Monitoring the Success of a Coastal Dune Restoration with Citizen Science

Lissa M. Leege

leege@georgiasouthern.edu

Georgia Southern University

Skyler J. Fox

Georgia Southern University

Research Article

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Abstract

Coastal sand dunes provide critical ecosystem functions but are threatened due to tourism and climate change. Nature-based solutions such as beach renourishment and dune construction may restore dune function but are costly to implement. Monitoring of dune restoration success is critical for protecting the investment and providing information for future efforts. The purpose of this three-year study was to evaluate the success of a dune restoration on Tybee Island, Georgia, using citizen scientists to collect quarterly data on sand accumulation and vegetation dynamics in restored and established dunes. We found a pairwise correlation of 0.999 for sand accumulation data collected by two different groups and 0.68 for vegetation cover data, suggesting an acceptable level of repeatability. Sand accumulated throughout the study and was highest at the dune toe, where it did not differ between restored and established dunes. Accumulation at the restored crest increased to exceed that of the established crest during the study, suggesting comparable ecosystem function. During hurricanes, however, sand accumulation was ~3-6 times higher in established dunes, suggesting that restored dunes are still inferior under extreme conditions. Species richness did not differ between dune types, and by five years post restoration, vegetation cover was comparable in restored and established dunes. Uniola paniculata was the most abundant species and Ipomoea imperati increased the most in cover, proving their utility in future restoration efforts. This study showed that citizen scientists can play a valuable role in monitoring restoration efforts and contribute to successful restoration planning for the future.

Introduction

Coastal sand dunes provide critical ecosystem services for coastal communities, including storm protection, biodiversity support, and nesting area for shore birds and sea turtles (Hays et al. 1995, Brown et al. 2005, Acosta et al. 2009, Elliot-Smith 2015, Druis et al. 2019). They act as a barrier for storm surge and absorb floodwaters, serving as the first line of defense between the ocean and the built environment located behind the dune (Swann et al., 2015). In particular, foredunes of 3-10m in height are of paramount importance for coastal protection during hurricanes due to their wave attenuation (Dahl et al. 1975, Matzke and Leege 2025). Vegetated dunes provide superior protection in the face of strong winds and storms, trapping and binding sand to build dune height and volume (Bryant et al. 2017).

Tourism and travel to America’s beaches generate an economic output of $520 billion annually, providing critically important revenue for the communities that support them (Houston 2024). Additionally, 39% of the U.S. population lives in coastal counties (Bryant et al. 2017) and therefore depend on coastal resources. However, coastal dune systems are increasingly threatened by sea level rise and storm surge oceanward (Nicholls and Cazenave 2010), and by landward development (Ramesh et al. 2015), leading to the phenomenon of “coastal squeeze” (Doody 2004). One mechanism of protecting coastal beaches from erosion and thereby preserving their ecological, recreational, and economic value, is the implementation of nature-based solutions, such as beach nourishment: the addition of sand to eroding beaches (Rodella et al. 2020, Staudt et al. 2021, Houston 2024).Nourished beaches expand recreational areas but also serve as a buffer against future storm damage, further limiting erosion (Landry et al. 2003, Hoagland et al. 2012). Coastal sediment removal and placement for renourishment can also harm marine life and alter natural physical and biological processes, however, and these impacts should also be taken into consideration when evaluating renourishment options (Miselis et al. 2021). In the U.S., 4,036 known nourishment events have taken place in 486 coastal communities since 1923, for a total of 1.4 trillion cubic meters (1.8 trillion cubic yards) of sand added to coastal beaches. On Tybee Island, Georgia, ten nourishment episodes were conducted by the U.S. Army Corps of Engineers from 1976 to 2020, for a total of 9 million m^3 (11.8 million cy) of sand placed on the beach at a cost of $59,869,953 (National Beach Nourishment Database).

In 2019-20 for the first time, the City of Tybee Island specified that its regularly scheduled beach nourishment would also include the construction of a new 2.5m tall, 900m long dune as a part of Tybee Island's Beach Management (2014) and Sea Level Rise Adaptation (2016) plans, in hopes that it would lengthen the return interval for renourishment (Evans et al. 2016, Matzke & Leege 2025). In early 2020 following its construction, this dune was vegetated with six dune species common to southeast Georgia, including *Uniola paniculata*, *Ipomoea imperati*, *Spartina patens*, *Panicum amarum*, *Iva imbricata*, and *Muhlenbergia capillaris* (Matzke and Leege 2025). Monitoring of ecosystem services to determine the success of the restoration was critical in order to protect this public investment; therefore, Matzke (2021) conducted fourteen months of intensive data collection on plant growth and sand movement following dune construction and installation of vegetation to monitor the ecological success of the project and evaluate best practices for restoration (Matzke & Leege 2025). Because intensive monitoring is costly and often excludes stakeholders, we sought an inexpensive, low-tech method by which we could continue critical monitoring at regular intervals as well as engage the community. Therefore, for this study, we determined key indicators of dune "health" and developed a relatively simple protocol by which able-bodied adults could monitor dunes based on the outcome of Matzke's findings (2021).

Public perception is critical to the support of nature-based solutions and is key to long-term conservation success (Bennett 2016, Hsiung et al. 2024). One way to positively influence public perception is to engage stakeholders in activities that increase their knowledge about and connection with the environment (Hsiung et al. 2024, Chandler et al. 2025). To that end, citizen science, also known as participatory science, can serve as an opportunity to both educate and engage the public in the process of science and, in doing so, potentially improve public perception of science (Bonney 2016, Strasser et al. 2019). Citizen science engages non-professionals in scientific research and can fall into several different typologies; contributory projects are designed by scientists and carried out by the public, collaborative projects are designed by scientists and refined and carried out by the public, and co-created projects are developed by scientists and the public together (Bonney 2016).

Citizen science has already been successfully employed in ecology and environmental studies (Fraisl et al. 2022). Furthermore, de Sherbinin and colleagues (2021) even identify the critical role of citizen science in supporting and monitoring the United Nations Sustainable Development Goals and 2030 Agenda. The benefits of citizen science are numerous, including education and engagement of stakeholders as well as reduced cost of data collection (Hughes et al. 2022; George et al. 2024).

Concerns persist, however, and range from limited skill of the participants, to inconsistent application of protocols, to bias in identification and data collection (Fraisl et al. 2022). Despite these challenges, researchers can employ methods of mitigation to improve outcomes, including but not limited to training participants before and during the project, supervision by experts, community consensus (i.e. working in groups to validate data), and data filtering by professionals (Fraisl et al. 2022). de Sherbinin et al. (2021) found that data quality is rarely an issue, as the vast majority of projects employ multiple robust mechanisms of quality assurance.

Numerous examples of citizen science are ongoing in coastal dune systems around the world. For example, citizens contribute to an understanding of the expanding coastal distribution of the invasive *Carpobrotus edulis* in Uruguay through reporting in iNaturalist (Grattarola et al. 2024); smartphone images of sand grains taken with a reference coin assist in measuring and mapping sand grain size on sandy beaches globally with the SandSnap app (McFall et al. 2024); and the Global CoastSnap Community Beach Monitoring program monitors coastal erosion via repeated crowd-sourced oblique cellphone images taken from the same location over time in numerous countries around the world (Harley et al. 2019). In particular, the CoastSnap program was a useful tool in monitoring beach erosion following Hurricane Fiona in Prince Edward Island, Canada, in 2022. Through analysis of citizen-contributed photos captured before and after the hurricane, George et al. (2024) documented 12-17m of retreat in the foredune and were able to calculate volumetric losses of 28-76 m^3/m along the shoreline. These estimates were within 2.8 m by length and 45% by volume of values determined by high precision drone imagery and represent a low-cost method of monitoring coastal erosion with a reasonable degree of error (George et al. 2024).

To improve public perception of the value of dune restoration and to facilitate long-term monitoring at a low cost, we developed a citizen science monitoring protocol to evaluate a dune restoration project on Tybee Island, Georgia, USA.

We addressed the following questions with this contributory citizen science project:

- Do restored dunes provide ecosystem services equivalent to those provided by established dunes with regard to sand movement and plant community dynamics?
- How do dunes respond to hurricanes on Tybee Island, and does this response differ between restored and established dunes?
- What is the level of repeatability of data collection with this citizen scientist protocol?

Here we describe the process by which we developed and adapted the monitoring protocol and evaluate the success of the dune restoration based on the data collected by citizen scientists.

Methods

Study site

This study was conducted on Tybee Island in Chatham County, Georgia, USA, the northernmost barrier island in the state (32°0′26″N; 80°50′27″W; Figure 1). Tybee is bordered to the north by the South Channel of the Savannah River, dredged first in 1897 and an increasingly busy shipping channel into the Savannah Harbor. A recent report determined that 73.6-78.5% of the beach erosion that has occurred on Tybee's beaches resulted from the historic dredging of this channel (McKee et al. 2008). As a result of the disruption of sand movement due to channel deepening, Tybee Island has partnered with the U.S. Army Corps of Engineers since 1976 for beach renourishment at an interval of approximately seven to ten years and most recently in December 2019, 2.5 years prior to the start of this study (National Beach Nourishment database, Matzke and Leege 2025). Rising sea levels also contribute to loss of beach area. As measured by the gauge at nearby Fort Pulaski, Tybee Island is experiencing 3.66 mm of sea level rise annually (NOAA 2025), for a total of 325.74 mm (12.8 inches) since measurements began in 1935.

Home to Georgia's most popular public beach, Tybee Island receives nearly two million visitors annually (Georgia Southern University, 2023). Though the majority of Tybee's revenue is generated from island visitors, their presence can also negatively impact the natural resources on which the city depends for its tourism dollars.

Citizen science recruitment and management

Citizen scientists were recruited for this study in two ways: through stakeholder groups on Tybee Island and via Biology-related courses, clubs, and research experiences at the affiliated university. The stakeholder participants comprised primarily resident retirees, young people seeking volunteer hours, and interested residents seeking community service opportunities. Prior to attending each monitoring event, participants were emailed logistical instructions for the day and encouraged to view the Tybee Island Dune Monitoring Protocol: A Visual Guide for Volunteers prepared by the researchers and available online (https://drive.google.com/file/d/1kSIdXvOLg7F71uu0DHbprVs9V2r_aBxu/view). At the event, participants convened in a park pavilion near the data collection site, where they signed a waiver and indicated their affiliation (university or stakeholder). Researchers then provided background information about the value of dunes, an overview of the project, and issued equipment to be used by groups of two or three. The researchers then provided on-site field training in plant identification and led participants through a full demonstration of the data collection protocol at one site. Researchers oversaw participant pairs and fielded questions as they collected their data. After all 35 sites were sampled, the participants returned to the pavilion and entered data from data sheets into a web form, in an effort to reduce any errors of interpretation from participant to researcher. Finally, researchers checked data sheets against the web form entries as an additional form of quality control.

Data collection protocol development

Based on previous research in this site (Matzke 2021), we set out to develop a relatively simple protocol for use by citizen scientists to monitor the continued success of the dune restoration and to evaluate ecosystem function in the restored dune relative to the established dune. To that end, we needed to 1) select key instructive variables to measure, 2) minimize the time requirement for sampling to limit heat exposure for participants to the morning hours, and 3) develop a simple protocol that could be replicated by volunteers with little to no experience in field ecology. 4) We also needed to build some redundancy into the protocol to ensure that citizen scientist measurements were accurate.

Previous research during June 2020-August 2021 determined that the toe of the foredune experienced the highest rates of sand accretion, while sand accumulation at the crest did not differ from that at the heel (Matzke & Leege 2025). Therefore, we focused foredune monitoring on the dune toe as representative of greatest sand movement and the dune crest as representative of highest vulnerability, as the crest plays a critical role in protection from intense storms and storm surge (Itzken et al. 2021). Plant density (# planted individuals/m^2) was positively correlated with sand movement and was the best predictor of accumulation in restored dunes; therefore, we included the number of “clumps” in the protocol as a proxy for plant density (Matzke and Leege 2025). Vegetation cover, plant height (average and maximum), and number of stems/m^2 were also predictors of sand accumulation (Matzke and Leege 2025). We included the measurement of vegetation cover as an additional measure of plant abundance but did not include plant height or number of stems, as they were time-consuming to measure and difficult to replicate among citizen scientists.

The standard method of measuring sand movement employed by Matzke (2021) was against wooden dowels (30.5 cm tall and 1.3 cm diameter), measured and repositioned monthly. However, relocating small wooden dowels would be nearly impossible for a rotating group of volunteers. Additionally, during the period of June 2020 – August 2021, the maximum sand accumulation measured was 13 cm for one month (September 2020) in the established dune (Matzke, unpublished data), which might result in dowel burial over a 3-month return interval. Instead, we based sand movement measurements against pre-existing signposts (~75-190 cm above the sand in height and ~10 cm in width) established by the city for other informational purposes (i.e. “Keep off the Dunes, $1,000 fine”). Although these posts were unevenly spaced and not equally replicated, we chose to use existing structures to avoid disturbing the dune with the installation of new posts and to avoid permissions required by oversight agencies. We identified 14 existing posts in the established dune (10 toe and 4 crest) and 21 posts in the restored dune (10 toe and 11 crest). Each post became the site marker for monitoring measurements (Figure 1). Posts were located 3 – 132 m apart from each other; several toe posts in the restored dune were clustered together in groups of three. The total length of Tybee’s dune measured for this study as determined by the post locations was 1,205 m (715 m in the restored dune and 490 m in the established dune). Sand movement was measured as the distance to the sand from the top of the posts on both the north and south sides of the site post, such that we could calculate sand movement over time since the previous measurement. Requiring measurements on both sides of the post, which were expected to be quite similar, built some redundancy into the protocol to serve as a check for the participants and a flag for us when reviewing the data for accuracy.

To evaluate vegetation characteristics, participants placed a 1x1 m quadrat frame at the base of each signpost with the eastern edge parallel to the shore, identified the plant species rooted within the plot, counted the number of clumps of each species, and visually estimated the cover class of total vegetation based on a Daubenmire-modified scale (Table 1). Participants were provided with a list of species to expect with photos and key character descriptions, a reference card to help estimate the cover in the 1x1 m plot, and a sample diagram indicating representative coverage for each cover class. Rather than percent cover for each species which might be estimated differently by each participant, we specified a cover class designation, which required less precision and allowed for more replicability among participants. However, due to plant growth and colonization in the restored dunes, we updated the protocol in March 2024 to add visual estimates of cover for each species in the plot. This measurement replaced the “number of clumps” measurement for each species because originally planted “clumps” were no longer evident due to the rhizomatous growth of grasses. Percent cover measurements for each species ultimately allowed for finer scale comparisons across quarterly sampling dates.

Table 1. Cover class designation used for 1x1 m plots during dune monitoring.

Cover class	% cover
1	0-1
2	2-5
3	6-35
4	36-50
5	51-75
6	76-100

The original protocol was tested by the first author’s undergraduate level Botany class in April 2022 prior to implementation, to determine ease of use and approximate duration of sampling time and then implemented in June 2022. To test for repeatability of sampling, we hosted a group of 12 citizen scientists on June 21, 2022, to collect data in 31 of the 35 sites, and hosted a completely different group of 15 participants on June 22, 2022 to re-sample a subset (23) of these sites.

Measurements were taken quarterly June 2022 – June 2025, though only sand movement measurements were taken in the winter quarter while the vegetation was dormant. Two hurricanes took place during the study period: Hurricane Ian which made landfall on Tybee Island on September 29, 2022, four days after the previous quarterly monitoring event, and Hurricane Helene, which hit Tybee on September 27, 2024, 14 days after the previous monitoring event. Follow-up sand movement measurements were taken by researchers and/or student groups within 10 days of each hurricane. In all, monitoring took place over the period June 21, 2022, to June 20, 2025 and included 17 sessions: 13 quarterly monitoring events, one resample event to evaluate variability in data collection, and two post-hurricane events.

Data Analysis:

Citizen Science

To evaluate repeatability of sampling, we used matched pairs analysis to compare post height measurements (the source of sand movement data across time) and vegetation cover class records between two groups of citizen scientists who collected data one day apart in June 2022. Cover class data were normally distributed and were compared with matched pairs t-tests. Because post height measurements were not normally distributed, Wilcoxon Signed Rank tests were used. Pairwise correlations were also calculated for matched pairs. Sampling repeatability analysis was conducted in JMP Pro 17 (JMP 2023). Basic summary statistics were calculated for monitoring events, including mean participants by type (university vs. stakeholder), number of volunteer hours, etc.

Sand Movement

To determine sand movement from post height measurements, the height from the top of the north and south side of the posts was averaged then subtracted from the subsequent quarterly measurement average to calculate the change in average post height between consecutive quarterly measurements. Positive values indicate accumulation, while negative values indicate erosion. When height measurements were missing (or removed) for a given month, the corresponding sand movement value was excluded for that quarter as well as the subsequent quarter, since sand movement is based on the change in height between consecutive measurements. Quarterly sand movement measurements exceeding ±13 cm were flagged and inspected by the authors; only two values were excluded due to likely human error.

Linear mixed models (LMMs) were fitted using the lmer function in the lme4 package (Bates et al., 2015) to analyze quarterly sand movement through the study period. Fixed effects included years since restoration (2–5), dune type (established vs. restored), month (March, June, September, or December), and the interaction between years since restoration and dune type. Signpost ID was included as a random effect to account for repeated measurements at each post. Month was included to control for seasonal variation, though our primary interest was in the effects of years since restoration, dune type, and their interaction. Separate models were conducted for the toe and crest due to expected differences in sand dynamics between these dune locations, with the toe experiencing more accumulation (Swann et al., 2015).

To assess storm-related sand movement, we calculated the change in the distance from the top of signposts before and after Hurricanes Ian and Helene by subtracting pre-storm measurements from post-storm measurements. Post-storm measurements were not included in the previously mentioned quarterly sand movement analyses. For each hurricane, a two-way ANOVA was conducted with dune type and post location (toe vs. crest) as independent variables. Because assumptions of normality and homogeneity of variance were not initially met, data were transformed prior to analysis. Tukey HSD tests were used post hoc to identify significant pairwise differences.

Vegetation Metrics

Species richness (the number of species per 1x1 m plot) was analyzed using generalized linear mixed models (GLMMs) with a Poisson distribution. Total percent cover and midpoint percent cover class were analyzed using LMMs with the same fixed and random effects structure described above. Because percent cover replaced the number of clumps method, data for total percent cover were only available for years 4 and 5. To assess consistency between sampling methods, we also ran a separate model for midpoint percent cover class using only years 4 and 5.

Cover of two planted species that were abundant in both restored and established dunes (*Uniola paniculata* and *Ipomoea imperat*i) was also analyzed using LMMs. Additionally, to assess planting success, we calculated the percent presence of five planted species within the restored dune. These presence data were not modeled due to a lack of variation (e.g., species were either always present or always absent in plots), which prevented model fitting.

Model diagnostics included visual inspection of residuals to assess normality and homoscedasticity and checks for overdispersion in GLMMs. In rare cases where the model fit was singular (i.e., the variance of the random effect was estimated to be zero), the random effect of signpost ID was retained to preserve consistency in model structure, and results were equivalent to those from standard (G)LMs. In all model output tables, fixed effects can be interpreted as follows:

- The effect of years since restoration reflects change within the established dune, which is the reference level for dune type.
- The effect of dune type (restored) represents the difference between the restored and established dunes at year 2 (the reference level for years since restoration).
- The interaction between years since restoration and dune type indicates how the restored dune changed over time compared to the established dune.

Figures displaying ecological data analyses are based on linear regressions of years since restoration; (G)LMM results presented in the tables are not incorporated, as including the seasonal differences accounted for in the (G)LMMs would have obscured temporal patterns. All ecological analyses were conducted in R version 4.4.3 (R Core Team, 2025).

Results

Citizen Science

During the three-year monitoring period from June 2022 to June 2025, we worked with 184 citizen scientists, with an average of 10.8 ± 1.4 data collectors per event. Of these participants, an average of 7.6 ± 1.4 were affiliated with the university responsible for this study and 3.3 ± 0.9 were not. This amounted to approximately 552 person-hours at 3 hours per person per session for 17 sessions. The expenditure of researcher person-hours was approximately 9 hours per event, including recruitment (0.5 h), supply preparation (2 h), training and facilitating (3 h * 2 facilitators), and reviewing data (0.5 h). One-time cost for data collection supplies was approximately $50 per team, for a total of $300 for six teams.

University-affiliated participants were usually students from classes requiring service-learning hours, students participating in research opportunities (i.e. National Science Foundation Research Experience for Undergraduates), or volunteers from Biology-related clubs. Several volunteers attended on more than one occasion. Non-university participants were residents of the region with an interest in Tybee's natural environment. Three citizen scientists became repeat participants, missing only one or two of the quarterly dune monitoring sessions over the three-year period.

Repeatability

Repeated measurements of post height and vegetation cover taken one day apart by two different groups of citizen scientists showed no statistically significant differences from each other after we removed two clearly erroneous data points. Mean difference in post height ranged from -1.5 to 2 cm with a mean of -0.119 +/- 0.186 cm ($S = -29$; $p = 0.37$; pairwise correlation = 0.9997; $p < 0.0001$ north side) and -4.5 to 3 cm with a mean -0.315 +/- 0.320 cm of ($S = -12.5$; $p = 0.70$, pairwise correlation = 0.9992; $p < 0.0001$ south side) between groups, while mean cover class, a more subjective measure, differed by 0.18 +/- 0.16 with a range of -1 to 2 between groups on a scale of 1-6 ($t = 1.16$; $p = 0.25$; pairwise correlation = 0.681; $p = 0.0005$). This gave us confidence in the repeatability of measurements taken by citizen scientists, though we continued to check for outliers throughout the study.

Sand Movement

Sand accumulated in all sites throughout the study. However, at the established toe, accumulation decreased over time, with an average of 9.12 ± 2.66 cm in year two after restoration and only 1.63 ± 0.41 cm in year five (Estimate = -1.8595, $p = 0.0254$; Figure 2; Table 1S). During the first two quarterly measurements (June 2022 – September 2022) of the study, there was no significant difference in accumulation between the restored and established toe, and the restored toe did not gain or lose more sand over time relative to the established toe. In contrast to the toe, the restored crest accumulated approximately one-fourth as much sand as the established crest during that same period (Estimate = -8.5553, $p = 0.0001$). However, over time, sand accumulation at the established crest decreased from 4.64 ± 2.4 cm in year two to 1.52 ± 0.57 cm in year five (Estimate = -1.406, $p = 0.0059$), eventually slowing to a lesser rate than the restored dune crest (Estimate = 1.3216, $p = 0.0175$).

During Hurricane Ian in 2022, the established dune (both the toe and crest) accumulated 2.6 times more sand than the restored dune ($F = 8.473$, $p = 0.0067$), and the toe (both restored and established) accumulated 8.8 times more sand than the crest (Figure 3a; Figure 1S). There was no significant interaction between dune type and post location ($F = 0.209$, $p = 0.6511$). Post-hoc pairwise comparisons indicated greater accumulation at the established toe than the restored crest ($p = 0.0001$) as well as at the restored toe compared to the restored crest ($p = 0.0018$). During Hurricane Helene in 2024, the established dune again accreted significantly more sand—5.43 times more than the restored dune ($F = 31.734$, $p < 0.00001$). However, no significant differences were found between post locations ($F = 0.712$, $p = 0.406$), and there was no significant interaction between dune type and post location ($F = 0.164$, $p = 0.689$) (Figure 3b; Figure 1S). Post-hoc pairwise comparisons indicated greater accumulation at the established toe than the restored toe ($p = 0.0056$), at the established toe than the restored crest ($p = 0.0005$), and at the established crest than the restored crest ($p = 0.0010$).

Vegetation: Whole Plot Metrics

The overall mean species richness in the restored and established dunes was $1.50 \pm 0.043/m^2$. At both the toe and crest, species richness did not change over time or differ between dune types (Table 2S; Figure 2S); however, vegetation cover did increase (Figure 4). The overall mean midpoint of total cover class was 18.85 ± 1.02%. Over the full study period, the midpoint of total percent cover class increased from 9.7 ± 3.3% in June 2022 to 38.4 ± 11.4% by June 2025 at the established toe (Estimate = 9.272, $p < 0.0001$; Figure 4; Table 3S), though the rate of change did not differ between the restored and established dune. At the crest, the established dune had 1.7 times higher midpoint cover than the restored dune at the start of the study in June 2022 (Estimate = -39.180, $p = 0.0009$). However, over time, the restored crest gained vegetation more rapidly than the established crest (Estimate = 9.514, $p = 0.0001$), which instead experienced a significant decline from 29.5 ± 29.0% to 26.25 ± 3.75% by June 2025 (Estimate = -7.250, $p = 0.0017$).

Using total percent cover (as opposed to midpoint of cover class values), the restored toe had 1.25 times higher total cover than the established toe in March 2024 (Estimate = 61.307, $p = 0.0209$; Figure 3S; Table 4S). However, from four to five years post-restoration, total percent cover declined at the restored toe compared to the established toe (Estimate = -14.804, $p = 0.0092$), which showed a significant increase (Estimate = 11.562, $p = 0.0093$). At the crest, total percent cover did not differ significantly between dune types or between years four and five post-restoration. When analyses were limited to March 2024 – June 2025, results based on the midpoint of total percent cover class were consistent with those from total percent cover, suggesting that both metrics led to the same overall conclusions (Table 5S).

Vegetation: Species Metrics

Between four and five years post-restoration, the restored toe lost more *U. paniculata* cover than the established toe (Estimate = -14.167, $p = 0.0457$), while the established toe showed a continued gain (Estimate = 11.868, $p = 0.0401$; Table 6S). In contrast, at the crest, *U. paniculata* cover did not differ significantly between dune types or over time. *Ipomoea imperati* cover did not significantly differ between dune types or years at either the toe or crest.

In the restored dune, *I. imperati* was present in ~5% of plots three years post-restoration and 37% in year five (Figure 5). *Iva imbricata* increased in frequency from ~10% of plots in year three to 14% in year four. *Panicum amarum* was absent from plots in years two, three, and five, appearing in 5% of plots only in year four. *Spartina patens* was the only species that showed a gradual increase in frequency, being absent in year two, present in 5% of plots in years three and four and in 11% of plots in year five. *Uniola paniculata* maintained a consistently high frequency, present in 95% of plots in year two and 89% in year five.

Discussion

Ecosystem Services

Overall, our monitoring data suggested that the restored dunes provided ecosystem services equivalent to or approaching those provided by natural dunes with regard to sand movement and plant community dynamics. To this end, all dune sites accumulated sand over time, growing vertically at a rate of 1.5 to 9 cm per year. However, the rate of accumulation slowed through the study period, suggesting a reduction of available sand for dune building as the width of the beach narrowed and renourished sand was washed to the south. Rates of sand accumulation at the dune toe were statistically indistinguishable between the established and restored dune, suggesting that both provide similar ecosystem services. At the dune crest, the pattern of accumulation changed over time, however, decreasing in established sites but increasing slightly in restored sites. These results also suggest that the ecosystem services of the restored dune crest are approximating that of the established crest under the current conditions. Our results indicate continued improvement of restored dune function since restoration; the superior accumulation in established dunes measured by Matzke and Leege (2025) in 2021 has now been matched by the restored dunes.

Sand movement was most extreme during the two hurricanes recorded during the sampling period. In both cases, the established dune gained more sand overall than the restored dune, though both showed accumulation. Sand fences installed by the City of Tybee at the dune toe in both the established and restored dunes may have influenced the high sand accumulation in this dune location, particularly during Hurricane Ian (2022) which took place closer to beach renourishment and dune restoration (2020), and during which more sand was available on the beach. Extreme weather events such as hurricanes are becoming more common (IPCC 2021, Kossin et al. 2020), and the dune response during these periods may be the most important to evaluate, as they represent the time of greatest storm-protection value and consequent vulnerability of the dune.

Though we detected no statistically significant signal for increased species richness over time, citizen scientists began to see species in restored sites that had not been planted in 2020, suggesting successful colonization by native dune vegetation. This prompted us to update the monitoring protocol to include identification guides for seven additional species beyond the five that were initially planted. Most of these species (for example, *Erigeron canadensis*, *Euphorbia polygonifolia, Heterotheca subaxillaris*, and *Oenothera humifusa*) represent passenger species in the dunes, providing no significant dune-building services, but instead serving as floral resources for pollinators and otherwise supporting native biodiversity (Hosier 1973). Coastal squeeze is known to reduce habitat and biodiversity (Lansu et al. 2025), and nature-based solutions, such as renourishment and dune restoration, are methods by which coastal width can be increased, potentially improving biodiversity and ecosystem services (Thorne et al 2025; Lansu et al. 2025).

Vegetation cover generally increased over the study period. Most notably, cover in the restored dune crest became indistinguishable from that of the established crest by the fifth year after restoration, suggesting restoration success, although declining cover at the established crest was partly responsible for the change. Additionally, vegetation cover, particularly of *U. paniculata,* declined in the restored dune toe during the final year, likely as a result of hurricane impacts, rising seas, and the erosion of renourished sand on the restored section of beach. Of the species planted by the City of Tybee in the restored dune in 2020, the burial-tolerant dune-builder, *Uniola paniculata* was most widespread throughout the study period, while *Ipomoea imperati,* a burial-tolerant dune-stabilizer and fast-growing vine, increased the most. Matzke and Leege (2025) found 82-99% survivorship and 150-230% increase in cover for these species, respectively, one year after planting at this restoration site, and the present results suggest that these species have continued to thrive in the five years since planting. Both species offer critical ecosystem services: in addition to building dunes, *U. paniculata* improves soil moisture retention and increases soil organic matter, enhancing the dune for colonization by new species (Woodhouse and Hanes 1967, Bessette et al. 2018). *Ipomoea imperati* is positively correlated with dune elevation (Miller 2015) and is known to produce stolons of 5-30m in length that can spread seaward (Maun 2009), further stabilizing the sand. Not all species were successful, however. Despite high survivorship in the first year following planting (Matzke and Leege 2025), *Panicum amarum* was mostly absent in our plots by 2022, suggesting limited utility for this species in dune restoration in this region. While other studies have recorded the successful co-occurence of *P. amarum* and *U. paniculata* in coastal dune restorations in the southeastern U.S. (Bessett et al. 2018), *P. amarum* was planted at a much lower density than *U. paniculata* at this site which may have led to its demise.

Citizen science

This study demonstrates the value of citizen science in conducting coastal dune monitoring as a mechanism of increasing community engagement and awareness, as well as reducing the cost of data collection. It also identified some challenges, particularly in the collection of data with non-scientists in dynamic, sensitive habitats.

During the three-year period, we were able to engage 184 citizen scientists for approximately 552 person-hours, equivalent to the $17,244.48 value of volunteer time at the 2023 rate of $31.24 per hour in Georgia (https://independentsector.org/research/value-of-volunteer-time/). While we did not measure the change in participants' perception as a result of the experience, anecdotal comments suggested that they better understood the role of dunes in the protection of the community behind it, that they improved their knowledge of dune species identification and understanding of their value in sand accumulation, and that they had significant respect for the role of the dunes during storm events. We were able to foster long-term participation by three community residents who documented the changes in the dune over the period. We also engaged city officials who came out to speak to the volunteers approximately annually and to thank them for their service. Beyond resident stakeholder involvement, we were able to provide hands-on service-learning field experiences for university students. Ecological service-learning such as this has been shown to improve classroom climate and empower undergraduates to engage in environmental action (Vance-Chalcraft and Goodwillie 2022).

We built training, redundancy, researcher oversight, and post-collection data accuracy checking into our protocol to ensure robust quality assurance. Vegetation cover, as measured by cover class was the most subjective measurement in the protocol, but still returned a strong pairwise correlation of 0.68 ($p = 0.0005$) across citizen science groups who sampled a day apart. Sand accumulation measurements were nearly identical across groups (pairwise correlation = 0.99; $p < 0.0001$). Throughout the study, we determined some errors in species identification, most often of dune grasses which may have slightly skewed the outcome of species richness values, and species frequency values. Overall, however, our study had a reliable level of repeatability and an acceptable level of data quality, similar to other citizen science studies (de Sherbinin et al. 2021). We were open to adaptation though the study period, and as the planted dune vegetation spread and new species colonized the site, we adjusted both the training and the data collection protocol to better capture these changes. One adjustment we made in year four post-restoration - the use of exact vegetation cover measurements for each species – was statistically indistinguishable from cover class measurements collected during the same period, therefore we recommend returning to the simpler and less subjective cover class measurements in future protocols.

One of our concerns in using citizen scientists in this research was that they would normalize walking in the fragile dune system, since this was required for the collection of data. Indeed, trampling of dune vegetation can significantly reduce vegetation cover (Fox 2025), and as such, we were very clear with citizen scientists that they were only to walk in dunes during data collection. For this reason, we chose not to work with school children who might have been more likely to misunderstand this behavior as acceptable under all circumstances, or the sight of whom might have influenced other children to perceive that walking in sand dunes was allowable. We regularly encountered beach visitors who questioned our presence in the dunes, but we took the opportunity to thank them for their interest in protecting the dunes and to educate them about the research we were conducting.

One additional challenge that we encountered during the study was the loss of site posts, particularly in the dune toe, during storms as water levels rose. Each fallen post resulted in the loss of two quarters of data per site because once the posts were reset, the new measurements could not be used until they had been in place for a full quarter. Future studies would benefit from driving posts deep in the sand, and placement a significant distance behind the high tide mark.

Conclusions

In conclusion, coastal sand dunes provide critical ecosystem services that can potentially be maintained via nature-based solutions, such as beach renourishment and dune construction. On Tybee Island, Georgia, five years after construction, the restored dune has become statistically indistinguishable from the established dune in both sand movement and vegetation dynamics; however, it still functions differently under extreme hurricane conditions. Citizen scientists can be trained to successfully monitor these valuable assets at low cost, providing useful information for future restoration planning, at the same time improving stakeholder engagement and education.

Declarations

Funding: The authors have no relevant financial or non-financial interests to disclose.

Data Availability: The experimental data that support the findings of this study will be available in the Digital Commons of the home university upon acceptance.

Ethics approval and consent to participate: All authors have reviewed the paper prior to submission and all consent to its publication.

References

1. Acosta A, Carranza ML, Izzi CF (2009) Are there habitats that contribute best to plant species diversity in coastal dunes? Biodivers Conserv 18:1087–1098 https://doi.org/10.1007/s10531-008-9454-9
2. Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48
3. Bennett NJ (2016) Using perceptions as evidence to improve conservation and environmental management. Conserv Biol. https://doi.org/10.1111/cobi.12681. .30:582 – 92
4. Bessette SR, Hicks DW, Fierro-Cabo A (2018) Biological assessment of dune restoration in south Texas. Ocean Coast Manag 163:466–477 https://doi.org/10.1016/j.ocecoaman.2018.06.019
5. Bonney R, Phillips TB, Ballard HL, Enck JW (2016) Can citizen science enhance public understanding of science? Public Underst Sci 25(1):2–16. https://doi.org/10.1177/0963662515607406
6. Brown SC, Schulte S, Harrington B, Winn B, Bart B, Howe M (2005) Population size and winter distribution of Eastern American oystercatchers. J Wildl Manag 69(4):1538–1545 https://doi.org/10.2193/0022-541X(2005) 69[1538:PSAWDO]2.0.CO;2
7. Bryant DB, Bryant MA, Grzegorzewski AS (2017) Erosion of coastal foredunes: A review on the effect of dune vegetation (ERDC/CHL;CHETN-I-94). U.S. Army Engineer Research and Development Center https://hdl.handle.net/11681/21464
8. Chandler BM, Cawthorn M, Huffling L, Leege LM (2025) Formal and non-formal education in Institutes of Higher Education positively impact sustainability knowledge and attitudes. In: Leal W (ed) World Sustainability Series. North American and European Perspectives on Sustainability in Higher Education. Springer Nature, Switzerland, pp 493–516 https://doi.org/10.1007/978-3-031-80434-2_28
9. Dahl BE, Fall BA, Lohse A, Appan SG (1975) Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas. Miscellaneous Paper No. 9–75. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia

10. de Sherbinin A, Bowser A, Chuang T-R, Cooper C, Danielsen F, Edmunds R, Elias P, Faustman E, Hultquist C, Mondardini R, Popescu I, Shonowo A, Sivakumar K (2021) The Critical Importance of Citizen Science Data. Front Clim 3:650760. https://doi.org/10.3389/fclim.2021.650760
11. Doody JP (2004) Coastal squeeze'—An historical perspective. J Coast Conserv 10(1/2):129–138 https://doi.org/10.1652/1400-0350
12. Drius M, Jones L, Marzialetti F, de Francesco MC, Stanisci A, Carranz ML (2019) Not just a sandy beach. The multi-service value of Mediterranean coastal dunes. Sci Total Environ 668:1139–1155 https://doi.org/10.1016/j.scitotenv.2019.02.364
13. Elliott-Smith E, Bidwell MT, Holland AE, Haig SM (2015) Data from the 2011 International Piping Plover Census. U.S. Geological Survey Data Series 922. U.S. Geological Survey, Reston, VA, USA
14. Evans JM, Gambill J, Hopkinson C (2016) Tybee Island Sea-Level Rise Adaptation Plan. Technical Report · April 2016 DOI 10.13140/RG.2.1.3825.9604/1
15. Fox SJ (2025) Evaluating impacts of footpaths on resiliency of restored dunes at Tybee Island, Georgia. Master's Thesis, Georgia Southern University
16. Fraisl D, Hager G, Bedessem B et al (2022) Citizen science in environmental and ecological sciences. Nat Rev Methods Primers 2:64 https://doi.org/10.1038/s43586-022-00144-4
17. George E, Smith A, O'Rourke C, Cherry N, Sfalcin A, Houser C (2024) Citizen science monitoring of beach and dune erosion during Hurricane Fiona. Phys Geogr 45(4):382–401. https://doi.org/10.1080/02723646.2024.2324516
18. Georgia Southern University Center for Business Analytics and Economic Research & EDA University Center Program (2023) Tybee Island Tourism Economic Impact Study. City of Tybee Island & Visit Tybee Island. https://www.cityoftybee.org/DocumentCenter/View/3926/TybeeIslandToursimEconomicImpact-Report?bidId=
19. Grattarola F, Rodríguez-Tricot L, Zarucki M, Laufer G (2024) Status of the invasion of *Carpobrotus edulis* in Uruguay based on citizen science records. Biol Invasions 26(4):1139–1155 https://doi.org/10.1007/s10530-023-03242-w
20. Harley MD, Kinsela MA, Sánchez-García E, Vos K (2019) Shoreline change mapping using crowd-sourced smartphone images. Coast Eng 150:175–189 https://doi.org/10.1016/j.coastaleng.2019.04.003
21. Hays GC, Mackay A, Adams CR, Mortimer JA, Speakman JR, Boersma M (1995) Nest site selection by sea turtles. J Mar Biol Assoc UK 75:667–674 https://doi.org/10.1017/s0025315400039084
22. Hoagland P, Jin D, Kite-Powell HL (2012) The cost of beach replenishment along the US Atlantic coast. J Coast Rsch 28:199–204 https://doi.org/10.2307/41332066
23. Hosier PJ (1973) The effects of oceanic overwash on the vegetation of Core and Shackleford Banks NC Dissertation, Duke University
24. Houston JR (2024) The economic value of America's beaches. Shore Beach 92(2) https://doi.org/10.34237/1009225

25. Hsiung A, Hartanto R, Bhatia N, Morris R (2024) Challenges and opportunities for implementing nature-based coastal protection in an urbanised coastal city based on public perceptions. J Environ Manag 370:122620 https://doi.org/10.1016/j.jenvman.2024.122620
26. Hughes C, Tremblett K, Kummer J, Lee TS, Duke D (2022) How can we do citizen science better? A case study evaluating grizzly bear citizen science using *principles of good practice* in Alberta, Canada. Animals (Basel) 12(9):1068 https://doi.org/10.3390/ani12091068
27. Intergovernmental Panel on Climate Change (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York https:// accessed 24 June 2026
28. Itzkin M, Moore LJ, Ruggiero P, Hacker SD, Biel RG (2021) The relative influence of dune aspect ratio and beach width on dune erosion as a function of storm duration and surge level. Earth Surf Dynam 9:1223–1237 https://doi.org/10.5194/esurf-9-1223-(2021)
29. JMP (2023) JMP Pro 17. JMP Statistical Discovery LLC, Cary, NC
30. Kossin JP, Knapp KR, Olander TL, Velden CS (2020) Global increase in major tropical cyclone exceedance probability over the past four decades. PNAS 117:11975–11980 https://doi.org/10.1073/pnas.2021573117
31. Landry CE, Keeler AG, Kriesel W (2003) An economic evaluation of beach erosion management alternatives. Mar Resour Econ 18:105–127 http://www.jstor.org/stable/42629388
32. Lansu EM, Hallie S, Fischman HS, Angelini C, Hijner N, Geelen L, Groenendijk D, Höfer S, Kooijman AM, Rietkerk M, Tonkens S, de Vries S, Wassen M, van Weerlee E, Wille D, Reijers V, van der Heide T (2025) How human infrastructure threatens biodiversity by squeezing sandy coasts. Curr Biol 35:5210–5219 https://doi.org/10.1016/j.cub.2025.09.027
33. Matzke S (2021) Measuring the success of a coastal sand dune restoration on Tybee Island: Plant growth, sand accretion, and implications for management. Master's Thesis, Georgia Southern University
34. Matzke S, Leege LM (2025) Measuring success: plant growth and sand movement in a coastal dune restoration on Tybee Island USA. Ecol Restor 43:102–115 https://doi.org/10.3368/er.43.2.102
35. Maun MA (2009) The biology of coastal sand dunes. Oxford University Press
36. McFall BC, Young DL, Whitmeyer SJ, Buscombe D, Cohn N, Stasiewicz JB, Skaden JE, Walker BM, Stever SN (2024) SandSnap: Measuring and mapping beach grain size using crowd-sourced smartphone images. Coast Eng 192:104554 https://doi.org/10.1016/j.coastaleng.2024.104554
37. McKee S, Stauble JDK, Williams BP, Wutkowski MJ (2008) Impact of Savannah harbor deep draft navigation project on Tybee Island shelf and shoreline. ERDC/CHL TR-08-5. U.S. Army Corps of Engineers, Savannah
38. Miller TE (2015) Effects of disturbance on vegetation by sand accretion and erosion across coastal dune habitats on a barrier island. AoB Plants 12:7:plv003 https://doi.org/10.1093/aobpla/plv003

39. Miselis JL, Flocks JG, Zeigler S, Passeri D, Smith DR, Bourque J, Sherwood CR, Smith CG, Ciarletta DJ, Smith K, Hart K, Kazyak D, Berlin A, Prohaska B, Calleson T, Yanchis K (2021) Impacts of sediment removal from and placement in coastal barrier island systems: U.S. Geological Survey Open-File Report 2021–1062, 94 p https://doi.org/10.3133/ofr20211062
40. National Beach Nourishment database https://gim2.aptim.com/ASBPANationwideRenourishment/ Accessed 16 June 2026
41. Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520 https://doi.org/10.1126/science.1185782
42. NOAA (2025) https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8670870. Accessed 16 June 2026
43. R Core Team (2025) R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/
44. Ramesh R, Chen Z, Cummins V, Day J, D'Elia C, Dennison B, Forbes DL, Glaeser B, Glaser M, Glavovic B, Kremer H, Lange M, Larsen JN, Le Tissier M, Newton A, Pelling M, Purvaja R, Wolanski E (2015) Land–ocean interactions in the coastal zone. Past, present & future Anthropocene 12:85–98 https://doi.org/10.1016/j.ancene.2016.01.005
45. Rodella I, Madau F, Mazzanti M, Corbau C, Carboni D, Simeoni U, Parente L (2020) Carrying capacity as tool for beach economic value assessment. case studies of Italian beaches) Ocean Coast Manag 189: 105130 https://doi.org/10.1016/j.ocecoaman.2020.105130
46. SAS (2023) JMP Pro 17
47. Strasser B, Baudry J, Mahr D, Sanchez G, Tancoigne É (2019) Citizen science? Rethinking science and public participation. Sci Technol Stud 32(2):52–76 https://doi.org/10.23987/sts.60425
48. Staudt F, Gijsman R, Ganal C, Mielck F, Wolbring J, Hass HC, Goseberg N, Schüttrump H, Schlurmann T, Schimmels S (2021) The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. J Coast Cons 25:34. https://doi.org/10.1007/s11852-021-00801-y
49. Swann C, Brodie KL, Spore NJ (2015) Coastal foredunes: Identifying coastal, aeolian, and management interactions driving morphologic state change (ERDC/CHL TR-15-17). U.S. Army Engineer Research and Development Center https://hdl.handle.net/11681/7358
50. Thorne KM, Buffington KJ, Osland MJ et al (2025) Nature-based solutions could offset coastal squeeze of tidal wetlands from sea-level rise on the U.S. Pacific coast. Sci Rep 15:11443. https://doi.org/10.1038/s41598-025-93437-z
51. Tybee Island Beach Management Plan (2014) https://downloads.regulations.gov/FWS-R5-ES-2021-0032-0002/attachment_12.pdf Accessed 24 June 2026
52. Vance-Chalcraft HD, Goodwillie C (2022) Ecological service-learning positively impacts classroom climate and empowers undergraduates for environmental action. Ecosphere 13(5):e4039 https://doi.org/10.1002/ecs2.4039

53. Woodhouse WW, Hanes RE (1967) Dune Stabilization with vegetation on the Outer Banks of North Carolina TM-22. U.S. Army Coastal Engineering Research Center Washington DC https:// erdc-library.erdc.dren.mil/server/api/core/bitstreams/81b728f8-a867-4ef8-e053-411ac80adeb3/content Accessed 24 June 2026

Figures

Figure 1

Map of Tybee Island, Georgia, USA and the restored and established (i.e., reference) dunes. In the right panel, red circles indicate the location of dune monitoring posts (21 in the restored dune; 14 in the established dune), while the black dotted line represents the separation of the two dune types

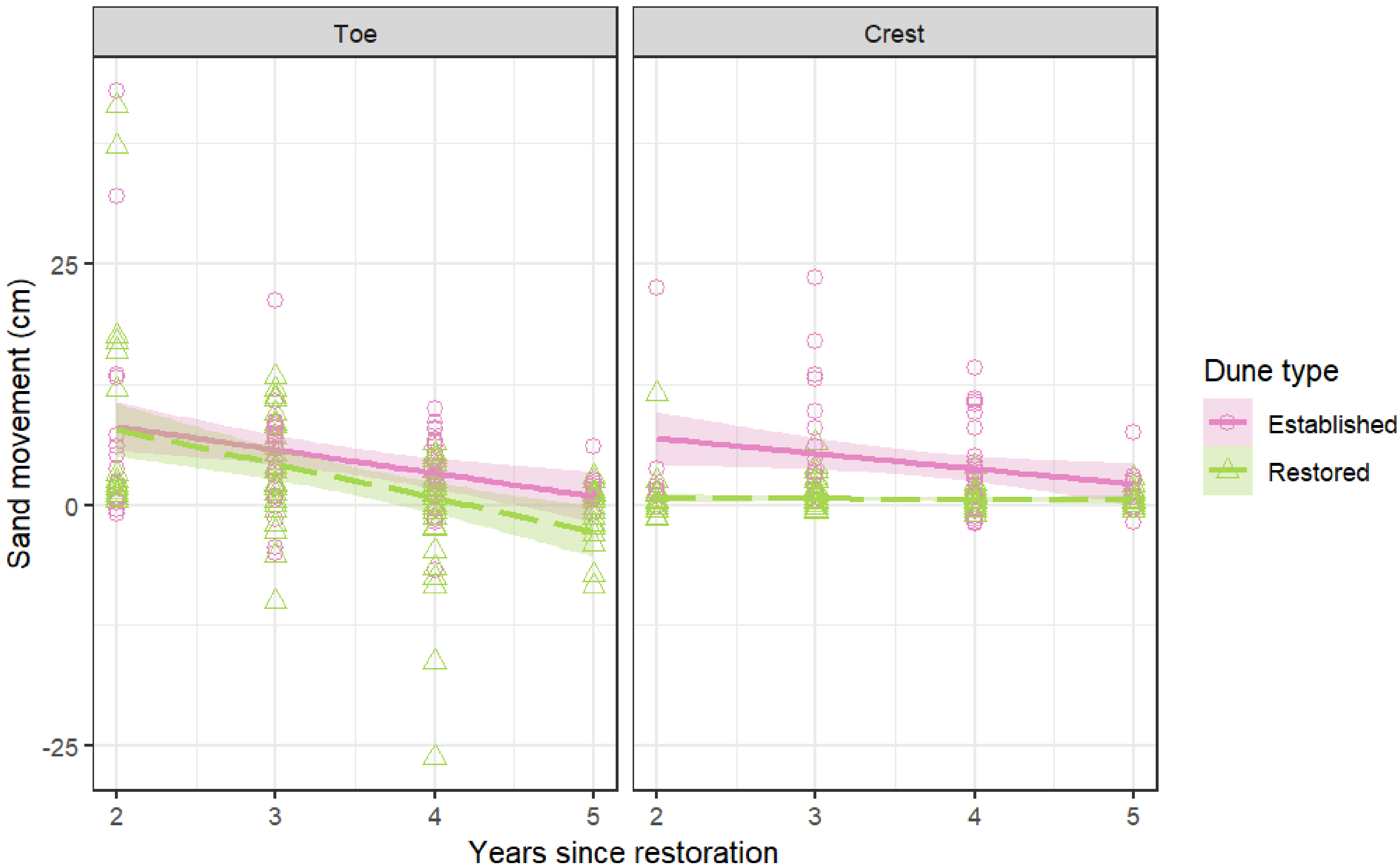

Figure 2

Sand movement (cm) over time in Tybee's established (circles, solid line) and restored (triangles, dashed line) dune at the toe and crest. Shapes represent quarterly measurements (i.e., between December–March, March–June, June–September and September–December) for years two through five since restoration with shaded areas indicating 95% confidence intervals. See Table 1S for linear mixed model results

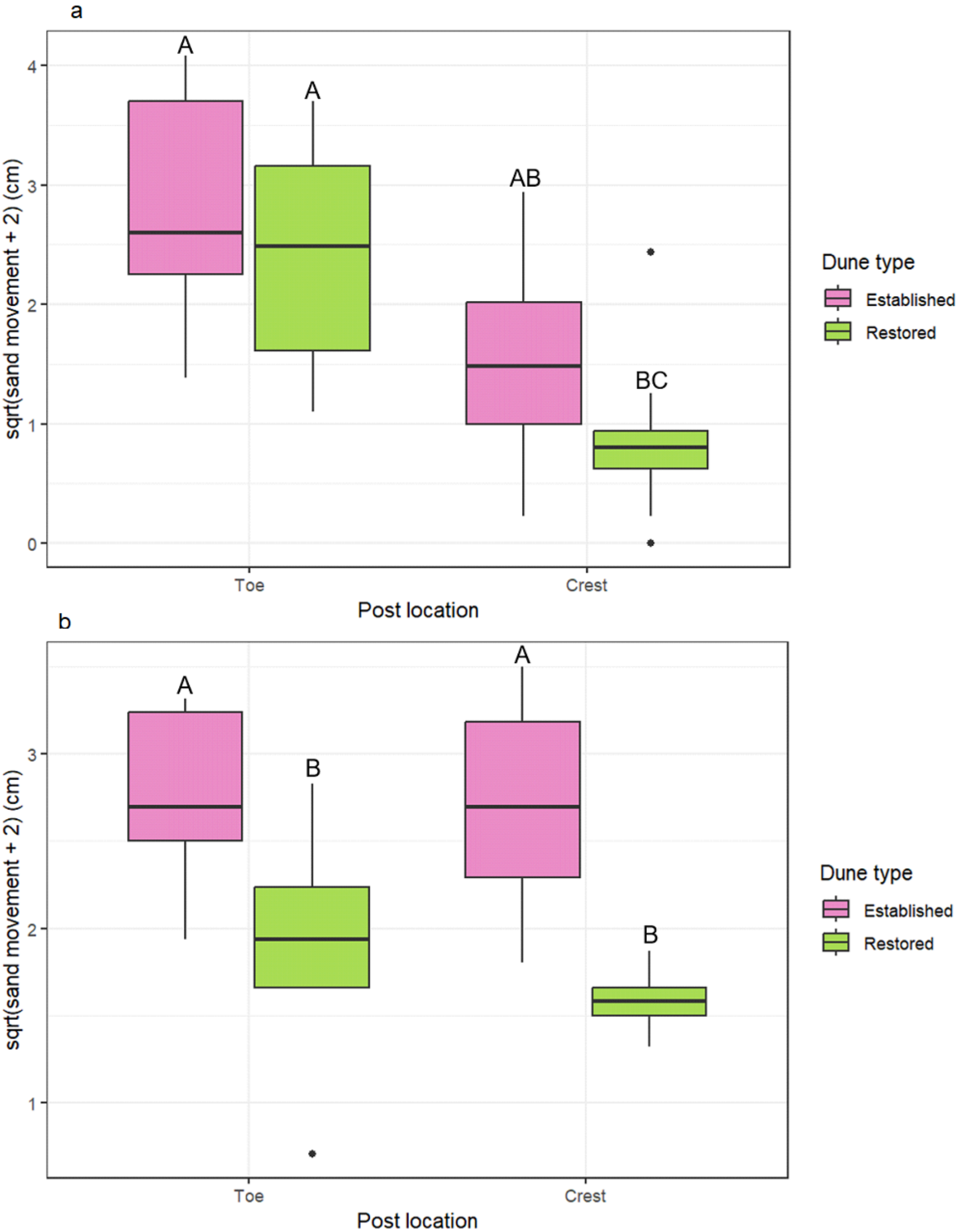

Figure 3

Sand movement (show as transformed data: sqrt(x+2) cm) in the established (pink) and restored (green) dune at the toe and crest during (a) Hurricane Ian (2022) and (b) Hurricane Helene (2024)

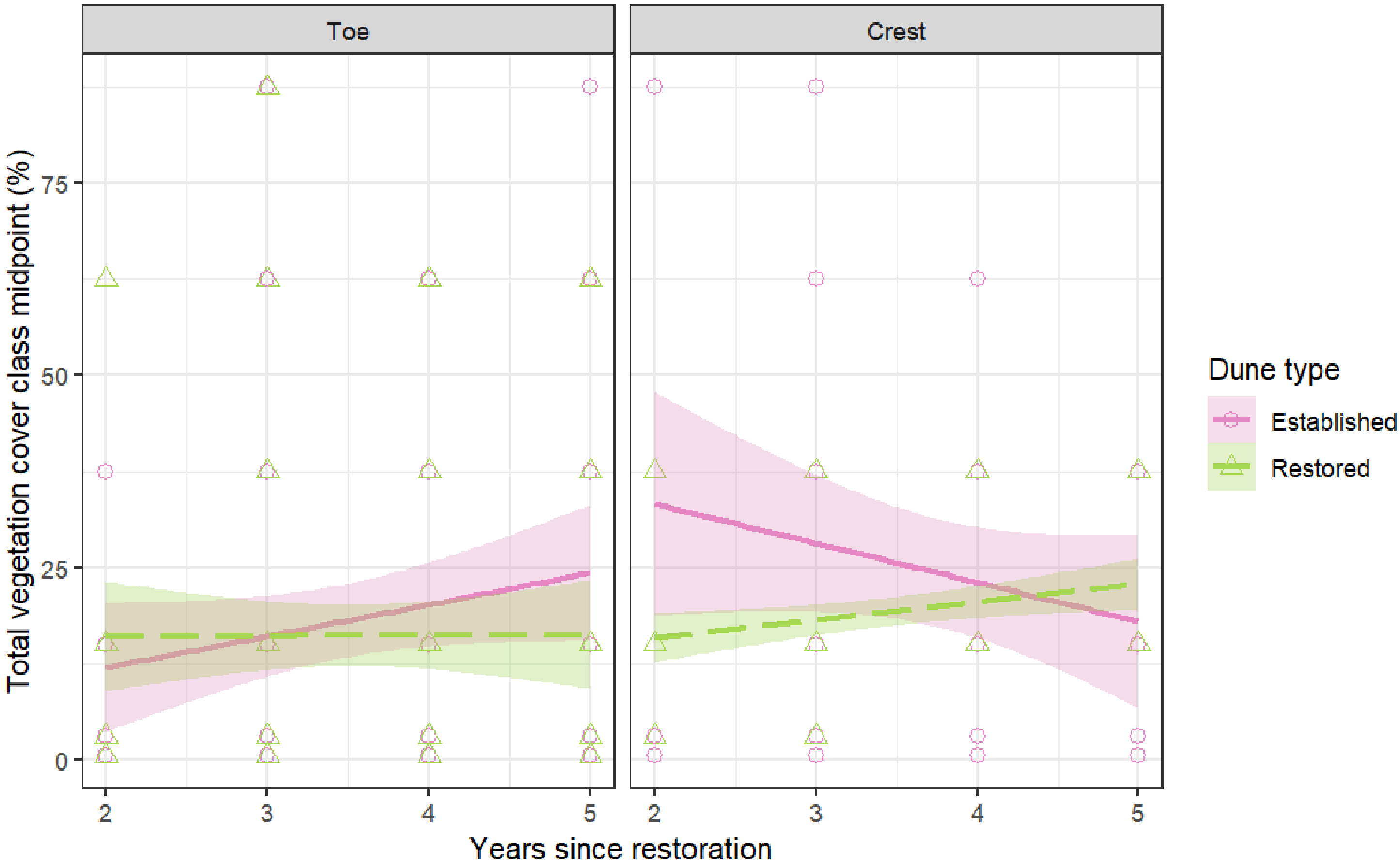

Figure 4

Total vegetation cover class midpoint (%) over time in Tybee's established (circles, solid line) and restored (triangles, dashed line) dune at the toe and crest. Circles represent measurements collected in March, June, and September for years two through five since restoration with shaded areas indicating 95% confidence intervals. See Table 3S for linear mixed model results

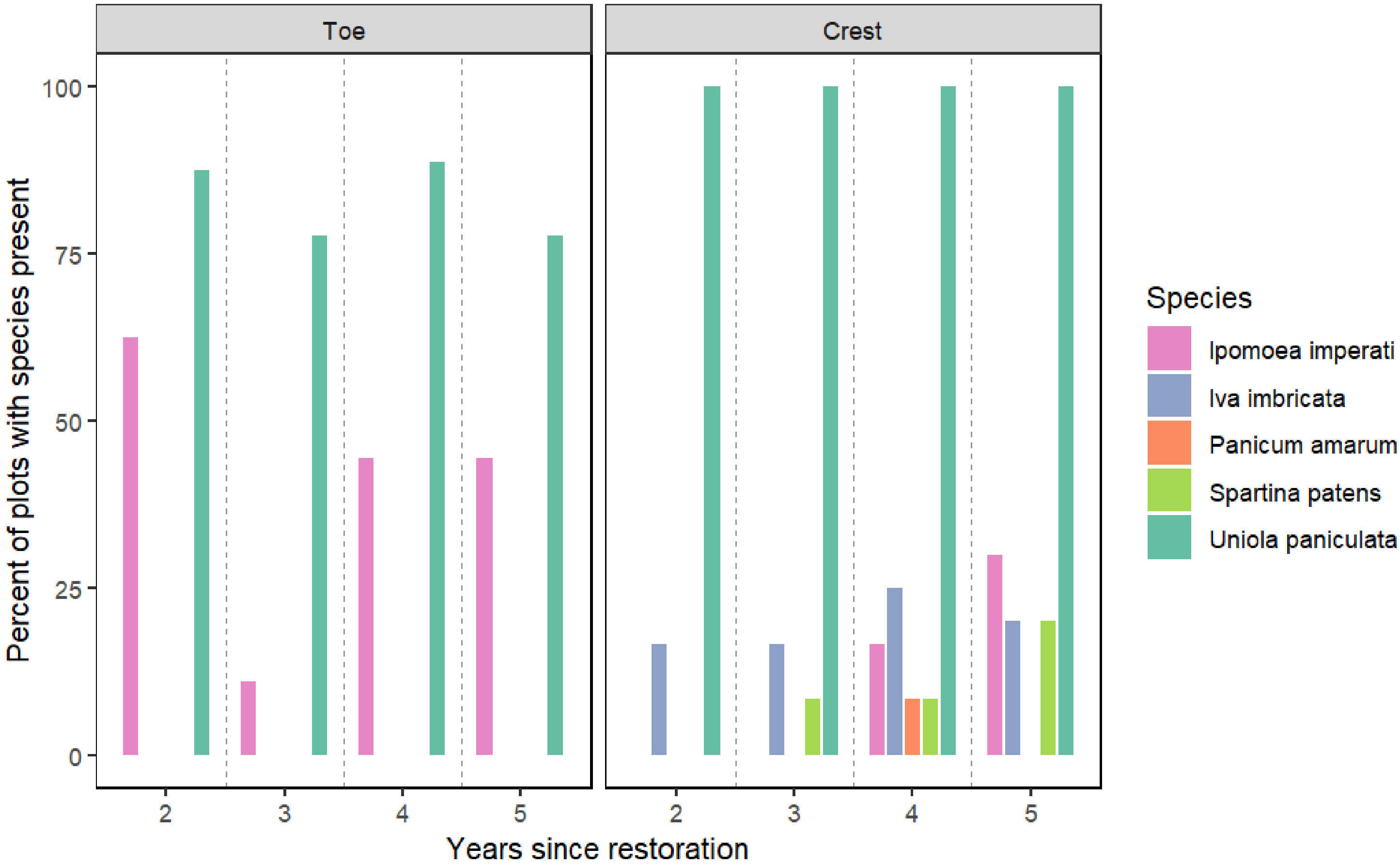

Figure 5

Percent of plots within the restored dune at the toe and crest containing the species planted during restoration from years two to five since restoration

Supplementary Files

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- SupplementaryFiguresTables.docx