is used to form or restore islands, creating the early successional habitat preferred by many beach-nesting birds. Studies in the 1970's recognized just how important the use of dredge material sites are to nesting waterbirds, documenting 50-90% of key nesting sites in the Atlantic and Gulf Coast states were on dredged material. Recommendations for creating suitable habitat for nesting waterbirds recognized the need for natural or man-made barriers for sites to deal with predators (Golder et al. 2008). Since that time, these man-made habitats have become even more important, especially in Louisiana where land loss is so rapid and widespread. Creation and restoration of dune, beach, and back barrier marsh through use of dredge materials to restore or augment Louisiana's barrier islands and headlands are commonly used (CPRA, 2016). Restoration projects on mainland beaches create early successional habitat; however, these efforts do not reduce predators that may negatively impact nest success. Studies have examined hatching success and nests site characteristics on dredge material islands, and they have found that the success of these sites for nesting depends on the type of material utilized (Golder et al. 2008, Krogh and Schweitzer 1999, Leberg et al. 1995, Mallach and Leberg 1999, and Owen and Pierce 2013). This leads to different rates of habitat suitability contingent on species-specific characteristics. Dredged material is often fine sand or silt, which is not ideal for Least Terns who prefer to nest on shell-rich substrates or coarse sand/loose gravel (Mallach and Leberg 1999 and Gochfeld 1983). Most of the current research has been conducted on dredge spoil islands and not large-scale beach nourishment projects like the Caminada Headland Beach and Dune Restoration Project. While Mallach and Leberg in their 1999 Louisiana based study on Black Skimmers supplemented dredge material by creating 64, $1m^2$ plots of 2.5cm deep shell, no studies are known that examine the effects of supplementation of dredge material on waterbird nesting at larger scale. Specifically, the large-scale addition of limestone and sandstone has not been tested.

BTNEP set out to conduct an experiment to evaluate nest site selection among substrate types and hatching success of Least Tern along the Caminada Headland. In addition to examining how birds utilized the new habitat created by restoration, the restored beach was supplemented with the placement of #57 grade limestone and #57 grade sandstone. These materials were selected for their availability and economic feasibility.

Nest predation by mammals, ghost crabs, and other birds can have devastating impacts on the success of ground nesting shorebirds. Predation is the primary cause of nest failure for most birds (Ricklefs 1969 and Martin 1992 in Smith et al. 2007). The experiment will evaluate if supplemental treatment applications placed on the study area may make it more difficult for predators to find the nests, leading to greater hatching success. The data collected will help define nest fate associated with each substrate type through use of a nest survivorship model. Statistical analysis of the data would also determine whether there are any significant differences in the selection of nesting substrate and any significant differences in nest fate by substrate type. The goal of this study is to utilize the results to guide best management practices of future beach restoration projects to include the application of supplemental material if it would benefit nesting birds on the Louisiana coast.

Methods

Research Area

The area of focus is the section of beach restored by the Caminada Headland Beach and Dune Restoration Project BA-45 (Figure 1). Nine areas of repeating units were marked off to serve as experimental plots; each approximately the area of a football field (~4,180m^2) separated by a distance of approximately 20m. Three plots were left untreated and served as the control, three were treated with a layer of approximately 2in of limestone, and three were treated with a layer of approximately 2in of sandstone. The nine plots are located south of the sand fencing, on the gulf-side beach of the Caminada Headlands and stretch from approximately 29° 6'46.27"N, 90°10'29.05"W to 29° 7'10.45"N, 90° 9'49.65"W (Figure 2). Substrates were placed randomly to meet the requirements of the experimental design (Figures 3 and 4).

The total amount of material purchased, transported, and placed per plot included 2,502 tons of material at a cost of $215,000. Three plots were treated with 417 tons of grade #57 limestone and three plots were treated with 417 tons of grade #57 sandstone (Clark, 2016). Each treated plot had 254m^3 of either limestone or sandstone placed approximately 5 cm thick. The approximate cost of each treated plot was $35,833.

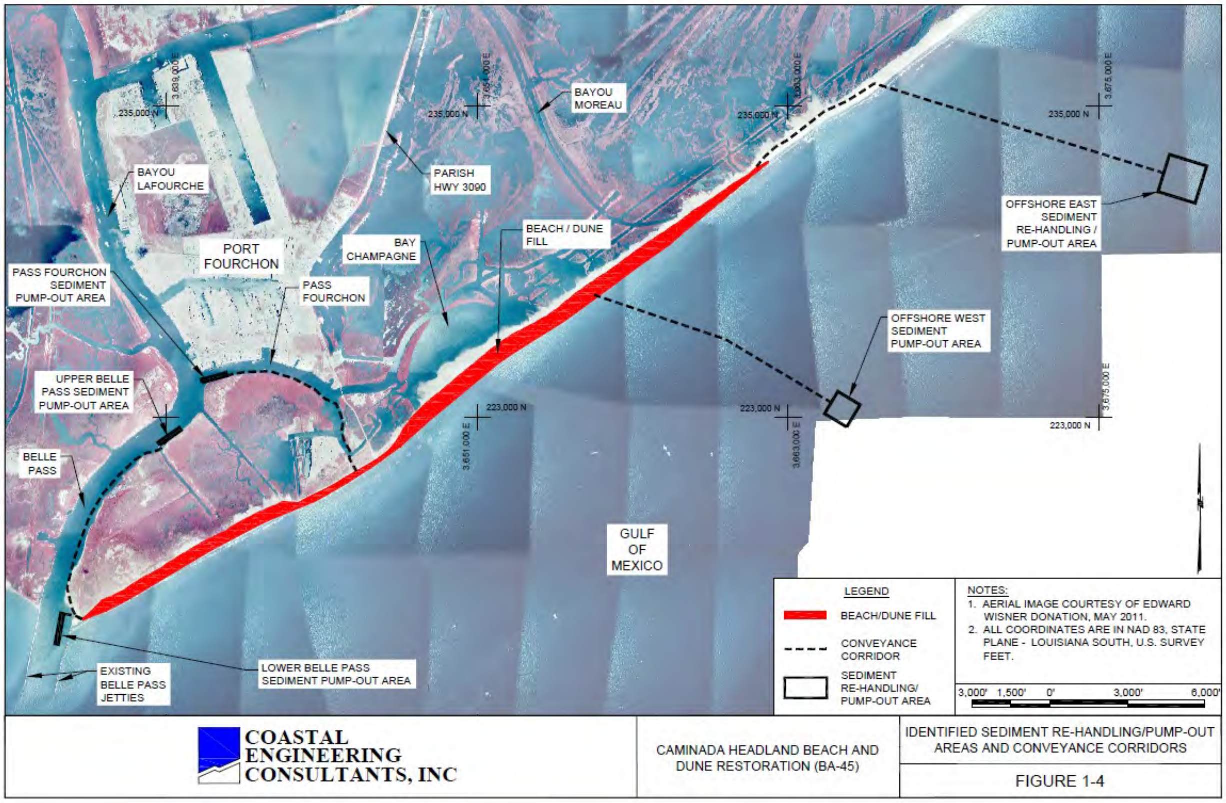


Figure 1. Location of the Caminada Headlands Beach and Dune Restoration Incr 1 Project (BA-0045).

Figure 2: Location of the research study plots (A-I) on East Beach, Port Fourchon.

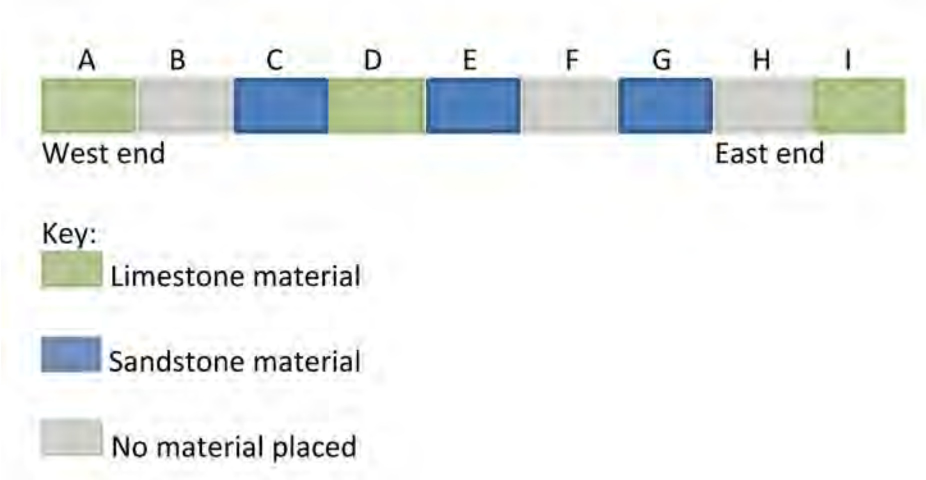


Figure 3. Substrate Placement by Plot.

Figure 4. Placement of material within plots at study site.

Field Techniques

Surveys of each study plot were conducted every 1-3 days during the entirety of the nesting season. This begins after the arrival of birds from spring migration and signs of courtship behavior begin (displays, vocalizations, scraping, territoriality), which generally occurs mid to late April for Least Terns. Surveys cease after all nests are hatched and no new nests occur for 10 consecutive survey days, typically in late July or early August. During each visit to the study area, the date, time of day (arrival and departure), weather conditions, human disturbance, and other wildlife present besides the focal species were recorded.

Plots were monitored in rotating order to avoid searching at the same time of day in each plot. Surveys took place between 5:30 am and 10:00 am to avoid heat stress to the birds. Time spent in each plot was recorded and was limited to a maximum of 25 minutes to ensure that birds were not being kept off nests for prolonged periods. Additionally, surveys were not conducted during inclement weather including rain or wet conditions, as well as wind speeds greater than 20mph or when sand is blowing on the surface, which could potentially damage eggs. The number of adults and their behavior, the number of scrapes, and evidence of predator activity (tracks, scat, missing nests) was noted. A systematic grid-search pattern was used to nest search (Figure 5). To perform this method, one to two observers formed a straight line on the edge of the boundary of the plot, perpendicular with the water. Researchers were evenly spaced and the distance between them (or consecutive turns if only one observer) did not exceed 3m apart to ensure visibility to the area 1.5m to the right and left of them. Researchers carefully, but swiftly, walked each plot looking for signs of nesting.

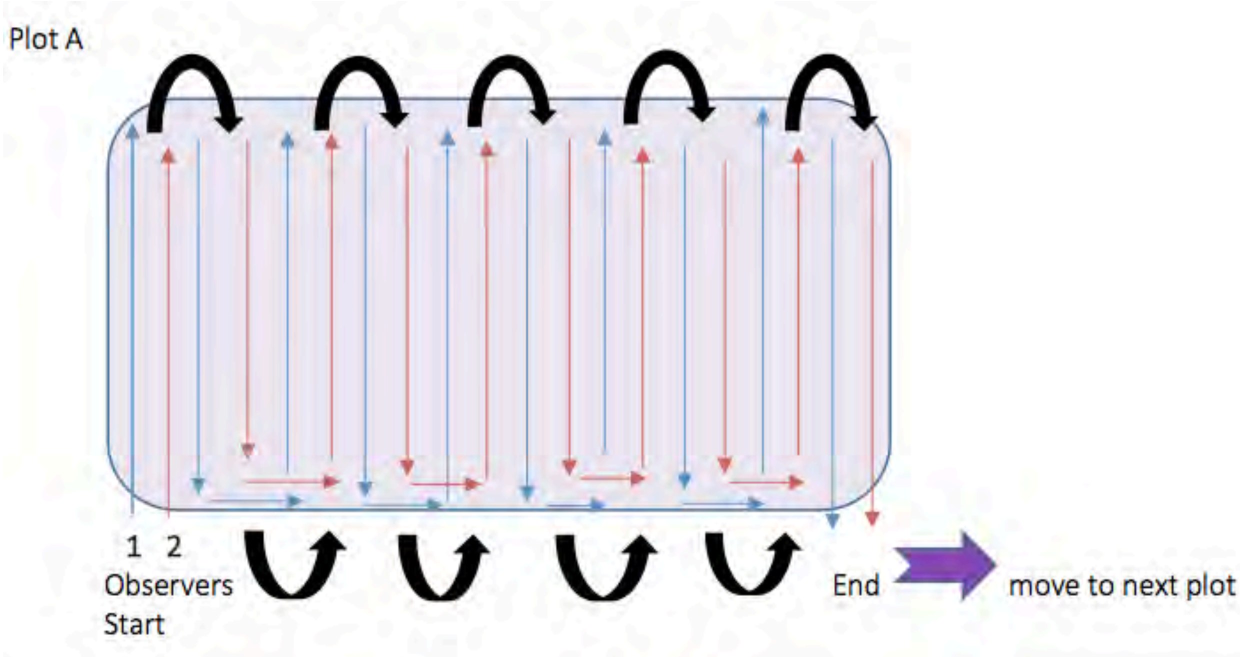


Figure 5. Systematic grid-search pattern used to locate nests within the study plots.

When a new nest was observed, researchers: 1) documented the presence of adults tending the nest, 2) recorded the number of eggs, 3) collected a GPS location of the nest (GARMIN GPSMAP 78), 4) floated eggs if the initiation date is unknown, 5) marked nests with unique code, and 6) took a photograph of the nest centered in a 1m² quadrant to later determine microhabitat characteristics. The nest markers (tongue depressors) were pre-labeled with a unique ID. The nest marker was first used as the unique identifier for the nest photograph by placing it flat on the surface in the bottom right corner of the quadrant (Figure 6). The marker was then placed into the sand 1m from the top right corner of the quadrant and at a 45˚ angle to allow researchers to locate and identify nests on subsequent visits. If the initiation date was unknown, eggs were floated on the first visit following the methods of Hays and LeCroy (1971) for Least Terns to determine the developmental stage.

Figure 6. **Placement of PVC grid and nest marker used to document the unique nest code and physical nest habitat characteristics.**

Nests were monitored until nest fate (hatching success) were determined. A nest was defined as successful if at least one egg hatched, and was considered failed if the nest was abandoned, depredated, or damaged prior to any eggs hatching. A nest was considered abandoned if the eggs appeared to be unattended (cold, covered in sand, out of the original nest bowl, or no adults present) for 3 consecutive nest checks. Nest fate was deemed undetermined if the eggs were missing on or around the hatch date, but no chicks were found, nor any signs of predator activity. Nests were examined for evidence of predation including tracks, broken eggshells, missing eggs, or yolk found in the nest bowl. The type of predator was determined if possible based on the evidence, but was listed as unknown if there was not sufficient evidence. The number of hatched chicks was recorded.

Ghost crab burrow surveys were conducted using the same systematic grid search pattern used to locate nests within the study plots. A full count of all burrows observed per unit area (each plot) was recorded 4 days prior to construction for the substrate project and two weeks after continuing monthly for the duration of the project.

After active nesting ended, temperature data was collected for 3 consecutive days. Each of the 9 plots was divided up into forty-two 10m squares. Ten sample sites were randomly selected from each plot using random sampling generated using R code, software for statistical computing (R Core Team, 2017). A waypoint was taken in the center of each 10m square using an infrared thermometer (Sper Scientific 800101 IR Thermometer Gun 8:1) then marked with a nest marker so temperature measurements could be replicated on subsequent visits. Each visit, three measurements of temperature were taken for each sample site (90 total). An average of the three measurements taken for each sample site was used to evaluate plot temperatures.

Analysis

Data was collected on several factors that could influence selection, predation, success and initiation; including nest documentation per substrate type, substrate type average temperature, crab burrow density, and evidence of predators.

Daily survival rates (DSR) of nests were calculated using the status of the nests from initiation date to hatching or failure to record changes in between observation points. Nests were observed at intervals in order to estimate DSR. A nest is considered to have survived an observation interval if it was still active at the end of the interval or if there was evidence that it had hatched. An active nest is considered to have failed if there was evidence that it had been depredated or abandoned at the end of the interval. A small number of nests were identified as having unknown status. These were nests nearing their expected hatch date when the eggs disappeared, and there was no evidence of the presence of predators or chicks. Observation intervals of these nests with unknown fates were excluded from estimates of daily survival rate.

Factors including differences due to pre and post treatment (year), time of year (date), Substrate type (treatment), crab burrow density, and substrate temperature were independently assessed and also paired to determine if interactions affected DSR.

Data collected was analyzed independently for 2016 and 2017 then comparatively for both years in plots where no treatment was applied. In 2017, limestone, sandstone and untreated plots were evaluated to assess any differences between treatments in bird use, temperature, and ghost crab burrow density on nest selection, predation, nest success and number of nest initiations. Ghost crab surveys collected over time explored burrow densities in relation to factors including treatment and month. These factors were analyzed independently and paired to evaluate interactions between variables.

The overall plot temperature average was analyzed by substrate treatment (control, limestone, sandstone). Details of the statistical analyses and results are provided in Appendix C.

Results

Evaluation of Nest Site Selection and Hatching Success Among Substrate Types

Plots treated with limestone had a higher number of nests when compared to plots with no treatment or plots with sandstone substrate. Plots with no treatment had the least number of nests (Figure 7). However, there were no differences attributed to substrate type (treatment) for nest initiation, hatching success, loss of nests to predation, or the number of chicks considered greater than would be expected by chance (Figure 8). The estimate of daily survival rate (DSR) and the probability of a nest surviving 21 days were slightly higher for nests in the limestone treatment compared to the control. However, the sample size was too small to show a significant relationship between DSR and the limestone treatment. Nest failure due to predation was equally high between all treatment types.

Application of limestone and sandstone affected the number of ghost crab burrows significantly. Both treatments reduced the density of burrows relative to the control sites. Plots treated with sandstone had the lowest densities of burrows. However, the density of ghost crab burrows had no significant effect on the number of successful nests on a plot.

Limestone and sandstone illustrated lower temperatures than the control. While there were differences in temperature between the control and treatments, the surface temperature between substrates did not affect the number of nesting pairs on a plot.

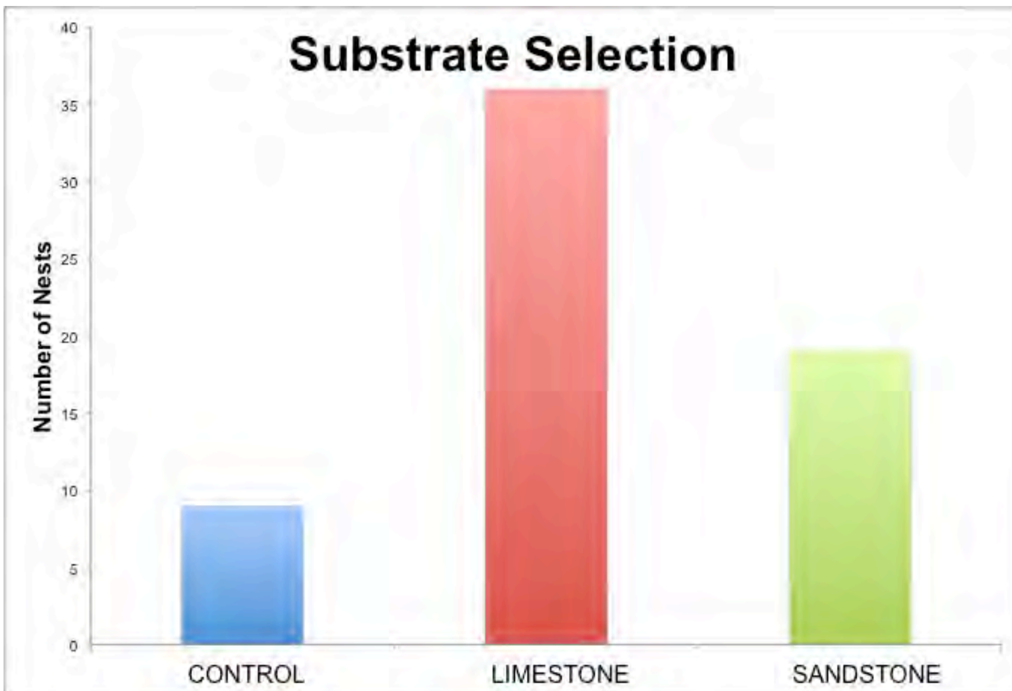


Figure 7. Number of nests per substrate in 2017.

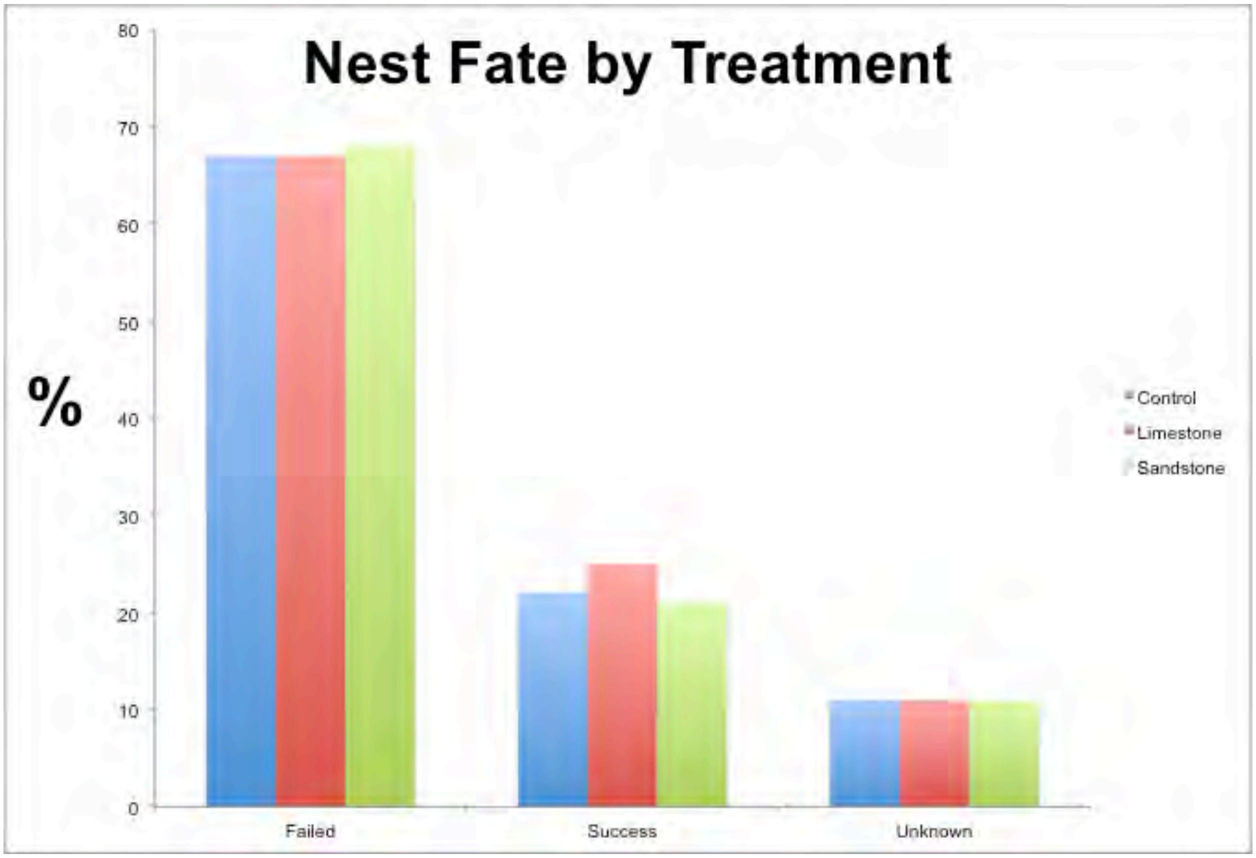


Figure 8. Comparing nest fates between treatments in 2017.

Nesting Activity of Least Terns Between Years 2016 and 2017

Plots B, F and H were analyzed in both years since no treatment was applied in those plots. In 2016, 24 nests were documented while only 12 were recorded in 2017. There were no Least Tern nests recorded during the month of April for either year. The highest number of nests differed between years with the peak occurring in June for 2016 and May for 2017. No Least Tern nests were documented in July of 2017 (Figure 9).

The low number of nests later in the season for 2017 was likely due to more than one cause. Potential influences include a weather event and an additional nesting shorebird research project taking place within 8 miles of this project. On June 21, Tropical Storm Cindy made landfall on Louisiana's coast. Water pushed toward the shore by the winds associated with that storm re-worked sections of the study site removing sandstone and limestone material. Additionally, a study by Louisiana Audubon and Louisiana Department of Wildlife and Fisheries used a broadcast playback system to lure nesting terns to an area with electrified fencing further east on Elmer's Island (Johnson, 2017).

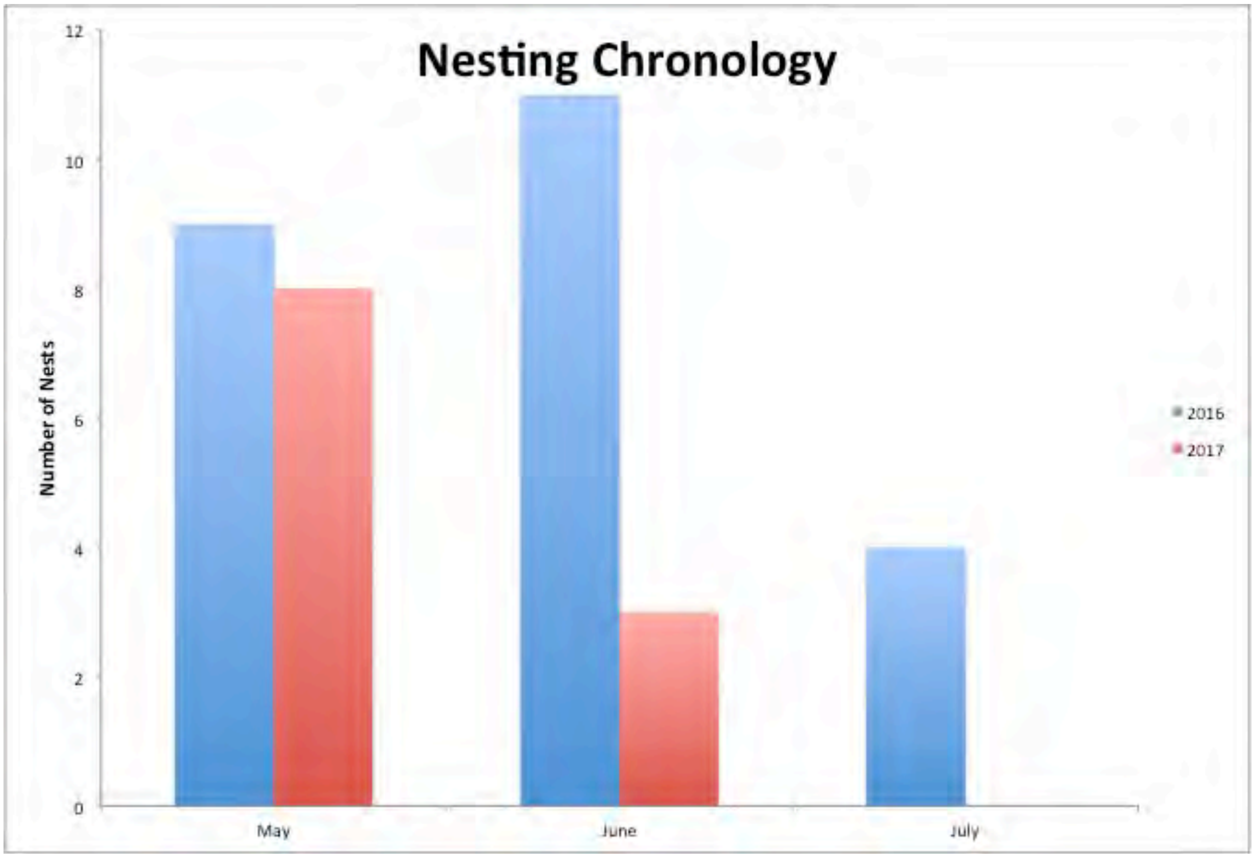


Figure 9. **Nesting chronology of Least Terns within the untreated plots by total number of nests laid per month per year.**

Nests were evenly distributed among all plots in 2016 before placement of additional material (Figure 10). In 2017, nests were clumped on limestone plots more than on control substrates (Figure 11).

In 2017, 2 nests successfully hatched while 2016 produced zero hatchlings. High nest failure was consistent over both years. One undetermined outcomes was recorded in 2017 but 3 were documented in 2016 (Figure 12).

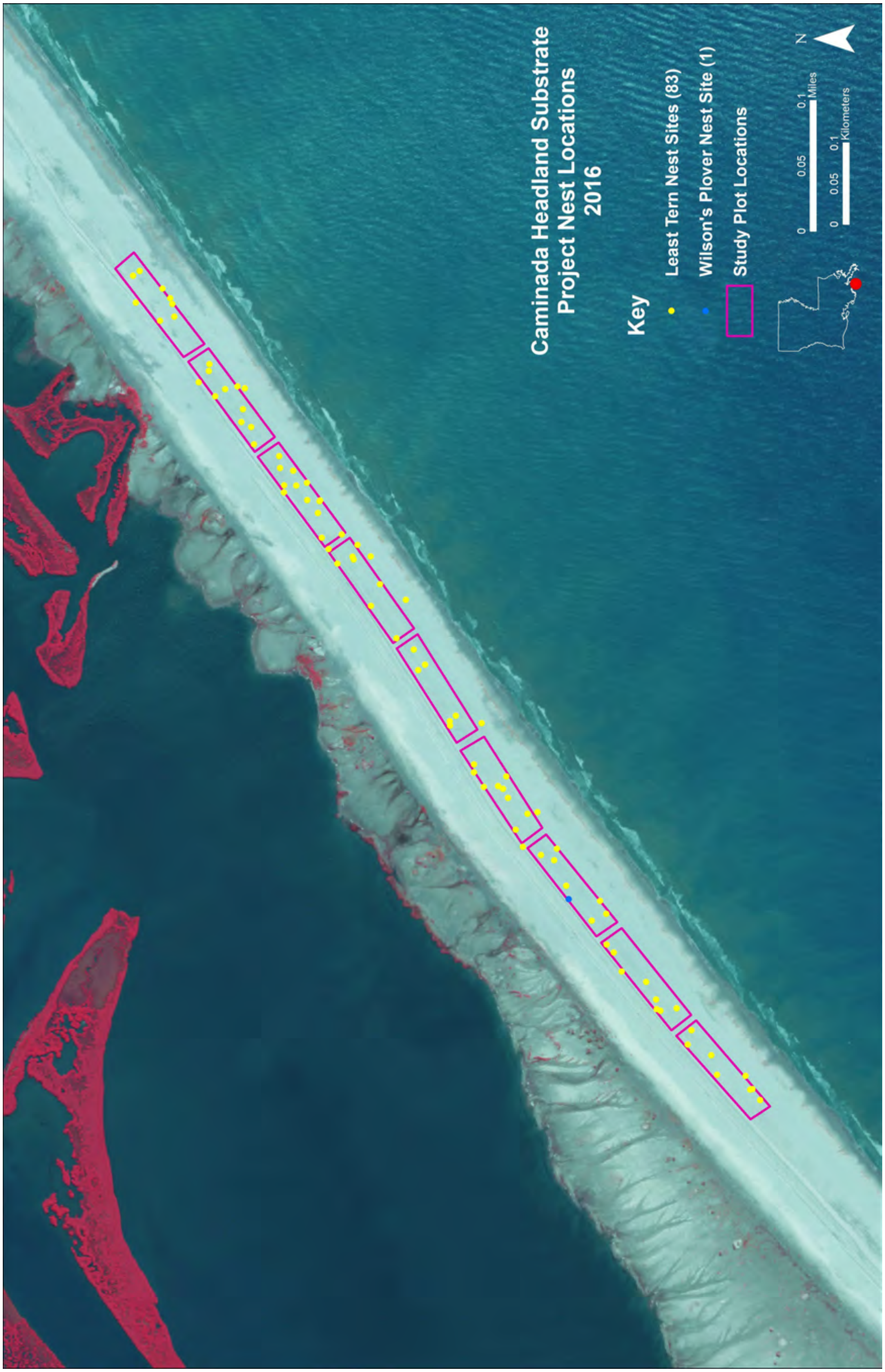


Figure 10. Distribution of Least Tern Nests within and near the study plots, 2016.

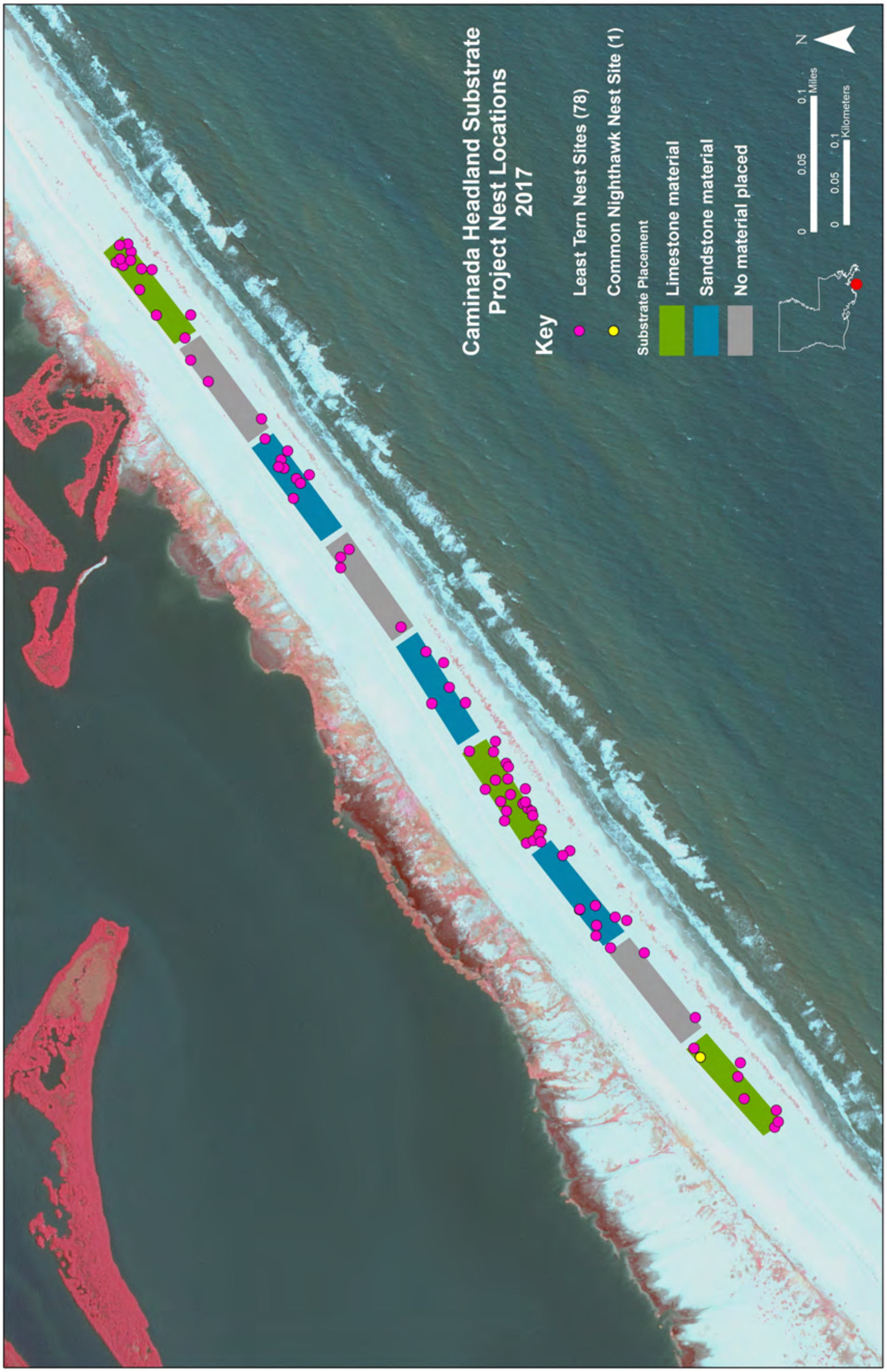


Figure 11. Distribution of Least Tern Nests within and near the study plots, 2017.

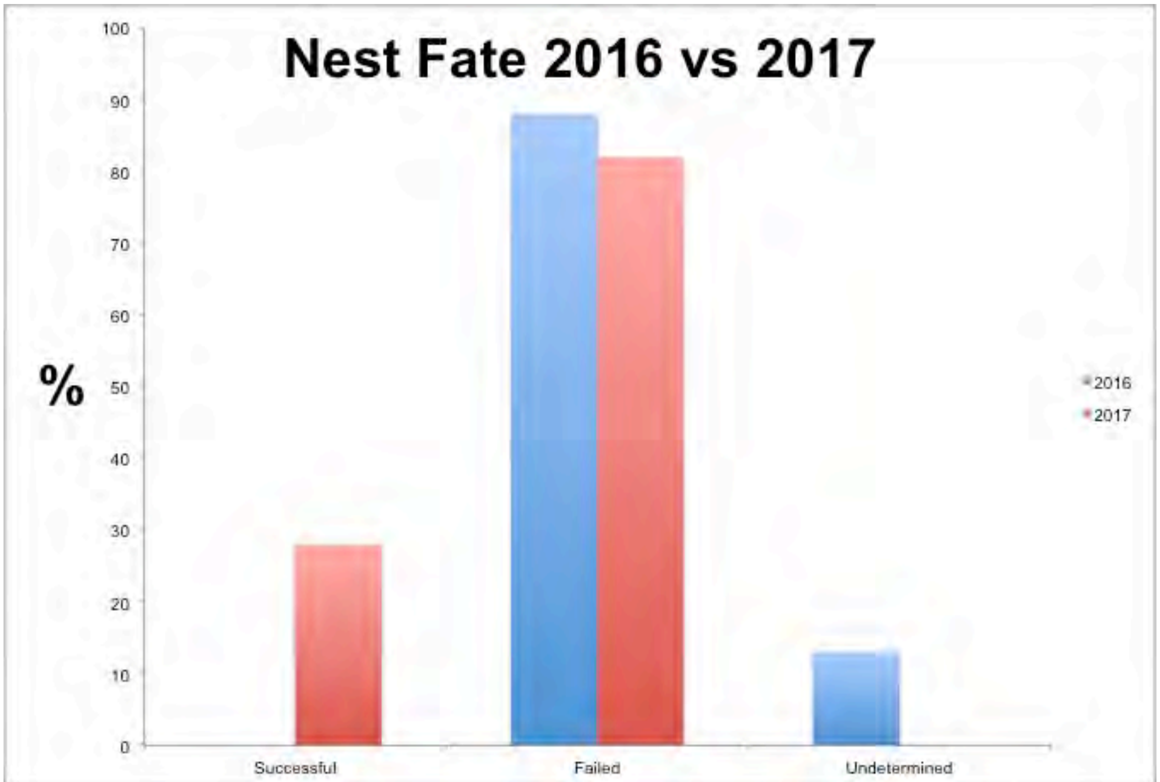


Figure 12. **Comparison of nest fates of Least Terns within the East Beach study region between years.**

Causes of Nest Failure for Least Terns

Predation was the predominant cause of nest failure in both years of the study. Other causes of nest failure included abandonment (2016) and storm surge (2017). Predation rates were proportionally equivalent from year to year; however, identification of predators was much lower in 2017 potentially as a result of limestone and sandstone substrates limiting detection of tracks and other signs from coyotes and ghost crabs.

Future Recommendations

Least Terns appeared to preferentially nest on limestone versus the untreated substrate; however, this did not generate any sort of effect on nest success, reduced predation, increased Daily Survival Rate, or number of chicks produced. However, the small sample size for this study coupled with the very high predation rate limited the capacity of producing a strong relationship between any of these factors. Meanwhile the application of limestone and sandstone did illustrate a significant reduction of ghost crab burrows and indicates a potential for management of that nest predator. Continued study would require additional replicates be added; however, the cost should be considered as each additional treated acre would add a minimum of $34,757 to any restoration costs.

These results, while limited, indicate that in locations where large bare areas of newly placed sand or sand shell have been restored, the addition of these substrates may not be worth the added costs. It might be informative to repeat this study on sites where nest predators were less abundant or in areas where open bare sand and shell is more limited.

Literature Cited

Brown, M.B., L.R. Dinan and J.G. Jorgensen. 2015. 2015 Interior Least Tern and Piping Plover Monitoring, Research, Management, and Outreach Report for the Lower Platte River, Nebraska. Joint report of the Tern and Plover Conservation Partnership and the Nongame Bird Program of the Nebraska Game and Parks Commission. Lincoln, NE.

Brown, S., C. Hickey, B. Harrington, and R. Gill, eds. 2001. The U.S. Shorebird Conservation Plan, 2nd ed. Manomet Center for Conservation Sciences, Manomet, MA.

Butcher, J.A., R.L. Neill and J.T. Boylan. 2007. Survival of Interior Least Tern Chicks Hatched on Gravel-colored Roofs in North Texas. Waterbirds 30 (4):595-601.

Clark, E. 2016. Project Construction Completion Report: Evaluation of Bird Nesting Use of Restored Beach Habitat, Caminada Headlands.

Coastal Engineering Consultants, Inc. (CEC). 2012. Caminada Headland Beach and Dune Restoration (BA-45) Borrow Area Final Design Report. LDNR NO. 2503-12-22 Lafourche Parish, Louisiana.

Coastal Protection and Restoration Authority of Louisiana (CPRA). 2015. Monitoring Plan for Caminada Headland Dune and Beach Restoration (BA-45) Project.

Coastal Protection and Restoration Authority of Louisiana (CPRA). 2016. Project Types. http://coastal.la.gov/our-work/projects/project-types/. Accessed November 18, 2016.

Forys, E. A. and M. Borboen-Abrams. 2006. Roof-top Selection by Least Terns in Pinellas County, Florida. Waterbirds 29(4):501-506.

Golder, W., D. Allen, S. Cameron, and T. Wilder. 2008. Dredged material as a tool for management of tern and skimmer nesting habitats. DOER Technical Notes Collection (ERDC TN-DOER-E24), Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/dots/doer/doer.html.

Gochfeld, Michael. Colony Site Selection by Least Terns: Physical Attributes of Sites. Colonial Waterbirds 6: 205-213.

Hays, H. and M. LeCroy. 1971. Field Criteria for Determining Incubation Stage in Eggs of the Common Tern. The Wilson Bulletin 83(4):425-429.

Holcomb, S R., A.A. Bass, C.S. Reid, M.A. Seymour, N.F. Lorenz, B.B. Gregory, S.M. Javed, and K.F. Balkum. 2015. Louisiana Wildlife Action Plan. Louisiana Department of Wildlife and Fisheries. Baton Rouge, Louisiana.

Johnson, E. I. 2016. Louisiana’s Coastal Stewardship Program 2015 Annual Report: Beach-nesting Bird Protection, Monitoring, and Community Outreach. National Audubon Society, Baton Rouge, LA.

Johnson, E. I. 2017. Louisiana’s Coastal Stewardship Program 2017 Final Report to American Bird Conservancy. National Audubon Society, Baton Rouge, LA

Kushlan, J.A., et al. 2002. Waterbird conservation for the Americas: The North American Waterbird Conservation Plan, version 1. Waterbird Conservation for the Americas. Washington, DC.

Krogh G., and S.H. Schweitzer. 1999. Least Terns Nesting on Natural and Artificial Habitats in Georgia, USA. Waterbirds 22(2):290-296.

Leberg, P.L., P. Deshotels, S. Prius, and M. Carloss. 1995. Nest Sites of Seabirds on Dredge Islands in Coastal Louisiana. Proc. Annu. Conf. Southeast. Assoc. Fish and Wildl. Agencies 49:356-366.

Mabee, T.J., A.M. Wildman, and C.B. Johnson. 2006. Using Egg Flotation and Eggshell Evidence to Determine Age and Fate of Arctic shorebird nests. Journal of Field Ornithology 77:163-172.

Mallach, T.J. and P.L. Leberg. 1999. Use of Dredged Material Substrates by Nesting Terns and Black Skimmers. Journal of Wildlife Management 63(1):137-146.

Owen, T.M and A.R. Pierce. 2013. Hatching Success and Nest Site Characteristics of Black Skimmer (*Rhnchops niger*) on the Isles Denieres Barrier Island Refuge, Louisiana.

R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Smith, P.A., H.G. Gilchrist and J.N.M. Smith. 2007. Effects of Nest Habitat, Food, and Parental Behavior on Shorebird Nest Success. The Condor 109:15-31.

Thompson, Bruce C., Jerome A. Jackson, Joannna Burger, Laura A. Hill, Eileen M. Kirsch and Jonathan L. Atwood. 1997. Least Tern (*Sternula antillarum*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online:http://bna.birds.cornell.edu/bna/species/290.

U.S. Army Corps of Engineers (USACE). 2004. Louisiana Coastal Area Ecosystem Restoration Study. Volume 1: LCA Study – Main Report.

USGS Patuxent Wildlife Research Center. 2015. North American Breeding Bird Survey 1966–2015 Analysis.

U.S. Fish and Wildlife Service. 2008. Birds of Conservation Concern 2008. United States Department of Interior, Fish & Wildlife Service, Division of Migratory Bird Management, Arlington, VA. 85 pp.

Appendix A. Detailed Statistical Analysis Report of 2016 and 2017 Least Tern nesting data

Methods

Crab Burrow Density

Estimates of crab burrow density were available for each month starting in November 2016 and ending in July 2017, however, the November 2016 surveys were incomplete and excluded from this analysis. This density estimate was the dependent variable in a mixed model analysis conducted using PROC MIXED (SAS Institute Inc. 2011) with restricted maximum likelihood estimation. Independent variables included treatment (control, sandstone, limestone) and month. Two sets of months were analyzed separately. To understand how substrate affected burrow density across seasons, all the months were included in one analysis. A second analysis was restricted to the months of May-July, to estimate the effects of substrate on burrow density during the period that terns were nesting. In addition to the main effects of substrate and month, their interaction was evaluated. If the effect of the interaction was not significant, the model was refit to examine only the main effects. Plot was modeled as a random effect, measured over days. Examination of residuals indicated that the residuals did not meet the assumptions of the statistical model. This issue was corrected by conducting a log transformation of burrow density.

Rather than assuming that measures of burrow density across months were independent, I evaluated 4 different structures of the covariance among measurements within plots: unstructured, complex symmetry, first order autoregressive, and heterogeneous autoregressive. I used AIC_c to evaluate the fit of the different covariance structures, with the smallest AIC_c indicating the best fit. In each case, the models with the compound symmetry structure fit the data as well or better than the other structures, and the results below are based on that covariance structure. A Tukey test was used to evaluate the differences among months, treatments, and interaction terms if those effects were significant at 0.05 level. The full analysis of log_burrow density, along with the data and SAS code, is provided in Appendix A.

Temperature

To determine average plot temperature, 10 random sample sites were chosen in a plot, where 3 measurements of temperature were conducted on each of 3 days. The average of these three measurements was used to represent each of the 10 sites on each day. The sample site measurements were averaged together to obtain one of two measures of mean temperature on each of the 3 sample dates. The first was *Mean Plot Temperature*, which was the average of 10 site averages. The second, *Mean Substrate Temperature*, was the same measure, excluding sample sites where the substrate treatment was notably affected by washouts or other deposits of sand. The number of sample sites that contributed to *Mean Substrate Temperature* varied between 3 and 10 (mean = 6.9). The use of mean temperature measurements to represent the temperature of a plot on a single day reduces the effects of pseudoreplication on analysis.

Mean Plot Temperature and *Mean Substrate Temperature* were the dependent variables in a repeated measures mixed model analysis conducted using PROC MIXED with restricted maximum likelihood estimation. Independent variables included treatment (control, sandstone, limestone) and date. The interaction between treatment and date was also evaluated. If the effect of the interaction was not significant, the model was refit to examine only the main effects. Plot was modeled as a random effect, measured over days. Examination of residuals indicated that no transformations of *Mean Plot Temperature* and *Mean Substrate Temperature* were required for the data to meet the assumptions of the mixed model analysis.

I evaluated the same 4 structures of the covariance among measurements within plots that were examined in the analysis of ghost crab burrows. As was the case with the analysis of burrows, the models with the compound symmetry structure fit the data as well or better than the other structures, and the results below are based on that covariance structure. However, the model fit was similar for different covariance structures and the choice of structure did not affect the outcome of the hypothesis tests. A Tukey test was used to evaluate the differences among days, treatments, and interaction terms if those effects were significant at the 0.05 level. The full analysis of the mean temperature variables, along with the data and SAS code, is provided in Appendix B.

Analysis of Daily Survival Rates

Following the corrections made to the data set of problems identified in preliminary analyses and in consultation with BTNEP personnel, the samples used in this portion of the study are described in Table 1. To be used to estimate daily survival rates (DSR), nests had to be observed more than once, creating observation intervals. A nest is considered to have survived an observation interval if it was still active at the end of the interval or if there was evidence that it had hatched. An active nest is considered to have failed if there was evidence that it had been depredated or abandoned at the end of the interval. A small number of nests were identified as having unknown status. These were nests nearing their expected hatch date when the eggs disappeared, and there was no evidence of the presence of predators or chicks. Observation intervals of these nests with unknown fates were excluded from estimates of DSR.

Table 1. Characteristics of data sets used to estimate daily survival rates.

Sample	Number of nests	Nests observed more than once	Number of observation intervals	Observation intervals survived	Observation intervals-failed	Observation intervals-Fate Unknown
2016	81	69	234	162	67	5
2016 plots that	29	25	90	59	28	3

were controls in 2017						
2017 control plots (including nearby nests)	26	26	28	18	9	1
2017 (on and nearby substrate plots)	146	145	291	227	55	9
2017 (substrate plots)	59	57	203	151	45	7

Logistic Exposure Analysis (Shaffer 2004a) was used to estimate daily survival rates and to test the hypotheses that Julian date year and substrate treatment had no effect on nest survival. This approach allows for observation intervals of variable length and compares favorably to similar analyses conducted in MARK (Rotella et al. 2004). For a similar analysis of Least Terns in South Carolina, see Brooks et al. (2013).

The effect of year, date, and their interaction on daily nest survival was evaluated by combining the 2016 and 2017 data sets for the three control plots (Table 1). This analysis was limited to the control plots to remove the confounding effects of other substrates. The 2017 plots included surrounding nests, because nests immediately adjacent to the future substrate plots were included in the 2016 sample. The 2016 data set for all plots (Table 1) was used to determine if Julian date influenced DSR in that year. The 2017 sample from the substrate plots (Table 1) was used to test the hypothesis that substrate treatments, Julian date, or their interaction did not affect DSR.

A full model with both main effects and their interaction was fit, with nest status (survived or failed) as the dependent variable. Terms that were not measurably different than zero at the alpha = 0.10 level were removed, using backward elimination, and the remaining terms were refit. The main effect of a term was not removed if it was involved in a higher order interaction that had a significant effect. An alpha of 0.10 was used in this process, rather than the traditional 0.05, because removal of important terms, regardless of their statistical significance, can bias the results of regression analyses. The relative information contained in a each regression model was also evaluated with the Akaike information criterion, corrected for small sample size (AIC_C).

Once the simplest model was determined through backward elimination of non-significant terms, daily survival rates were determined following Shaffer and Thompson (2007). When Julian date proved to be an important influence on daily survival rates, we estimated daily survival for a Julian date of 160, which was the average of the mean Julian date of all the observation intervals for 2016 and 2017. To plot the influence of Julian date and its interaction with other factors, we also estimated daily survival for a date at the beginning and end of the nesting period (Julian dates 127 and 210, respectively). These dates were the averages of the Julian dates for the first and last nest observations made in 2016 and 2017. Julian date was determined from the mid-point of each observation interval.

Although the data collections were organized across a series of plots, plot was not included in the DSR analyses presented below. I initially conducted similar analyses using plot as both a fixed, or more appropriately, as a random effect. Many of the plots had insufficient data to estimate DSR at the plot level. This made it impossible to estimate these effects with any confidence, and it was impossible to examine interaction terms. Furthermore, inclusion of random effects can bias estimates of nest survival, especially when the number of samples varies across plots (Heisey et al. 2007). In general, plot effects were rarely different within treatment levels, when they could be estimated, suggesting that ignoring this factor would not seriously affect the results presented below.

Nest period survival, or the probability of a nest surviving 21 days, a typical incubation period for Least Terns, was then determined from the DSR (Brooks et al. 2013). All analyses were conducted using SAS 9.3 (SAS 2011), using code and macros found at www.npwrc.usgs.gov/resource/birds/nestsurv/index.htm (Shaffer 2004b). See Appendices C1, C2, and C3 for the data, sas code and results of the DSR analyses.

Nest fates in 2016 and 2017

To make the data set from 2017 comparable to that of 2016, all nests on or near the experiment plots were included in the analysis (Table 1). A contingency table was used to test the hypothesis that nest fates were independent of year. Fisher's exact test was used to determine P-values, as chi-square analyses can be biased by small expected cell sizes. There were insufficient identifications of predators at nests in 2017 (n=5) to conduct a more detailed analysis of predator type by nest substrate. SAS Code, data, and supporting results are found in Appendix D.

Influence of substrate on nest selection, predation, success, and initiation

A number of nesting characteristics were best analyzed using plot as the unit of replication. Preference of the birds for a substrate was assessed by examining the average number of nests testing the hypothesis that there was no difference in bird use of the different substrate treatments. Differences among substrates were assessed with negative binomial regression in Proc Genmod (SAS Institute Inc. 2011). In addition to substrate treatment, the effects of plot temperature and ghost crab burrow density were included as covariates. The measure of burrow density used is the mean of density estimates for the months of May, June and July. Burrow density was log transformed for this and other analyses. Sample sizes were too small to test the interactions between independent variables. Models were evaluated with backward elimination; if a term was not approaching significance ($P < 0.10$), it was removed from the model and a model containing the remaining factors was again fit to the data. Terms approaching statistical significance were left in the regression models, as their removal can affect the estimates of other parameters. Because of the association between log burrow density and substrate type, results of models containing both factors are questionable due to collinearity, and are not discussed below. If an effect was found to be significantly greater than zero, the odds ratio was estimated from the regression coefficient.

This same approach was used to analyze the number of nests lost to predation. Nests with unknown fates were excluded from this analysis. Because number of nests varied between plots, its effect on the numbers of nests lost to predators was controlled through its use of an offset. The null hypothesis being evaluated is that substrate type, temperature, or ghost crab burrow density did not affect the number of nests lost to predation (controlling for the total number of nests on each plot). Initially there was a plan to estimate differences in depredation among substrate treatments by different species of nest predators; however, the number of cases where the species of predator could be identified was too small for statistical analysis.

Negative binomial regression was also used to analyze the factors affecting number of nests that hatched. Unlike the DSR analysis, which estimated the success of individual nests, this analysis, without an offset, examined the effects of substrate type, temperature, and ghost crab burrow density on the number of nests that succeeded on a plot. Thus it examined the productivity of the plots rather than of the average nest on a plot. The number of chicks observed to have hatched on the study plots was also examined using this approach.

Finally, I tested the null hypothesis that birds did not nest on one substrate type earlier than the others using PROC LIFETEST (SAS Institute Inc. 2011). In this time to event analysis, differences between the three substrates were assessed with a Wilcoxon test. For the purpose of this analysis the dependent variable is the Julian date the first nest was recorded on a plot. SAS Code, data, and supporting results are found in Appendix E.

Results

Burrow density

December– July -The null hypothesis that month, substrate treatment, and their interaction did not affect burrow density was rejected ($F_{14,42} = 2.10$, $p = 0.032$). The multiple comparison test suggests that some of the highest means were from July 2017, but also from December 2016 for the control treatment (Table 1).

The significant interaction was mostly due to differences in the densities of the three treatments immediately after the substrate treatments were created in November 2016 (Fig. 1). After December 2016 the temporal pattern in burrow density variation among treatments was similar with a trend of increasing density from January to July. There was a brief deviation from this pattern of increasing densities, with a decrease between April and May. Likewise mean burrow densities were always lowest in sandstone plots and highest on the controls. There was no month in which densities differed between the sandstone and limestone plots (Table 2).

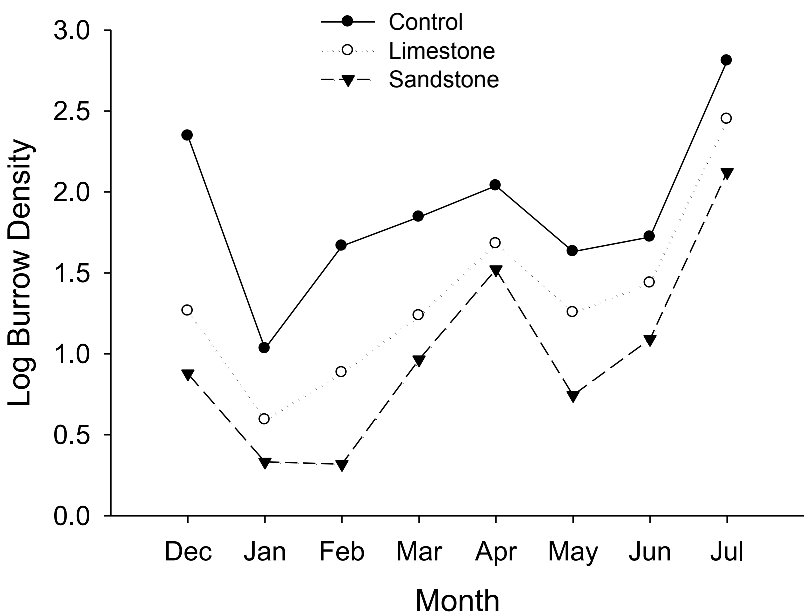


Figure 1. Least square means of ghost crab burrow densities from December 2016 to July 2017 for three substrate treatments.

Table 2. Monthly least square means of burrow density from December 2016 to July 2017 for three substrate treatment levels. Letters indicate non-significant subsets; month-treatment combinations that share the same letter were not significantly different.

Treatment	Month	Log_burrow Density																
SANDSTONE	**Fed**	0.32	A	B	C	D	E											
SANDSTONE	**Jan**	0.33	A	B	C	D	E	F										
LIMESTONE	**Jan**	0.59	A	B	C	D	E	F	G									
SANDSTONE	**May**	0.74	A	B	C	D	E	F	G	H								
SANDSTONE	**Dec**	0.88	A	B	C	D	E	F	G	H	I	J						
LIMESTONE	**Fed**	0.88	A	B	C	D	E	F	G	H	I	J						
SANDSTONE	**Mar**	0.96	A	B	C	D	E	F	G	H	I	J						
CONTROL	**Jan**	1.03	A	B	C	D	E	F	G	H	I	J						
SANDSTONE	**Jun**	1.09		B	C	D	E	F	G	H	I	J	H					
LIMESTONE	**Mar**	1.24		B	C	D	E	F	G	H	I	J	H	I				
LIMESTONE	**May**	1.26		B	C	D	E	F	G	H	I	J	H	I				
LIMESTONE	**Dec**	1.27		B	C	D	E	F	G	H	I	J	H	I				
LIMESTONE	**Jun**	1.44			C	D	E	F	G	H	I	J	H	I	J			
SANDSTONE	**Apr**	1.52				D	E	F	G	H	I	J	H	I	J			
CONTROL	**May**	1.63				D	E	F	G	H	I	J	H	I	J			
CONTROL	**Feb**	1.67				D	E	F	G	H	I	J	H	I	J	K		
LIMESTONE	**Apr**	1.68				D	E	F	G	H	I	J	H	I	J	K		
CONTROL	**Jun**	1.72				D	E	F	G	H	I	J	H	I	J	K		
CONTROL	**Mar**	1.85					E	F	G	H	I	J	H	I	J	K	L	
CONTROL	**Apr**	2.04						F	G	H	I	J	H	I	J	K	L	
SANDSTONE	**Jul**	2.12								H	I	J	H	I	J	K	L	M
CONTROL	**Dec**	2.35									I	J	H	I	J	K	L	M
LIMESTONE	**Jul**	2.45										J	H	I	J	K	L	M
CONTROL	**Jul**	2.81											H	I	J	K	L	M

May-July-The null hypothesis that the interaction between month and substrate on burrow density was not rejected ($F_{4,12} = 0.22$, $p = 0.924$). After fitting the model without the interaction term, the null hypotheses that month ($F_{2,16} = 70.70$, $p < 0.001$) and substrate treatment ($F_{2,6} = 7.25$, $p = 0.025$) had no effect on burrow density were rejected. Pairwise comparisons of months indicate that burrow density was higher in July than in May or June (Fig. 2). A similar comparison of substrates found a higher density of burrows on sandstone than on the control plots, with no significant difference between limestone and the other treatments. An examination of the untransformed means suggests that crab burrow densities were much higher on the control plots than on either the sandstone or the limestone treatment plots.

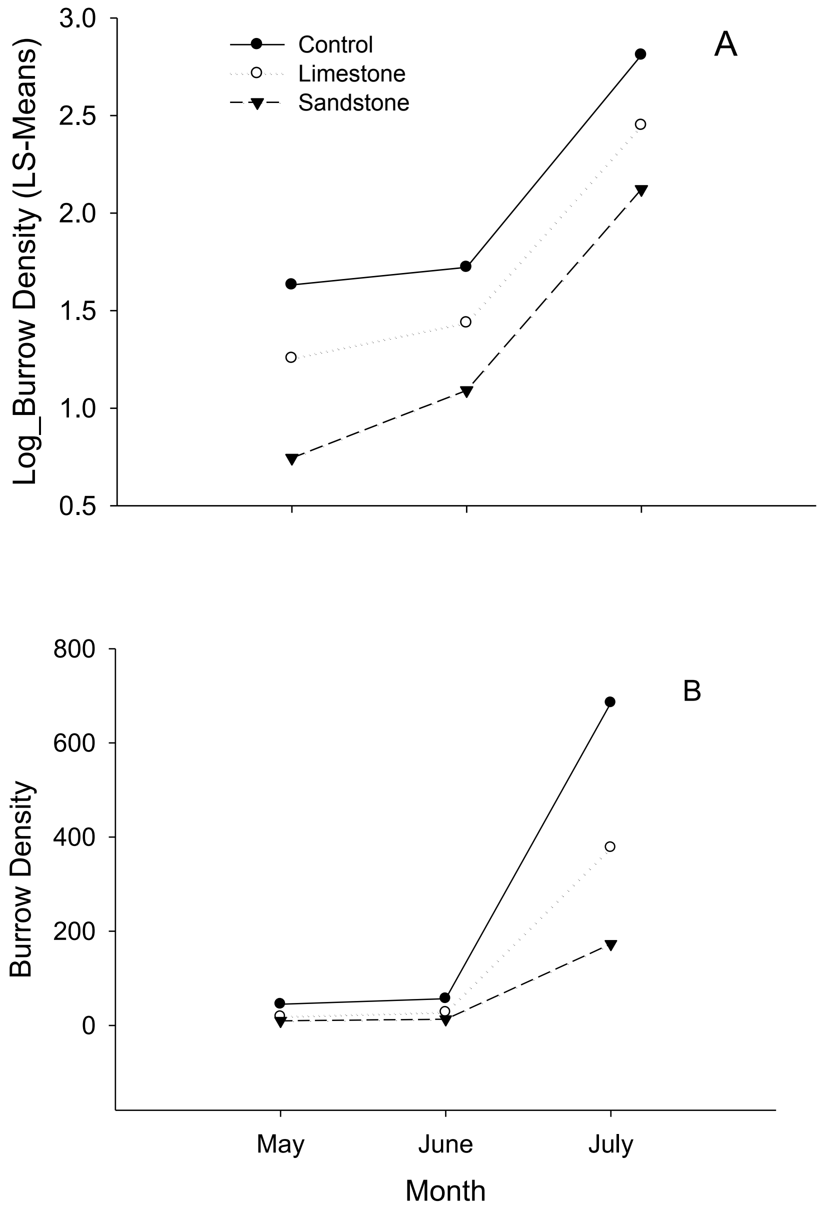


Figure 2. The relation between month and substrate type on ghost crab burrow density during the months Least Terns were nesting on the site. Both the least square means of

the log transformed data (A) and means of the untransformed data (B) are presented to aid in interpretation.

Summary:
There was a significant effect of substrate on the density of ghost crab burrows. Limestone, and especially sandstone, reduced the density of burrows relative to the control sites.

Temperature
The effect of day*treatment interaction on *Mean Plot Temperature* was not significant ($F_{4,12}$ = 0.80, p = 0.549), so the model was refit without that term. Although limestone and sandstone tended to have lower temperatures than the control treatments (Fig. 3), there was no effect of substrate treatment on temperature ($F_{2,6}$ = 1.74, p = 0.253). The failure to detect a difference between substrates may be due to the small number of plots used in this analysis. There was a large day effect ($F_{2,16}$ = 11.41, p < 0.001), suggesting that any variation in temperature due to substrate was much smaller than variation due to day. The Tukey test indicated that the *Mean Plot Temperature* was significantly lower on July 24 (Mean = 33.2C) than it was on July 25 (Mean = 37.2C) or July 27 (Mean = 38.5C).

The effect of the day*treatment interaction on *Mean Substrate Temperature* was not significant ($F_{4,12}$ = 1.22, P = 0.351) so the model was refit without that term. Although limestone and sandstone tended to have lower temperatures than the control treatments (Fig. 3), this analysis found no effect of substrate treatment on temperature ($F_{2,6}$ = 1.69, p = 0.261). The failure to detect a difference between substrates may be due to the small number of plots used in this analysis. As was the case with *Mean Plot Temperature*, there was a large effect of day on *Mean Substrate Temperature* ($F_{2,16}$ = 8.91, p = 0.003). The Tukey test indicated that the *Mean Substrate Temperature* was significantly lower on July 24 (33.9C) than it was on July 25 (37.4C) or July 27 (38.4C).

The similarity between the results of the analyses of *Mean Plot Temperature* and *Mean Substrate Temperature* is not surprising as they were highly correlated (r = 0.989). One should be chosen for the final report as the results are redundant.

Summary:
There was no significant effect of substrate on surface temperature.

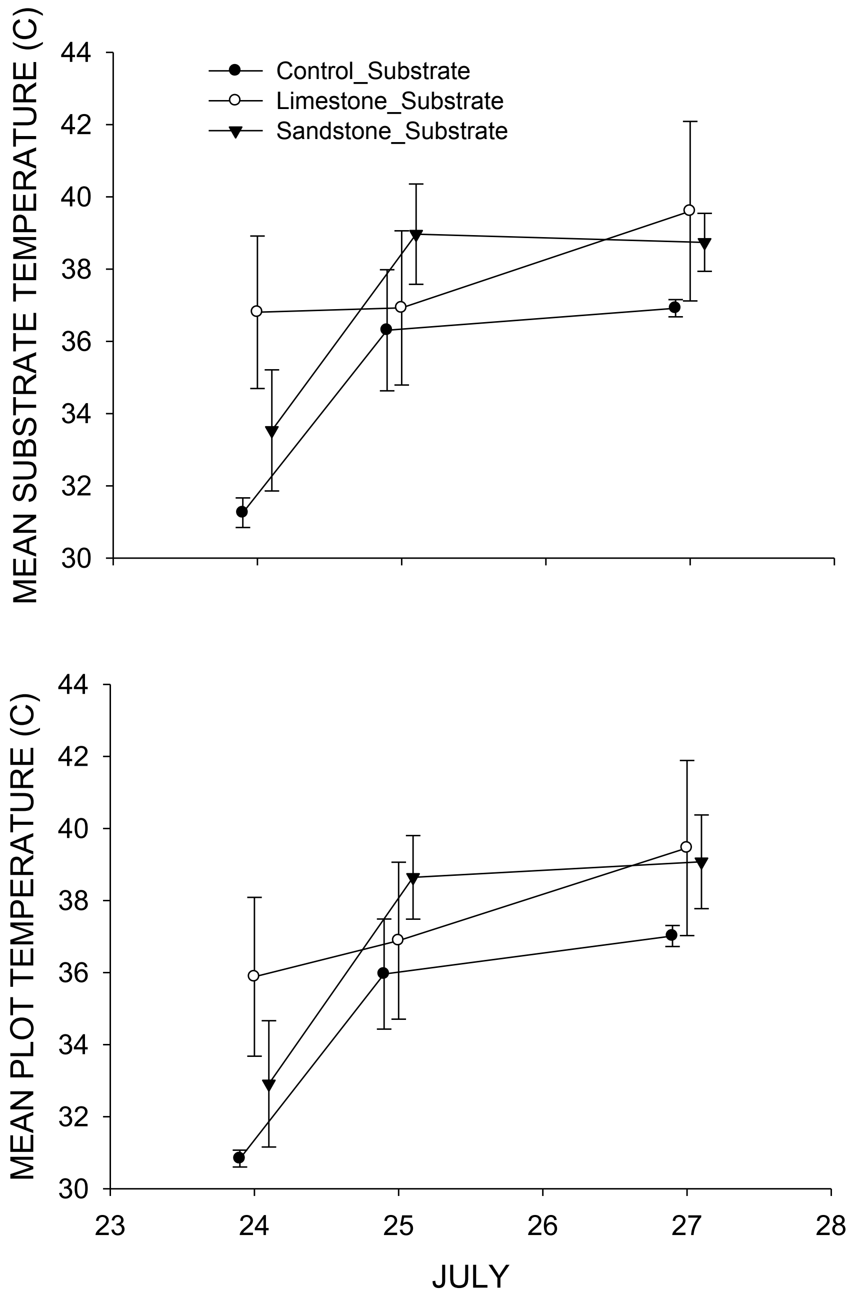


Figure 3. Means (and SE) of substrate temperature and plot temperature for experimental substrate plots across 3 dates in July. Error bars represent one SE.

Analysis of Daily Survival Rates

Year and date effects on DSR

There was little evidence that Julian date interacted with year to affect nest survival (X^2_1 = 2.67, p = 0.102). This model also had the strongest support based on Akaike information criterion AIC_C, although the model with only date had almost as much support (Table 2).

Table 2. Akaike information criteria (AIC_c) for sets of models evaluating the effects of year and date on nest daily survival rate (DSR). K is the number of parameters in the model. Models with the smallest AIC_c values are considered to have the most information about DSR. Delta AIC_c is the difference between the most informative model and the model under consideration; values <2 are considered to be similar to the top model in terms of information content. The model weight (w_Akiake) is the relative likelihood of each model with values closer to 1 having the highest likelihood.

Model	**n**	**k**	**aicc**	**delta_aicc**	**w_Akaike**
DATE*YEAR interact effect	220	4	129.841	0.000	0.349
DATE main effect	220	2	130.305	0.465	0.276
YEAR & DATE main effects	220	3	130.439	0.599	0.259
Constant Survival	220	1	132.665	2.824	0.085
YEAR main effect	220	2	134.660	4.819	0.031

In case the interaction was important, DSR was estimated for both years on Julian dates associated with the initiation, mean, and end of nesting activity (Table 3). The most striking feature of these estimates is the strong decline in DSR with date in 2017, with only a minor decline in 2016.

Table 3. Comparison of DSR estimates between years for the plots that would serve as control plots in 2017.

Year	Julian Date	DSR	Lower 95% CI Limit	Upper 95% CI Limit
2016	127	0.948	0.821	0.987
2016	160	0.886	0.817	0.931
2016	210	0.679	0.403	0.869
2017	127	0.982	0.819	0.999
2017	160	0.568	0.166	0.897

2017	210	0.005	0.000	0.924

This decline in DSR in 2017 may be biased due the absence of late season nesting on the control plots in that year. There are no nest observation intervals from the control plots after Julian date 175 in 2017, while approximately a third of the nesting on the control plots took place after that date in 2016.

Removing the interaction term, there was no effect of year on DSR ($X^2_1 = 1.92$, $p = 0.166$). In this reduced model, Julian date had a significant effect ($X^2_1 = 4.40$, $p = 0.036$), with DSR declining across the nesting season (Fig. 4). However, since the distributions of nesting on the control plots were so different between 2016 and 2017, the influence of observation date needs to be evaluated within the individual years, across data from all the plots.

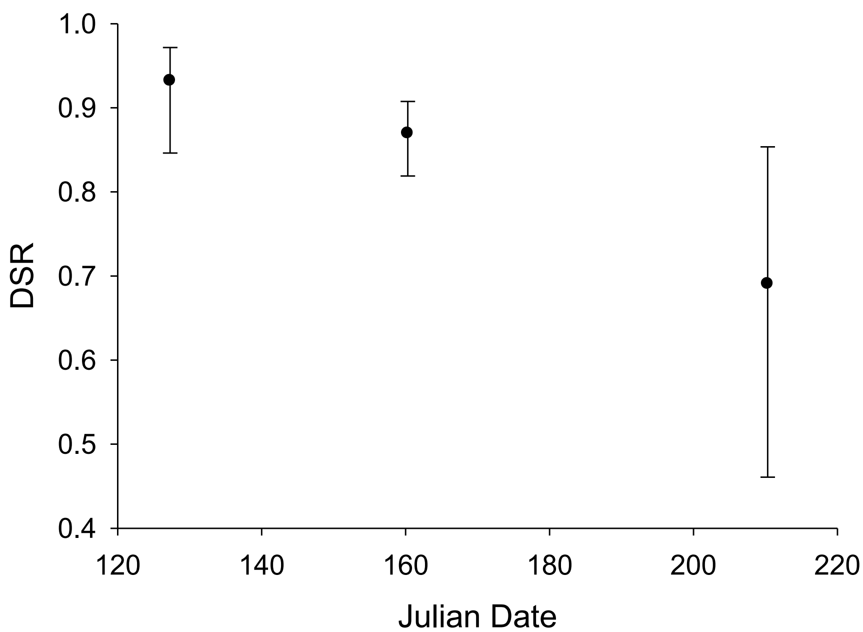


Figure 4. Relationship between date and DSR for nests on control plots in 2016 and 2017. Bars represent 95% CIs.

Date effects on DSR in 2016

There was no evidence that Julian date affected DSR ($X^2_1 = 2.14$, $p = 0.143$). The constant survival model also had a slightly smaller AIC_c estimate than the model including date, again suggesting that Julian date had little effect on nest survival. Based on the constant survival model estimated DSR to be 0.870 (95% CI = 0.873 – 0.896). Based on this estimate the period nest survival of a 21 day incubation period would be 0.053 (95% CI = 0.024 – 0.100).

Date and Treatment effects in 2017

There was evidence that DSR may have been influenced by the interaction of substrate treatment and Julian date ($X^2_2 = 5.73$, $p = 0.057$). When the estimates of DSR are plotted for the different time points and substrates we see that the estimates for the control for either the mid or late Julian dates are not reasonable (Fig. 5). The highly skewed confidence intervals and low DSR estimates in the control treatment are probably due to the lack of late season nesting on this substrate. Clearly there are insufficient data to model the date*treatment interaction. Furthermore, the AIC_C values for the constant survival model (Table 4) are smaller than for the model containing the interaction term, or for most of the other models under consideration.

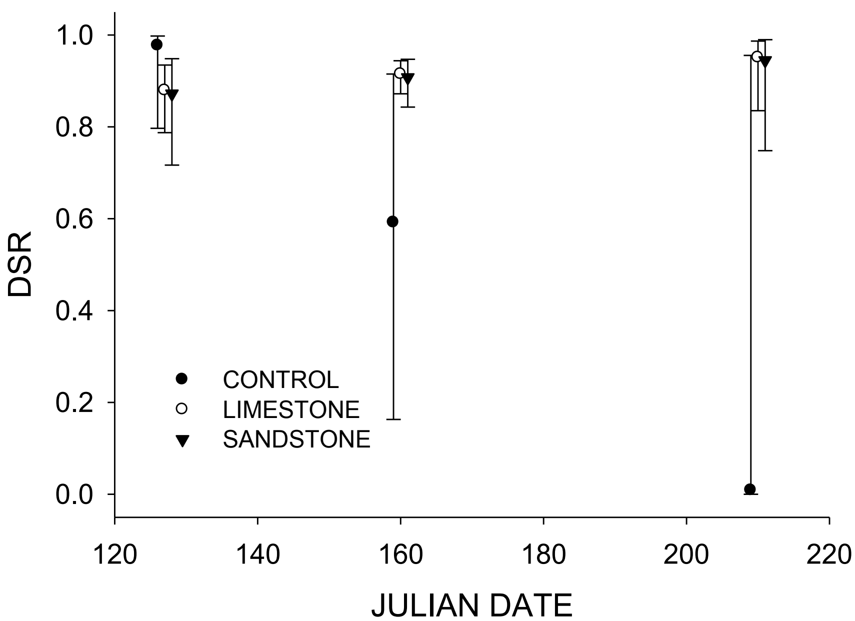


Figure 5. Estimates of DSR for Julian date (127, 160, and 210) and substrate treatment (Control, Limestone, and Sandstone) combinations for 2017. Error bars represent 95% CIs.

Table 4. Akaike information criteria (AIC_c) for sets of models evaluating the effects of substrate treatment and date on nest daily survival rate (DSR). K is the number of parameters in the model. Models with the smallest AIC_c values are considered to have the most information about DSR. Delta AIC_c is the difference between the most informative model and the model under consideration; values <2 are considered to be similar to the top model in terms of information content. The model weight (w_Akiake) is the relative likelihood of each model with values closer to 1 having the highest likelihoods.

Model (Unknowns treated as Survived)	K	AIC_c	Delta	w_Akaike

			AIC_c	
constant survival	1	200.864	0.000	0.465
DATE main effect	2	201.854	0.990	0.284
DATE*TREATMENT interact effect	6	203.750	2.886	0.110
TREATMENT main effect	3	204.097	3.233	0.092
TREATMENT & DATE main effects	4	205.372	4.508	0.049

The only model with similar likelihood to the constant survival model is the model with the Julian date; however, the parameter estimates for the effects of Julian date are not different from zero ($X^2_1 = 1.03$, $p = 0.310$). There is also little evidence that the substrate treatments had any effect on DSR ($X^2_2 = 0.82$, $p = 0.665$; and Table 4). However, because understanding the influence of substrate on DSR was one of the main motivations for the experiment, substrate-specific estimates of DSR and nest period survival are provided for comparison with the more appropriate estimates from the constant survival model (Table 5).

Table 5. Comparison of DSR estimates for the constant survival model and for the 3 substrate treatments for 2017.

Model/ Factor level	DSR	Lower 95% CI Limit	Upper 95% CI Limit	Probability of surviving 21 days	Lower 95% CI Limit	Upper 95% CI Limit
Constant survival	0.902	0.871	0.926	0.115	0.056	0.201
Treatment/Control	0.866	0.741	0.936	0.048	0.002	0.247
Treatment/Limestone	0.908	0.868	0.937	0.133	0.051	0.258
Treatment/Sandstone	0.904	0.841	0.943	0.119	0.026	0.295

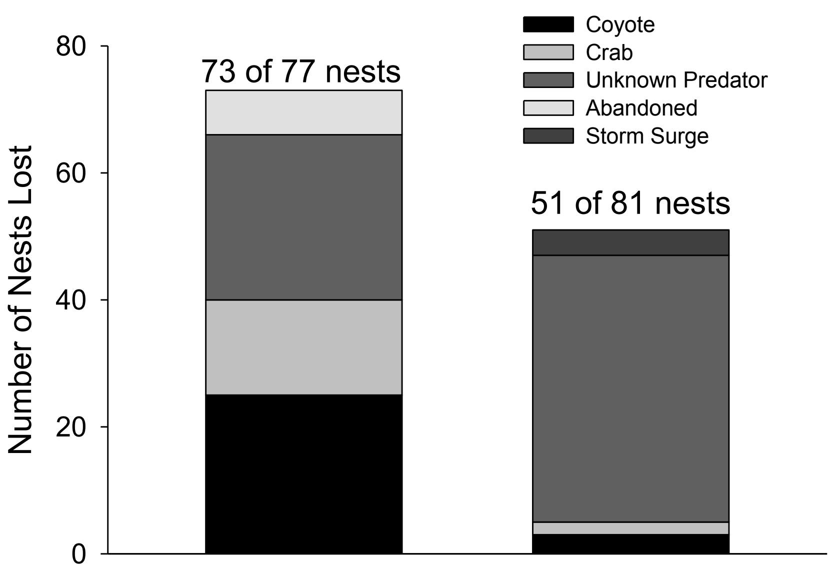
There is no obvious effect of treatment on estimates of DSR, and the constant survival model is sufficient to describe the very low nest success found across the experimental plots. There is a slight suggestion in the estimates of DSR and period survival might be higher for nests in the limestone treatment than in the control treatment. This difference, if real would need much larger sample sizes to be statistically significant.

Summary:

Comparisons of 2016 and 2017 are difficult because the birds nesting on the control plots (the only shared substrate between years), had very different temporal nesting patterns. Within year, there was no strong effect of substrate treatment (2017) or date (both years). Estimates of DSR and nest period survival are quite low and much lower than observed in Brooks et al. (2013). It is unlikely that at such low rates of nest success that the population would be sustainable without immigration.

Causes of Nest Loss in 2016 and 2017

There were 73 and 51 nests in 2016 and 2017, respectively, that were unsuccessful (Fig. 6). The proportions of nests lost to the various sources detected by the field crew varied significantly by year (Fishers Exact Test, $P < 0.001$). However, it is not clear that the sources of loss varied between years or if sampling issues contributed to this variation. For example, most of the nest predators in 2017 were not identified. This is potentially the result of the limestone and sandstone substrates making it harder to find the tracks and other signs from coyotes and ghost crabs in that year; such substrates were absent in 2016. Overall, the proportions of failed nests that were lost to coyotes, crabs and unknown predators was remarkably similar between 2016 (0.90) and 2017 (0.92). For comparison, predation accounted for 47% of all nest losses in South Carolina (Brooks et al. 2013). In 2016 approximately 10% of all nests were abandoned while no nests were recorded as abandoned in 2017. In 2016 no nests were recorded lost to flooding (high rainfall or storm surge), while 8% were lost to storm surge in 2017.



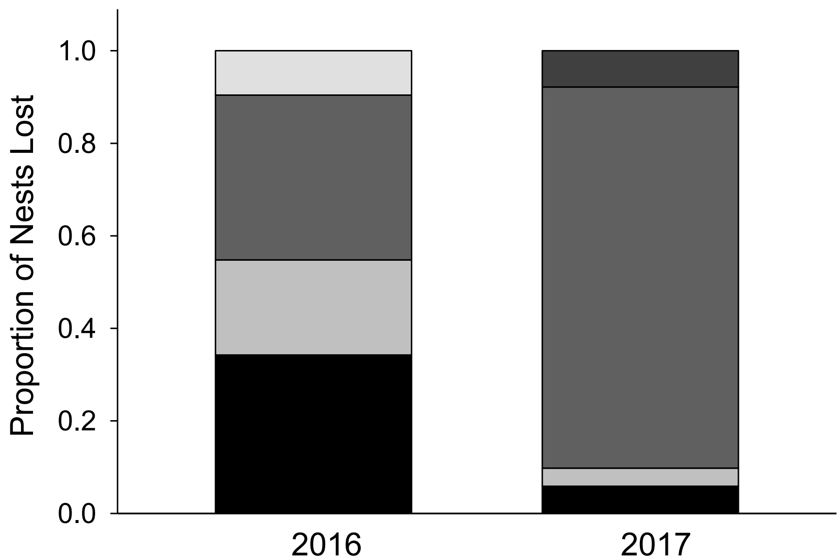


Figure 6. Frequencies and proportions of nests lost to various causes in 2016 and 2017.

Influence of substrate on nest selection, predation, success, and initiation
Nest selection--Fifty-nine nests were located in the substrate plots in 2017. There was no evidence that either burrow density or plot temperature affected the number of pairs nesting on a plot ($p > 0.20$ in both cases). The effect of substrate on the number of nests per plot was statistically significant (X^2_2=10.91, $p = 0.004$). The least squares mean number of nests for the limestone plots was greater than the estimate for the control plots (Fig. 7, $z = 3.19$, $p = 0.001$). The odds of a nest occurring on a limestone plot was 3.2 (95% CI = 1.3 – 8.0%) times higher than on a control plot. The difference between the mean for the limestone and sandstone plots also approached statistical significance ($z = 1.80$, $p < 0.072$). There was no difference between the estimated number of nests on the sandstone or control plots ($z = 1.62$, $p = 0.105$).

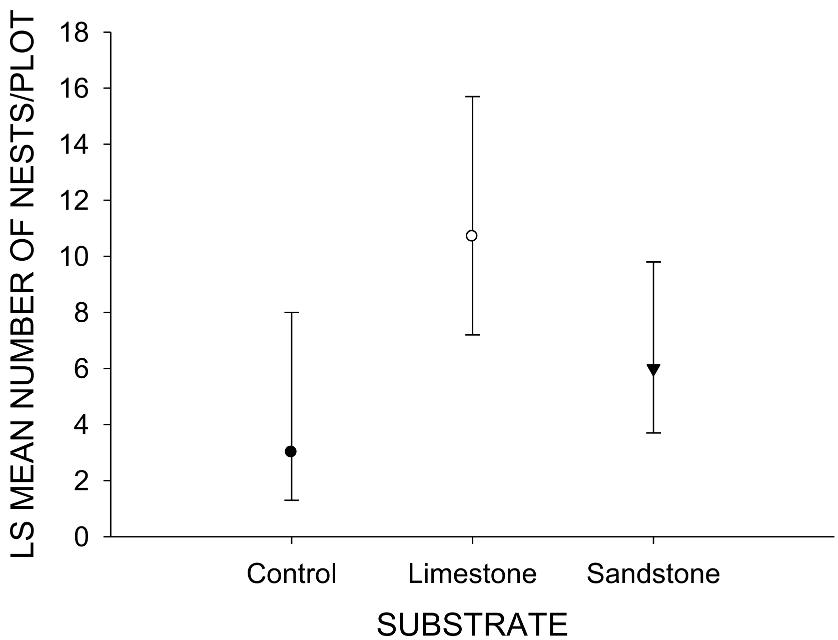


Figure 7. Least square mean number of nests per plot for three substrate treatments. Error bars represent 95% CIs.

Predation and other sources of nest loss-Thirty-eight of the 59 nests on the substrate plots in 2017 were lost to predators. There was no evidence of differences in the numbers of nests lost to predators (controlling for the total number of nests) due to substrate type, crab burrow density, or plot temperature ($p > 0.2$ in all cases). However, the models for these analyses did not meet convergence criteria, calling the estimates of effect sizes into question. Therefore, I also compared the proportions of nests lost to predation among substrates using a contingency table. This pools nests across plots requiring the assumption that nests within plots have independent probability of being depredated, but it does allow for a test of the hypotheses that the proportion of nests lost to predation does not differ among sites. Proportions of nests lost to predation were 0.44, 0.66, and 0. 72 for control, limestone, and sandstone respectively. There was no significant association between predation and substrate ($X^2_2 = 2.06$, $p = 0.356$). There were insufficient numbers of nests lost to abandonment (0) or storm surge (5) to analyze the influence of substrate type or the two covariates on these sources of nest failure.

Nest success-Twelve of the 59 nests on the substrate plots in 2017 were recorded as hatched. The model containing both temperature and substrate treatment did not converge on a solution, so all factors were considered separately. There was no significant effect of the number of ghost crab burrows, temperature, or substrate treatment on the number of successful nests on a plot ($p > 0.2$).

Number of chicks-A minimum of sixteen chicks were determined to have hatched on the nine substrate plots. Substrate type, plot temperature, and burrow density were not significantly associated with nest success ($p > 0.2$ in all cases).

Time to nest initiation on different substrates-There was no significant difference in the time of nest initiation on the different substrate types ($X^2_2 = 0.602$, $p = 0.740$, Fig. 8).

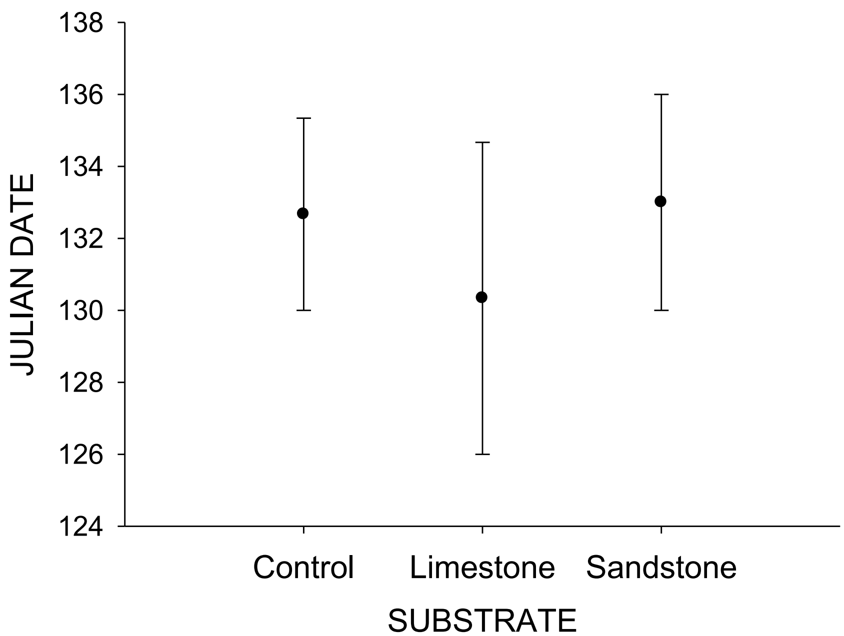


Figure 8. Mean Julian date of initiation of first nest on experimental substrate plots. Error bars represent 1 SE.

Summary:
There was a large significant effect of terns selecting to nest on the limestone substrate relative to the control, and to a lesser extent on sandstone. Substrate did not affect the loss of nests to predation, the overall number of nests that were successful, the number of chicks hatched, or the date on which nests were first initiated. The larger number of terns nesting on limestone substrate than controls did not translate to more productivity per plot, perhaps because of the high rate of predation and the low DSR on all substrate types.

Literature Cited

Brooks, G. L., F. J. Sanders, P. D. Gerard, and P. G. R. Jodice. 2013. *Daily survival rate* for *nests* and *chicks* of Least Terns (*Sternula antillarum*) at *natural nest sites* in *South Carolina*. Waterbirds 36:1-10.

Heisey, D. M., T. L. Shaffer, and G. C. White. 2007. The ABC's of nest survival: theory and application from a biostatistical perspective. Studies in Avian Biology 34:13-33.

Rotella, J., S. Dinsmore, and T. Shaffer. 2004. Modeling nest-survival data: a comparison of recently developed methods that can be implemented in MARK and SAS. Animal Biodiversity and Conservation 27.1:187-205.

SAS Institute Inc. 2011. Base SAS® 9.3 Procedures Guide. Cary, NC: SAS Institute Inc.

Shaffer, T. L. 2004a. A unified approach to analyzing nest success. Auk 121:526-540.

Shaffer, Terry L. 2004b. Logistic-Exposure Analyses of Nest Survival. Jamestown, ND: Northern Prairie Wildlife Research Center Online. http://www.npwrc.usgs.gov/resource/birds/nestsurv/index.htm (Version 28AUG2008)

Shaffer, T. L. and F. R. Thompson III. 2007. Making meaningful estimates of nest survival with model-based methods. Studies in Avian Biology 34:84-95.