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In the Face of Climate Change, Does Human Trampling Affect Dune Resilience and Alter Ecosystem Services?

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Biology.

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Abstract

Sand dunes play a valuable role on the coastline supporting unique native species and protecting beach communities. The City of Tybee Island, Georgia, USA has undergone extensive dune restoration to expand and rehabilitate its shoreline to better defend the town against the increasing frequency of hurricanes and storm surge. The project included the recovery of existing dune structures and construction of new dunes filled with sand pumped from offshore and vegetated with a variety of native species. To analyze the impact of human trampling on dune vegetation occurring adjacent to footpaths and crossovers in new and established dunes, we measured plant data, sand accumulation, path width, and colonization of previously trampled regions. A greenhouse study was also conducted on the species *Uniola paniculata* to examine the impacts of trampling at various levels under controlled conditions. Vegetation in sites adjacent to the footpaths had lower chlorophyll content and decreased growth in comparison to the sites adjacent to crossovers. The footpaths experienced erosion rather than sand accumulation and widened further into the dunes throughout the study. In the greenhouse, trampled plants had lower chlorophyll content, slower growth, and a loss of stems. Human trampling is detrimental to dune vegetation and their function in supporting the dune structure. These impacts are present around footpaths on the dunes but less so around the crossovers, and are more profound in the younger, newly constructed dunes. These results encourage limiting allowance of trampling on dune, particularly in restoration areas.

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Introduction

Dune Structure

According to US census data, roughly 30% of the United States population lives in coastal communities, and of those people 60.2 million are living in areas vulnerable to hurricanes (Cohen 2019). Engineers are constantly working to create new methods of defense against these massive storms, including flood gates, levees, and elevated buildings, but nothing has proved nearly as effective as nature's natural barriers. Coastal barriers are composed of sediment and uniquely adapted vegetation that is subject to wind, wave, and tidal energies and can withstand storm surges and sea level rise, and include structures such as mangroves, barrier islands, and dunes (U.S. Fish and Wildlife). However, like many other elements of nature these valuable resources are under threat from human intrusion and anthropogenic climate change (Miller et al. 2018).

Sand dunes, which are hills of sand formed by wind that can reach tens of meters high, are a common example of a coastal barrier and immensely important in coastal land defense (Nordstrom 2021). The general structure of coastal sand dunes includes a foredune and backdune (Figure 1). The foredune is in closest proximity to the tidal range and takes the majority of onslaught from winds and waves, and vegetation there is most limited by the conditions (Miller et al. 2010). The foredune is divided into the toe, crest, and heel based on slope and elevation (Miller et al. 2010; Figure 2).

When sand dunes are vegetated with native flora, they become even more efficient, providing more protection against erosion especially on the foredunes that are most exposed to the ocean (Silva 2016). The ecosystem services of dune plant species include 1) providing a buffer or cover against weather above ground, 2) trapping sediment deposits to grow the dune structure, and 3) binding dune sediments and nutrients in place underground (Rogers and Nash 2003, Martinez et al. 2016). Dune plant species consist mainly of coastal grasses and shrubs that have special adaptations for high salt concentration and sand burial over their roots and stems, especially the pioneers that thrive on the foredunes facing most of the ocean spray and wind (Miller et al. 2018, Rogers and Nash 2003). They can be categorized based on their role in the dune ecosystem as well as their resistance to burial (Stallins 2001). Dune builders or pioneer species such as American beachgrass (*Ammophila breviligulita*) and sea oats (*Uniola paniculata*) are highly effective in trapping and accumulating large volumes of sand to aid in increasing the size of the dune and allowing the process of succession to occur (Ehrenfeld 1990, Penney 2010). Beachgrass, for example, has rhizomes in its underground root structure that grow horizontally across the dune and hold sand as well as nutrients and moisture in place (Penney 2010, Rogers and Nash 2003). Dune stabilizers, which may be burial tolerant (e.g., *Ipomoea imperati* and *Spartina patens*) or burial intolerant (e.g., *Muhlenbergia capillaris*) begin to grow after primary succession has occurred on the dune foundation and help to reduce sand being eroded by wind or rain (Ehrenfeld 1990, Martinez et al. 2016). Dune passenger species include any vegetation that does not have a significant role or niche in the habitat (Stallins 2001).

When left alone in its natural habitat, dune vegetation builds a thriving ecosystem that offers coastline protection and supports the local community, including multiple endangered species that rely on the dunes (Martinez 2004). Sea turtles like the loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) use beach dunes for nesting (Miller et al. 2018). Shorebirds such as plovers (*Charadrius alexandrinus* or *Charadrius wilsonia*) find themselves in dune habitats for rest and nesting during their migrations (Miller et al. 2018). Pollinators like the beloved monarch butterfly (*Danaus plexippus*) also rely on dune vegetation for their survival (Miller et al. 2018).

Due to the uniqueness of the habitat and its limited range on the shoreline, dunes have also produced many rare, endemic species in both the plant and animal kingdoms (Miller et al. 2018). Degradation of the dune ecosystem in addition to other pressures such as rising sea levels, invasive species, and habitat loss can cause the extinction of any one of these species that rely on dunes. Preservation and restoration are vital to the biodiversity of this region and protection of coastal biological and human communities (Nordstrom 2021).

Beach Access

The intrusion of humanity onto once pristine coastal ecosystems has severely compromised the integrity of dune communities (Martinez et al. 2004). The attraction of coastal living has led to massive development in the past century that has severely strained and disrupted natural processes (Martinez 2004). At the same time, sea level rise and storm frequency are increasing as global warming intensifies (Shukla 2017). Tourism, land development, and climate change all constitute a significant threat to the integrity of dune ecosystems (Martinez 2004). In many locations along the US coastline, this barrier between beach and land has been built over, trampled down, or removed entirely (Nordstrom 2021).

In places where dunes still exist and may even be protected, passage across the dunes to reach beaches causes trampling and destruction of vegetation that erodes sand, prevents new growth, and divides the dunes (Lemauviel et al. 2003). There are multiple methods for beach entry over dunes with varying levels of direct human contact and trampling, with footpaths and wooden crossovers being the most common. Footpaths are simply human carved pathways across the sand. The more people that use the path in greater frequency, the more they expose the dunes to wind and disturb vegetation (Purvis et al. 2015). Footpaths are also disruptions in the continuity of the foredunes and create the potential for storm surge to breach the dunes (Purvis et al. 2015). Wooden crossovers, which may be built at varying heights above the sand, offer protection to vegetation from trampling and fragmentation (Purvis et al. 2015). Vegetation is sensitive to disruption, so constant trampling can reduce plant assemblages which will compromise the integrity of the dune (Acosta et al. 2013). Even just a small path for a single household over time can have major effects (Purvis et al. 2015). Proper management of these beach access points is necessary to protect the integrity and maintain ecosystem services of sand dunes and their vegetation.

Dune Restoration

As humans cause these problems, they also create solutions. Dune restoration is the process of recovering existing dune landscapes that have been degraded by human interaction and rebuilding dunes in areas where they have been destroyed (Martinez 2004). Less intensive restoration projects have different methods of decreasing destruction of the dunes (Martinez 2004). Sand fences are one popular solution to dune degradation, as they reduce wind intensity and are very effective at trapping sand (Woodhouse 1978). Sand fences are cost effective in production and labor costs and provide dune building and stabilization, although not to the same extent as vegetation (Woodhouse 1978). Revegetation is another simple solution to supplement the dunes and aid their recovery, and involves planting native dune species that will act as dune builders and stabilizers so that new material is not lost again to erosion and the new dunes may recover (Rogers and Nash 2003). More extensive projects may be necessary in areas where dunes have been highly affected. This includes the addition of new sand deposits to replace eroded material which may be transferred from offshore or nearby regions as well as revegetation, monitoring, and greater protection (Bessette et al 2018). However, recovering dunes are still more vulnerable to human intrusion and extreme weather events. While the weather cannot be controlled, human impact can. Policy and legislation protection dunes are essential to limiting human impact in the future and ensuring the investment of restoration projects are not wasted (Nordstrom 2021). With a combination of the described efforts, dunes may continue their function as nature's terrestrial barriers against marine weather events and storm surge.

Tybee Island Restoration Project

On Georgia's barrier islands, surging development has caused dune habitats to face new threats as cities build into the beaches and tourists trample vegetation to access the ocean (Rodgers 2002). Recent storms such as Hurricane Irma (2017) and Matthew (2016) also have had a major impact on dune integrity on the islands (Department of Natural Resources 2018). One island located merely miles from the bustling port city of Savannah has experienced such degradation of its shoreline. Tybee Island, GA, the most developed and populated of Georgia's barrier islands, has been unable to keep their dunes at a healthy level through previous shoreline nourishment projects (Tybee Beach Management Plan 2014). With over one million annual visitors heading to Tybee's beaches and 3,100 residents, providing easy beach access while maintaining its significant dune structures is crucial (Armstrong 2015).

In 2018, the City of Tybee Island and Army Corps of Engineers began a dune and shoreline restoration project that included the construction of two new dunes (Figure 3) and recovery of existing ones (Department of Natural Resources 2018; Figure 5B). The constructed dunes encompassed over one mile of beach and were built eight feet high (Department of Natural Resources 2018; Figure 4). The city also opened existing footpaths in those areas, installed new crossovers and sand fences, and planted over 271,000 seedlings to vegetate the area (Department of Natural Resources 2018; Figures 3 and 4). Tybee already had some existing healthy dune habitat, but the crossovers in these areas did not extend to through the edge of the dune structure. This resulted in widespread trampled and bare regions radiating from the crossover end, so the city extended all the existing crossovers beyond the base of the dunes to allow these regions to recover (Shore Protection Act 2019; Figure 6). In total, this restoration project involved footpaths of varying sizes, wooden crossovers, and vehicle access points in both the established and newly constructed dunes. For the purpose of this study, only crossover and footpaths were included for observation.

The process of studying human trampling has been developed on many national and international coastal locations, such as one study on the Carolina coast that did a similar comparison between footpaths and crossovers. Measurements from that study included species richness, percent cover, and path size (Purvis et al. 2015). The Carolina study served as a model for many of the practices in this one, as the coastal dunes of the Carolinas share the same features and species composition as the dunes found in Georgia. The impact of human trampling may be studied from a conservation perspective or as a management tool (Lemauviel et al. 2003).

The restoration project presented the opportunity to 1) study how human trampling impacts vegetation in areas where it is already established as well as areas of new growth, 2) evaluate the effectiveness of constructing wooden crossovers versus footpaths in order to protect vegetation, 3) examine the impact of human trampling on vegetation growth and health, 4) measure the impact of footpaths on the ecosystem services of dune vegetation, and 5) determine how human trampling limits the growth and stability of the dune. The objective of this project was to determine the overall impact of human trampling, identify what methods of defense are most effective against it, and examine the resilience of dune vegetation. I hypothesized that human trampling has a negative impact on plant density, growth, and health which would reduce their ecological role as dune builders and stabilizers. I predicted that if a footpath is used as a beach access method rather than a crossover, there would be lower overall coverage and diversity of species, limited growth, and greater erosion.

This project consisted of an observational study of the restoration site to determine the overall impact of trampling, and a controlled greenhouse experiment to analyze the effects on *Uniola paniculata*.This study served as a management tool as results can be applied to improving the overall restoration project on Tybee Island.

Methods

Study Site

Tybee Island is located in Chatham County, Georgia, USA at the mouth of the Savannah River at 32.0002° N, 80.8457° W. The restoration project took place landward of the Ordinary High Water Mark (OHWM) and ranged over 1.5 km along the beach (Figure 3). The first phase of restoration, which included over 6,000 m^2 of newly constructed and vegetated dunes and access points, began in 2017 and ranged from Chatham Avenue to the Tybee Beach Pier (Figure 5A). I sampled one crossover and one footpath site in this area, referred to as Phase 1 sites. The second phase involved over 22,000 m^2 of new dunes and began in 2019 on the north end of the beach. This area ranged from Center Street to the 2nd Avenue access point (Figure 5B). I sampled three crossover and three footpath sites, referred to as Phase 2 sites (Figure 4). The established dunes ranged from the north side of the pier to 6th street, and had four of each type of access point (Figure 5C).

Experimental Design: *Field Study*

The observational study took place along the footpaths and crossovers on both the established dunes and the newly constructed dune. As there is a significant change in the conditions and species composition from the foredunes to back dunes, this study was restricted to the foredunes (Figure 1). 16 study sites (eight for the established region and eight for the new construction) were randomly chosen from all possible sites, and consisted of four crossovers and four footpaths in each region.

Three 1x1 meter plots were placed on each transect of the dune labeled the toe (A), crest (B), and heel (C) of the foredune (Figures 2 and 9). The side of the access point of which the plots were placed was also chosen randomly by the cardinal direction (north or south side).

These three plots per transect were placed perpendicular from the edge of the access point with Plot 1 being zero meters out and Plot 2 at 1.5 meters (Figure 7). Plot 3 was placed at a randomly chosen distance from 5-10 meters from the edge of the access point to serve as a control (Figure 7). All sites were marked using a labeled 12” wood dowel that was ½” in diameter in the northwest corner, which was also used to measure sand accumulation based on the rise or fall of the sand level at a marked height (Figure 7). One plant in each of the plots was randomly selected and tagged to return to for measuring the growth and health of a specific plant.

Each site had the three transects consisting of three plots each for a total of 144 replicates; 72 in the established dunes and 72 in the restored dunes, for a total observational area of 144 m^2. These sites were compared with each other to evaluate what methods of beach access best support the vegetation and sand collection necessary to maintain or increase dune elevation, and how human trampling limits the growth and spread of vegetation across the dunes.

Experimental Design: Greenhouse Study

A greenhouse experiment was also conducted to evaluate plant health and growth under controlled conditions. Examples of native plant species found on Tybee Island’s dunes include *Ipomoea imperati, Panicum amarum, Uniola paniculata, Muhlenbergia capillaris,* and *Spartina patens* (Matzke, 2021). These species have varying tolerance to sand burial and may act as either a dune stabilizer or builder. The most commonly found in Tybee’s dune and most important for its structure is the sea oat, *Uniola paniculata,* which was used in this study. In this experiment, 36 healthy plants of the same age were purchased, repotted into half gallon pots, and placed under controlled conditions within the greenhouse. 12 plants were grown without any interference to serve as the control. The remaining 24 were split into two in experimental groups receiving varying levels and frequency of ‘trampling’ to mimic humans stepping on the plants as they would on the dunes. This was accomplished using a 945 gram concrete weight dropped onto the plant four times from 6 inches each session. The low frequency group were ‘trampled’ once every four days, while the high frequency group was trampled daily from February 25 to April 3. The growth of control versus affected plants helped to determine how much trampling affects plant health.

Data Collection: Field Study

Data collection in the replicate sites of the observation study for each 1m x 1m plot of the field study included 1) plant species composition, 2) number of individual plants per species, 3) percent cover of each species in the plot area, 4) total percent cover of the plot area, 5) Normalized Difference Vegetation Index (NDVI) to determine photosynthetic capacity based on reflection of visible and infrared light wavelengths, in which healthier patches reflect more infrared and absorb visible light resulting in a higher NDVI values (up to 1), while unhealthier patches are the opposite resulting in a lower NDVI (down to -1), using Spectrum Tech’s CM 1000 NDVI Meter, 6) chlorophyll concentration, only on *Uniola paniculata,* on a scale of -9 to 99.99 in SPAD units using Spectrum Tech’s SPAD 502 Chlorophyll Meter, and 7) sand accumulation measured by change in height from a marked line on the dowels.

The tagged plant in each site was measured for 1) percent cover of that individual, 2) tallest stem height, 3) tallest inflorescence height (if present), and 4) number of hard stems, which was categorized as small for 0-5 stems, medium for 5-20 stems, and large for over 20 stems.

For footpaths, the width of the path at each transect was measured with an electronic meter wheel. The wheel was placed at the furthest point of rooted vegetation parallel to the wooden dowel of Plot 1 and rolled across the extent of the path to the next nearest point of rooted vegetation.

For crossovers, the encroachment of pioneer vegetation along previously trampled regions was measured. In the established dunes, all crossovers were extended beyond the base of the dunes where they had previously ended halfway through the foredune (Figure 6). This caused immense trampling through the dunes leading to wide bare regions that expanded from the base of the crossovers. The new, longer crossovers protect the bare regions from continued trampling, and allow for new growth to occur. In order to track colonization of these areas by dune plants, we measured the distance from the base post of the crossover to the furthest point of vegetation beyond the toe of the dunes using an electronic meter wheel.

Vegetation data was collected monthly from August 2021 to November 2021 until plants entered their dormant period from December 2021 to February 2022. One final vegetation data set was done in March 2022 as new spring growth began. Site data, including sand accumulation, total cover, path width, and crossover recolonization was collected monthly from August 2021 to March 2022.

Data Collection: Greenhouse

Data collected in the replicates of the greenhouse study include 1) chlorophyll concentration, 2) three tallest stem heights, 4) number of stems, 5) below ground and above ground biomass at end of study. The experiment began Friday, February 25, 2022, and data collection took place weekly every Friday until the experiment end date of April 1, 2022. The plants were taken down and divided into shoots and below ground portions, rinsed of soil, then dried at 80 degrees, four days for leaves and six for roots. After drying, roots were weighed with an analytical balance and aboveground parts were weighed with a standard electronic balance.

Statistical analysis

Data was analyzed using JMP software.

For the observational study, a multi-factor ANOVA with dune age (Established, Phases 1 and 2), site type (crossover vs. footpath), transect (toe, crest, heel), and plot location (1, 2 and 3) as effects and interactions was used to determine the effect of human trampling on wooden crossovers versus footpaths, and those access points on the newly constructed dunes versus the older, established dunes. This was done to determine the effectiveness of each type of beach access and the resilience of new, constructed dunes in comparison to the older, natural ones.

As for the greenhouse study, a one-way ANOVA was again used to measure the effect of trampling on growth of *Uniola* plants in comparison to those that do not experience that disturbance.

Results

As hypothesized, footpaths had a negative impact on vegetation and dune structure in many areas. The crossovers prevented the effects seen by trampling on the footpath sites, and even provided some benefit to the plants directly adjacent to them. The impacts found in the different observations varied based on location along the shoreline, elevation on the dune, and the age of the dune structure. Similar results were also seen on the species *Uniola paniculata* in the greenhouse experiment, in which trampled plants grew less than, if at all, in comparison to non-trampled plants and had lower chlorophyll content.

Chlorophyll and NDVI Values

Chlorophyll concentration of the species *Uniola paniculata* in Plot 1 (closest to the access point) was higher in the new and established dune crossovers in comparison the new dune footpaths (F= 10.473, p= 0.0001; Figure 8). When comparing Plot 1 versus Plot 3 (control site), the Plot 1 chlorophyll content of both the established and new dune crossovers were higher than their respective Plot 3 (F= 7.321, p= 0.00104; Figure 8). There was no significant difference between the plots in either footpath type. The results did not vary based on transect. The overall results were the same for data collected in November 2021 and in March 2022. There was no difference between the site types for the Normalized Difference Vegetation Index (NDVI) data collected in November. The established dunes had lower NDVI values than the two regions of newly constructed dunes (Figure 9; F= 0.9515, p= 0.00216). Transects A and B did not differ, but C had the highest NDVI values (Figure 10; F= 0.9515, p= 0.00952).

Change in Total Vegetation Cover

All sites on average had a positive increase in total vegetation cover in each plot over the course of the study. Crossovers had twice as much increase in cover on the crest and heel in comparison to the footpaths (F= 0.904, p= 0.0203; Figure 11). There was not a difference in the change in cover on the dune toe between the two site types. The change in vegetation cover in established sites and Phase 1 sites did not differ, but were both more than double the change in cover of phase 2 sites (F= 0.904, p= 0.0005; Figure 12).

Species Richness

There was no significant difference in the species richness between the crossovers and footpaths when comparing the total number of species per site (F= 0.044, p= 0.90391) as well as the total when only including Plot 1 (F= 0.179, p= 0.66274). There was a difference in species richness between the dune ages. Phase 1 sites had the highest average number of species, followed by the Established sites then Phase 2 sites with the fewest (F= 10.415, $p < 0.0001$; Figure 13). There was a significant difference between the site types when looking at the richness at each transect. Richness did not vary between crossovers and footpaths at the toe. At the crest, crossover sites had higher richness, but the opposite was true for the heel (F= 4.923, p= 0.00001; Figure 14). The number of individuals for the species *Uniola paniculata* varied and was not impacted by site type or other factors (F= 0.4167, p= 0.9537).

Plant Growth

There was no significant difference in the growth of tagged plants between crossovers and footpaths, including the changes in percent cover, height, number of stems, and inflorescence over the course of the study. A loss or gain of hard stems was observed in a few plants in both the crossover and footpath sites but did not follow a pattern. The only factor affecting the growth of plants and change in percent cover was the dune age. Tagged plants in the Established sites grew in percent cover significantly more than those in the Phase 2 sites, but neither differed from Phase 1 sites (F= 0.8944, p= 0.0002; Figure 15). Dune age was also the only factor that varied in the change in height of the tagged plants. Tagged plants in the Phase 1 and 2 sites increased in height at similar rates, and more than the plants in the Established sites (F= 0.00134, p= 0.00134). Inflorescences were found almost solely in the Established sites and did not vary in abundance between the crossovers and footpaths.

Sand Accretion

The most impactful factors on sand accretion were dune age and location, site type, and transect. Overall, crossovers accumulated twice as much sand as footpaths over the study. On the crest and heel (transects B and C), the crossovers accumulated much more sand than the footpaths, which were actually eroding (F= 2.649, p= 0.00328; Figure 17). Although the footpaths on the dune toe (transect A) were not eroding, most footpath sites had a lower total accretion than the crossovers, although this result varied (Figure 17). The dune toe accumulated 2.5 times more sand than crest or heel plots. The established and Phase 1 sites, which are located on the middle and south end of the island, accreted more sand than the Phase 2 sites located on the north end (F= 2.649, p= 0.01011; Figure 17). Phase 1 sites accumulated more than 2.5 times more sand than Phase 2 sites.

Recolonization of Trampled Areas and Path Expansion

From August 2021 to March 2022, the footpaths widened at an average of 33.9 cm. The greatest effect was found on the toe of the dune of all sites, with an average change of 41 cm. The dune crest had a change of mean of 38 cm, and the heel of the dune had an average of 23 cm. Only two sites, sites 8 (Established dune) and 16 (Phase 2 dune), shrank in width. Dune age and transect were not impactful factors (Figure 18; F= 0.334, p= 0.7215). At the extended crossovers in the Established sites, there was little to no recolonization of bare regions between the dune edge and base of the crossover. There was also little to no beyond the base of the dunes to the edge of the newly constructed crossovers in Phase 1 or 2 sites.

Greenhouse Experiment

From February 25 to April 3, the trampled plants in the greenhouse study experienced a decline in chlorophyll concentration and number of stems, as well as much slower growth in height than the control plants. Trampled plants on average lost stems, while the control plants gained more than one (F= 8.4002, p= 0.0011; Figure 19). The same trend was seen with chlorophyll value, as both levels of trampling decreased in chlorophyll concentration in the leaves while the control plants increased (F= 10.6178, p= 0.0003; Figure 20). When looking at the change in height for only the tallest leaves, the highest trampled level differed from the non-trampled, but the low level of trampling did not differ from either (F= 5.0047, p= 0.0126). When the three tallest leaves were included for the change in height, both levels of trampling had a much lower increase in height than the control plants did (F= 5.1462, p= 0.0113; Figure 21). There was not a difference in above, below, or total biomass between the trampled and control plants (F= 0.6485, p= 0.5294).

Discussion

Location and Age as Factors in the Effects of Trampling

Three major factors in this study helped to explain patterns of vegetation growth and sand accumulation. The first was the age of the dunes. The established dunes are much older than both restoration areas, and have more mature, denser, and larger vegetation. These sites had higher chlorophyll content and more accumulation than their counterparts in the restoration sites. The Phase 1 sites are also three years older than the Phase 2 sites, so the differences were seen between the two as well. The Phase 2 dunes had the lowest species richness, while Phase 1 had the highest, although it was hypothesized that the Established dunes would be highest. This could be due to the space available for species that cannot compete with the dominant *Uniola* plants. In one study, foredunes were found to be the most disturbed and had lowest species richness as they were dominated by *Uniola* (Miller et al. 2010). Similarly, *Uniola* is the dominant species on Tybee's dunes, and could be most resistant to trampling, which is why it is most dominant on the new dunes which had the greatest impacts by footpaths. As for the dune ages, the Established dunes have more mature and larger vegetation, which creates more competition that limits the number of species that can reside in the areas dominated by large *Uniola* (Miller et al. 2010). In Phase 1 dunes, the plants are smaller and much more space is available for smaller and less competitive species. In Phase 2, similar richness could be expected as the dune reaches the current age of the Phase 1 dunes. Phase 1 also experienced the greatest change in cover, likely for similar reasons. There is more space available than in the established dunes to expand into, and they have reached a more mature stage than Phase 2 that includes more expansion and colonization.

The second factor was the location of the site along the shoreline of the three dune ages, which also impacted the levels of accumulation. The wind blows from North to South, so the southern end of the island receives sand deposits blown from the northern end (Linhoss 2021). The Phase 1 sites located on the northern end had the lowest accumulation levels, which can be attributed to it being both the youngest of the three areas and the lack of sand deposits it receives from up the shoreline to replace what is blown off. The Phase 1 and Established sites are located further south and have more mature and larger plants, allowing them to receive and trap more sand. In addition, the location of the Phase 1 dunes as the furthest south allows them to receive the most sand deposits and keep up with the accumulation rates of the much more mature Established sites.

The third was the location along the transects. The toe of the dune receives the majority of wind and wave action but also most of the sand deposited by them, and therefore had the highest accumulation rate in all areas. The heel is more protected from wind and wave action, so while less sand is deposited there less is removed. The crest had the greatest erosion of all, with little protection and little deposited. Therefore, the impacts of human trampling were greatest in the crests of the younger dunes.

Effectiveness of Crossovers in Protecting Dune Habitats

The wooden crossovers in this study exceeded the expectation that they would negate some of the impacts caused by human trampling on the footpaths, and even showed some benefit to the plants adjacent to them. Chlorophyll concentration was much higher in the crossover sites compared to the footpaths, but also higher in the plots directly next to the crossover in comparison to the footpaths. This could be due to several various reasons, such as protection from harsh winds, increased shade, or differences in soil moisture and content. Few plants live directly under the crossovers, so access to that open space and less competition may have also contributed to this result. Although the plants adjacent to the footpaths also have access to more open space, they did not experience the same benefits. This difference may be due to greater compaction of the soil along footpaths as well as a stressful environment that negates the benefit that decreased competition provided, if that was a contributing factor.

The crossovers also had higher overall growth in plant cover within the plots. By preventing human trampling along and possibly within the sites, dune vegetation was able to expand and spread more throughout the study area. This is supported by results in another study on Georgia dunes, which found that the cover of native dune species on protected refuge areas with little human disturbance was higher than areas that experience heavy human traffic (Rodgers 2002).

As dune vegetation is vital in stabilizing and building the dunes, it is not surprising that the crossovers accumulated more sand than the footpaths and had little to no erosion. When the vegetation is stronger, bigger, and healthier, it is more effective in serving its role in the dune ecosystem (Martinez 2016). As the sites with crossovers had more positive increase in cover and greater chlorophyll concentration, they also had greater sand accretion. The Phase 2 footpaths had the lowest chlorophyll content and slowest growth, and instead experienced erosion. This aligned with the results from the Carolina study, which found lower vegetation cover in plots adjacent to footpaths (Purvis et al. 2015). It was expected that crossovers sites would possess a greater diversity of plant species, but the variation in richness in this study was only found to be due to the age. This varied from a study done on dunes in Italy, which found that areas protected from trampling had a greater diversity than trampled sites (Santoro 2012). This variation could be attributed to the difference in species composition as well as study period, as their study was much longer and covered the spring and summer seasons that my study lacked (Santoro 2012).

There was less recolonization of the bare sites at the newly extended crossovers than was expected. This can be due in part to a number of factors. As the construction on these crossovers did not occur until mid to late summer, data was not collected during the spring and early summer when a majority of the growth occurs. The main species that colonize open regions are vining or rhizomatous plants such as *Ipomoea* and *Sporobolus virginicus*, which die back during the fall and winter when the majority of data was collected. If data collection were to continue in these areas during the growing season, it is likely that far more recolonizations would be observed, which was the result of preventing trampling in the Italy study (Santoro 2012). Another reason is storm surge. These areas are not elevated from the shoreline like the majority of the dune habitat. When major storms came through and the storm surge reached the base of dunes, these bare regions were flooded, and colonizers were washed away or destroyed by debris and waves. There were multiple instances where a plant had established itself in a bare region but was unable to survive a storm surge that had occurred (Figure 22). Installation of sand fences in order to reduce the impact of storm surge and increase elevation of the base of the dunes and beyond is a possible solution to creating a space to allow for recolonization to occur without potential destruction during storms (Santoro 2012).

Trampling on a Key Dune Species

The greenhouse study provided data on the health of a control versus trampled *Uniola* plant, and how that changes based on the level of trampling. The non-trampled plants suffered in every aspect, indicating there is a strong correlation between trampling and decreased health of the plant. There was not a major difference in the results between the low and high levels of trampling, so any level of consistent trampling was detrimental to the *Uniola* plants. The trampled plants lost some stems and leaves which decreases the overall biomass of the plant and reduces its ability to trap sand and stabilize the dunes. Trampled plants also decreased in chlorophyll concentration and had lower or negative height changes. The overall health of the plant was much lower, and it is likely that over a longer period of study time this would impact the survivorship of trampled plants. This study is indicative of the health of the plants on or adjacent to frequently used footpaths.

Implications for Management

The results in this study inform the City of Tybee about the impact of different methods on the established and newly constructed dunes and how this may be limiting the benefits of the restoration project. It also provides more information as to what methods allow for greater defense against trampling, including the construction of wooden crossovers and planting bare regions. There is a demonstrable effect of trampling on dune vegetation particularly on younger dune structures, so reducing or preventing human contact with the dunes is imperative to ensure the full success of dune restoration. The recommendations from this project, similarly suggested in the Carolina study, would be to reduce the number of available footpaths for residents to use by encouraging joint use rather than separate paths or constructing additional crossovers to replace the most high traffic footpaths (Purivs et al. 2015). Sand fences would also be beneficial to the extended crossovers in the established sites to protect colonizing vegetation from future storms. Most importantly, public outreach and education for residents and tourists on the importance of dune and dune vegetation and how humans can impact it can foster a community that is respectful and even protective of their local dunes.

Figures

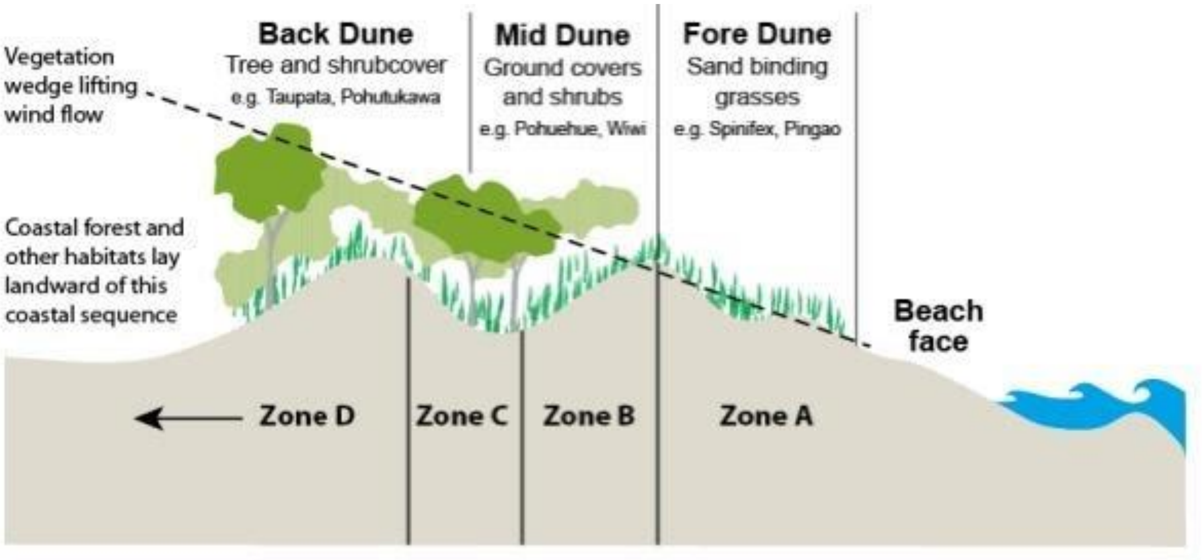

Figure 1. Dunes consist of multiple zones based on their distance from the shore that vary in vegetation types. Only foredunes contained measurement plots.

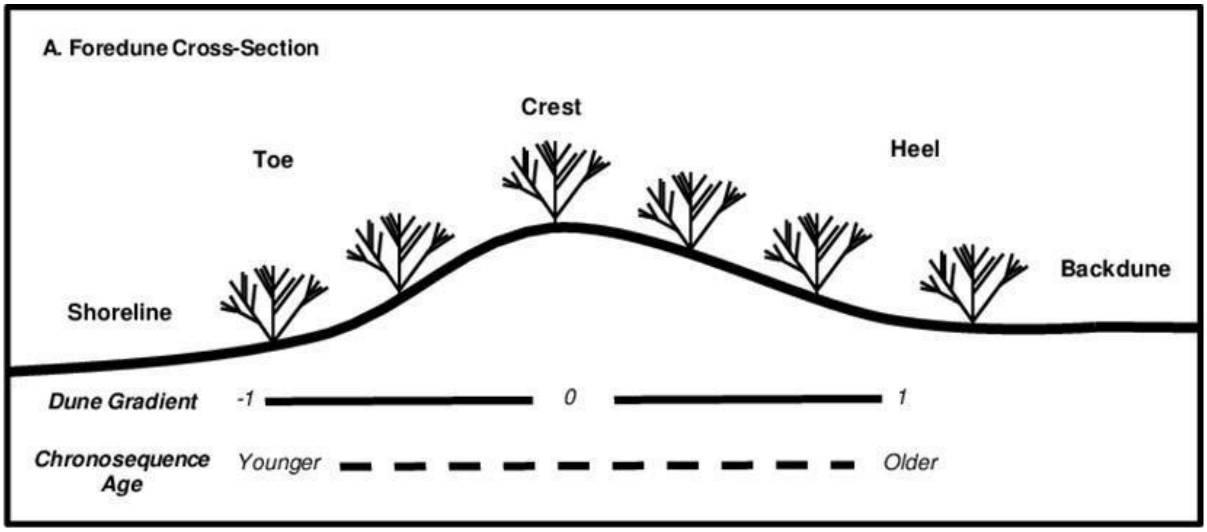

Figure 2. Foredunes cross section schematic depicting terms for locations of plots on different elevation points and shoreline distances (David et al. 2015).

Figure 3. Location of Phase 2 restoration site in Tybee Island off of Highway 80 in Chatham County dune restoration where sand deposition and vegetation has occurred

Figure 4. Visual of crossover and footpath locations on the newly constructed dune region.

Figure 5A. Satellite image of Phase 1 site locations dated 3/9/2021, taken from Google Earth.

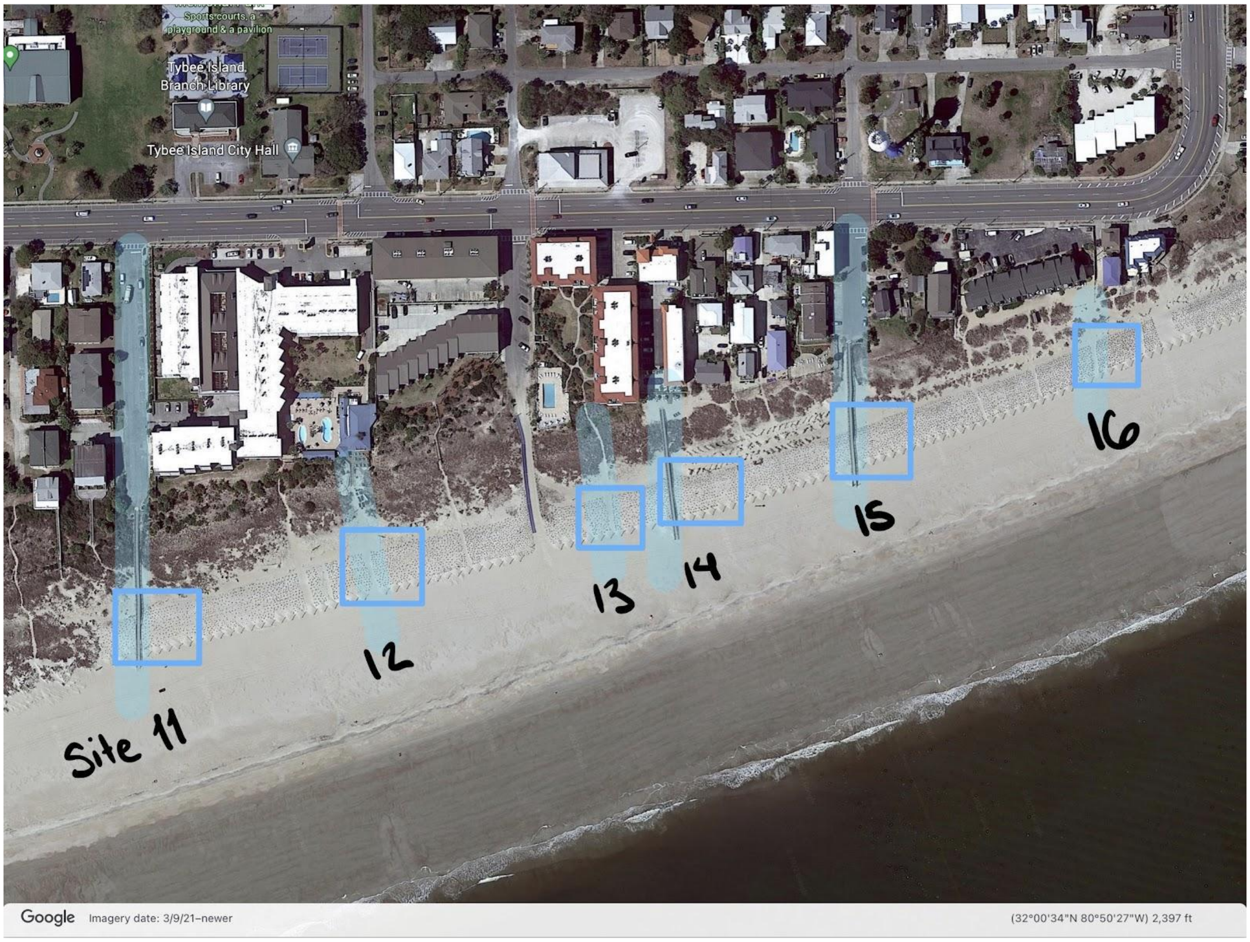

Figure 5B. Satellite image of Phase 2 sites dated 3/9/2021, taken Google Earth.

Figure 5C. Satellite image of Established sites dated 3/9/2021, taken from Google Earth..

Figure 6. Satellite image of construction on crossover extensions dated 3/9/2021, with visual of trampled regions the crossover now passes over, taken from Google Earth.

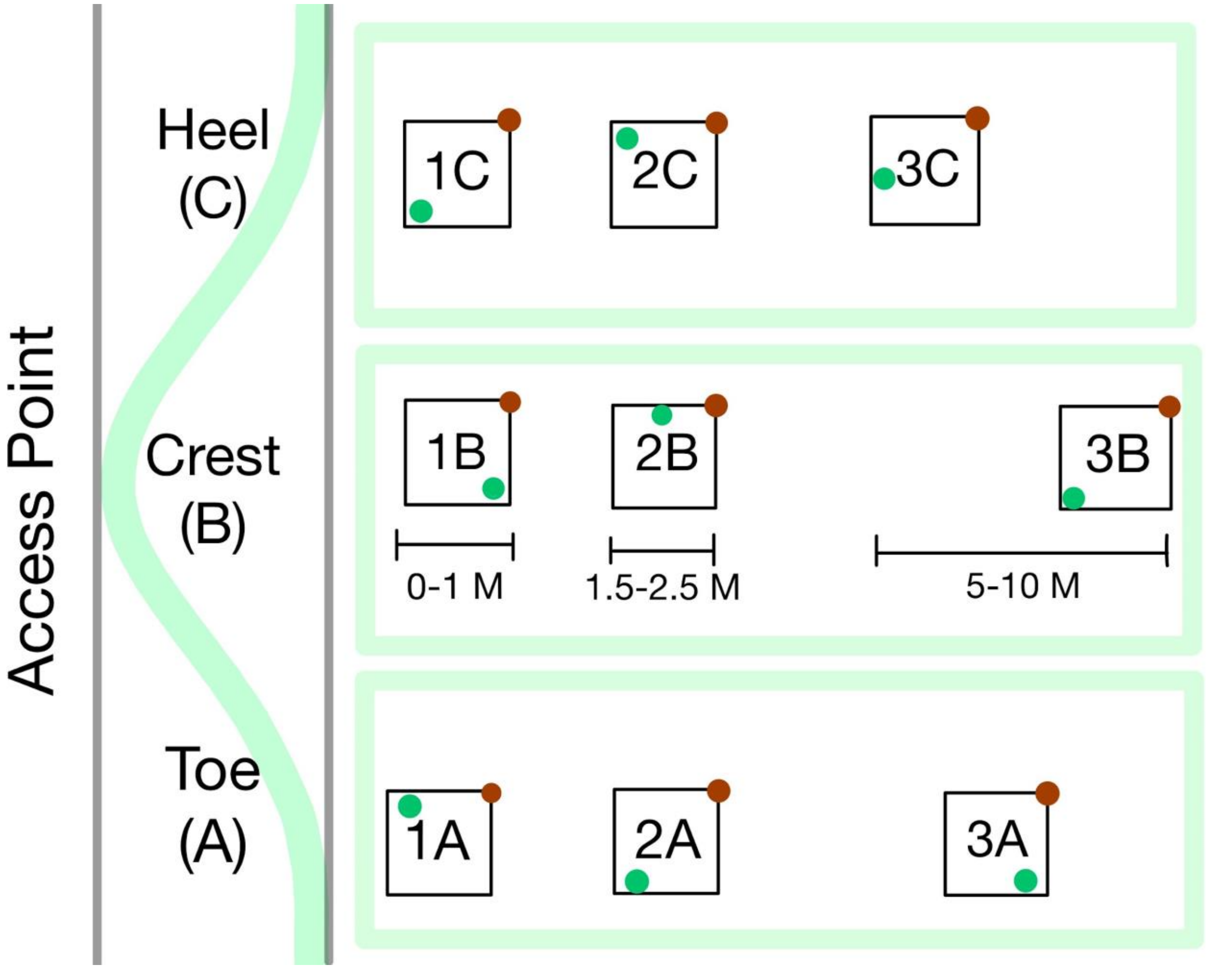

Figure 7. Visual representation of plot layout at each access point. Curved green line represents the slope of the dune, brown dots represent wooden dowels, and green dots represent tagged plants. All sites are directly adjacent to the access point, either to the right or left.

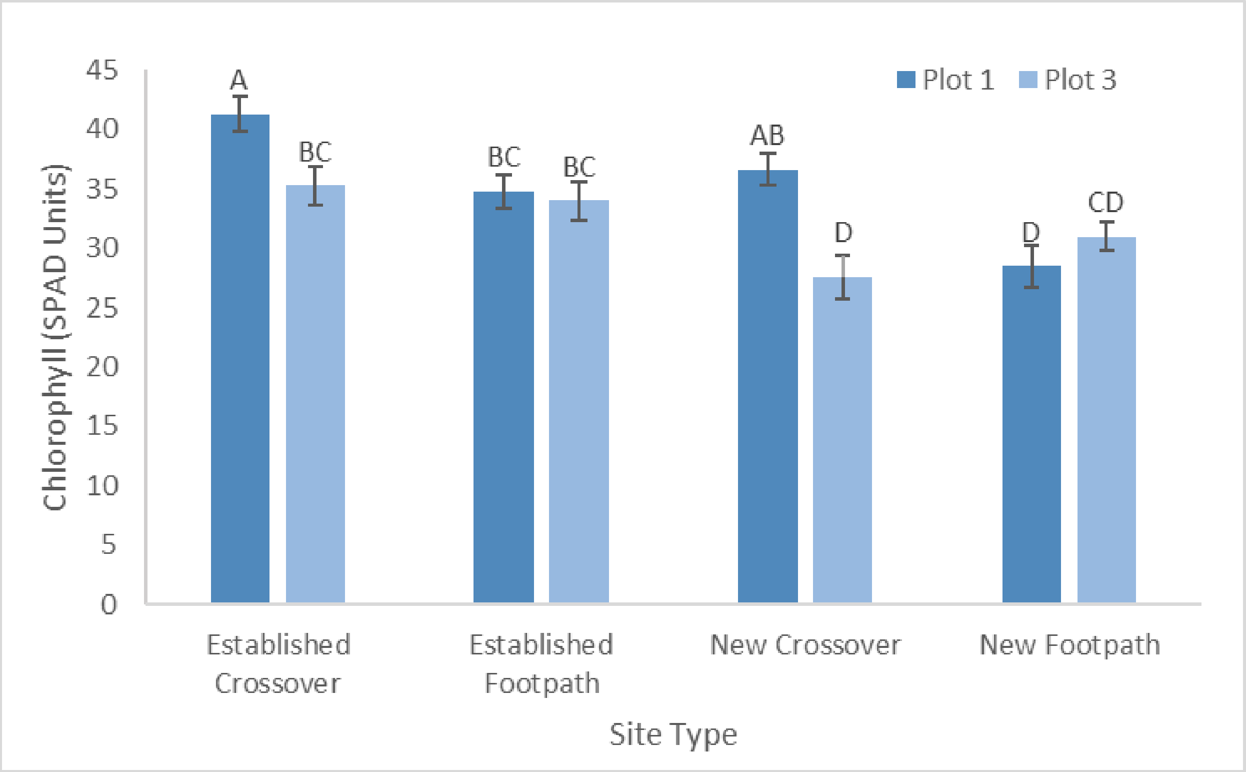

Figure 8. Average chlorophyll concentration +/- standard error of *Uniola paniculata* plants in Plot 1 versus Plot 3 in all site types, measured in November. Bars denoted with different letters are statistically significant from each other.

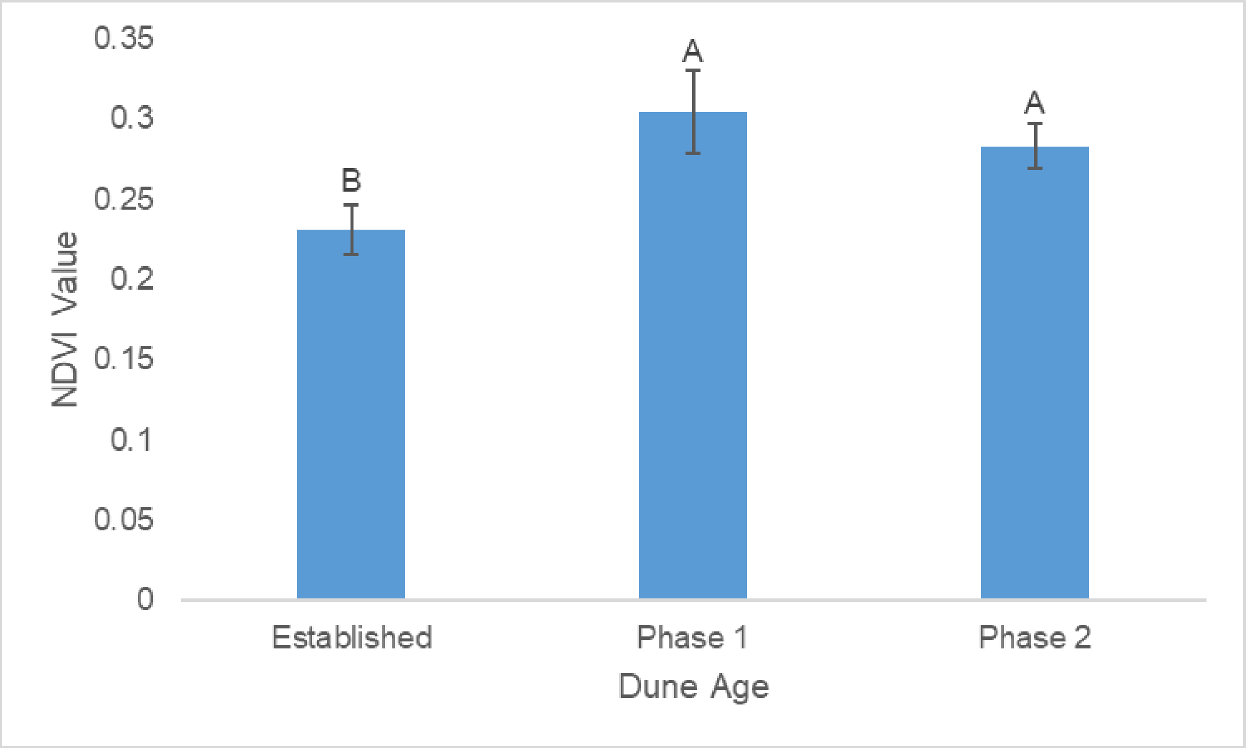

Figure 9. Average NDVI value +/- standard error of all sites in each dune age, collected in November. Bars denoted with different letters are statistically significant from each other.

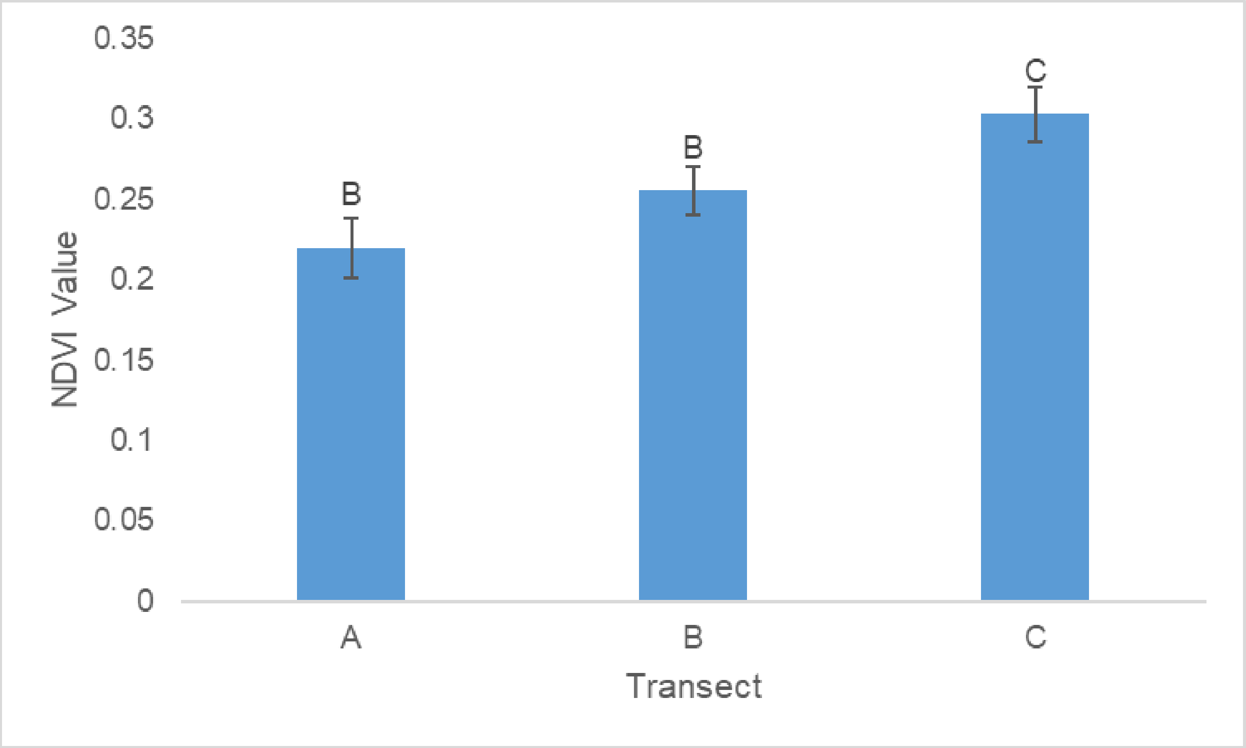

Figure 10. Average NDVI value +/- standard error of all sites at each transected, measured in November. Bars denoted with different letters are statistically significant from each other.

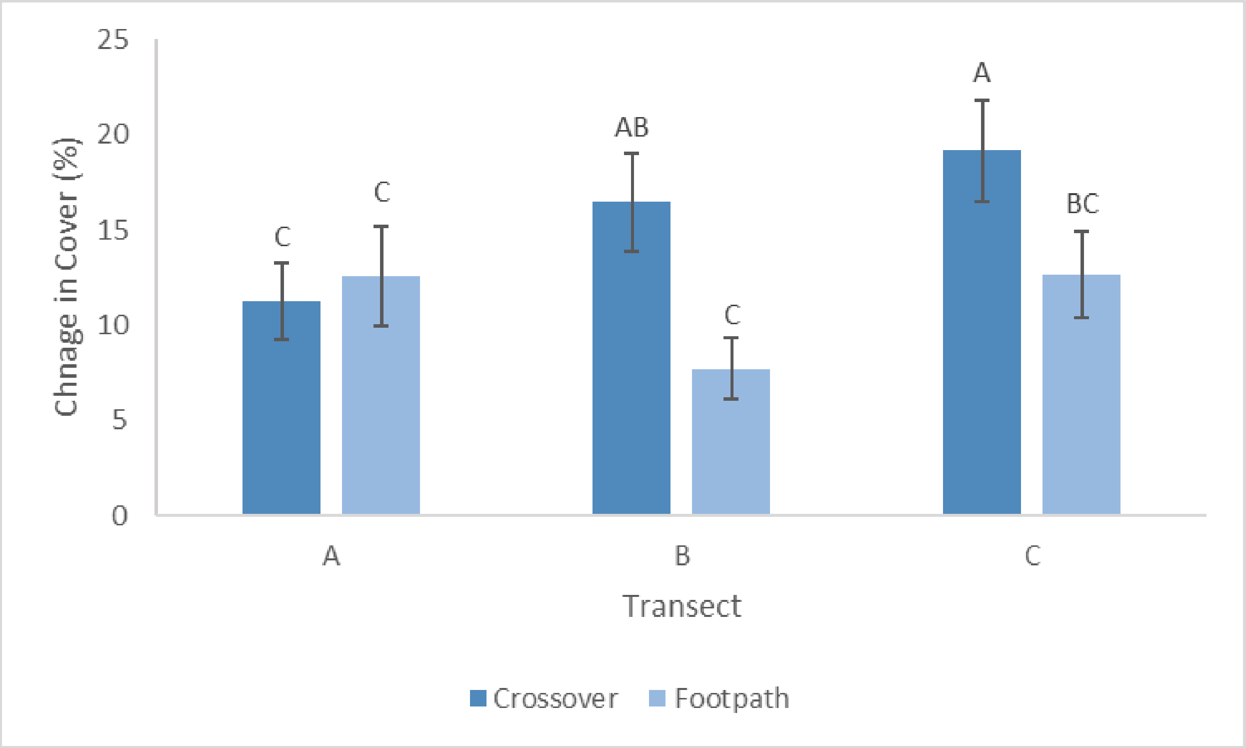

Figure 11: Change in total percent cover of dune vegetation in Plot 1 of all sites at each the toe ‘A’, crest ‘B’, and heel ‘C’ transects +/- standard error, measured from September to March. Bars denoted with different letters are statistically significant from each other.

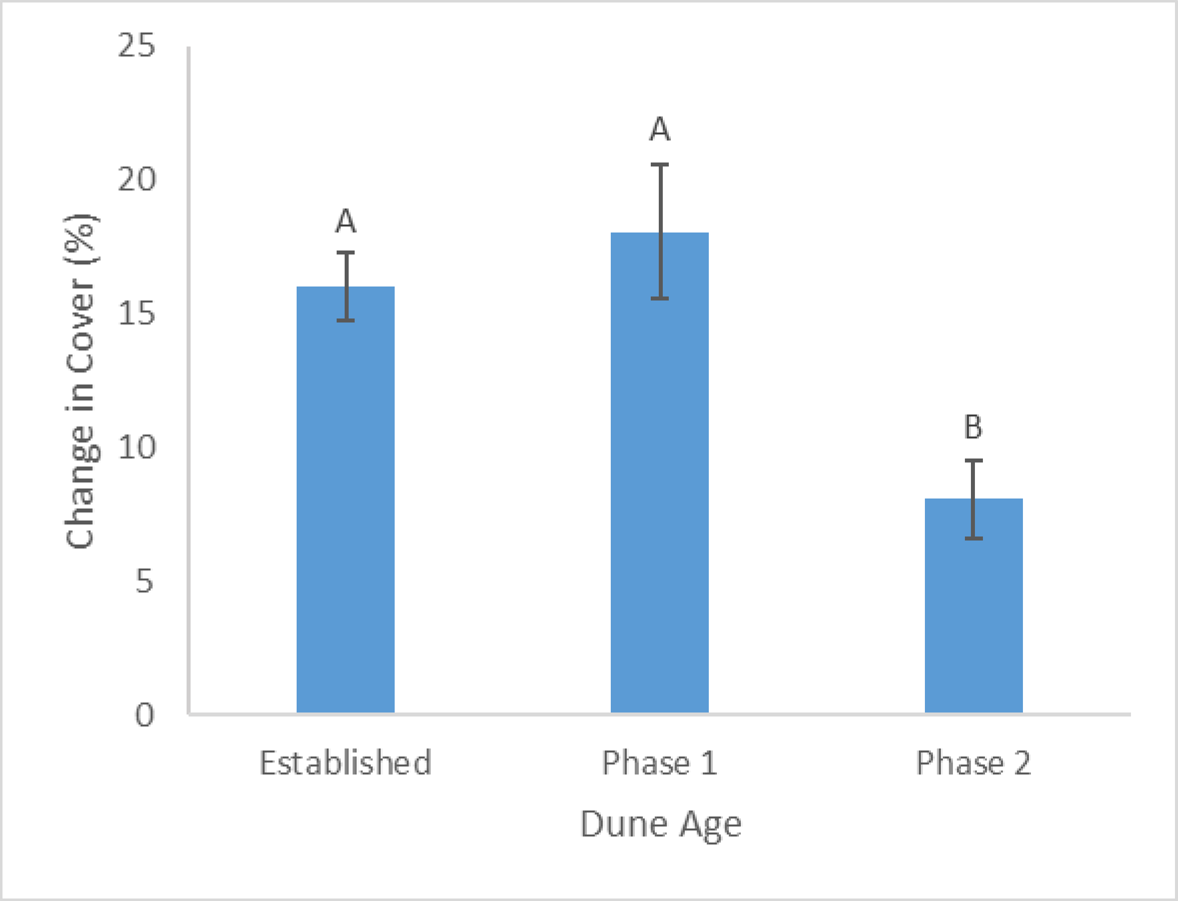

Figure 12: Change in total percent cover +/- standard error of dune vegetation in Plot 1 of all sites in each different dune age, measured from September to March. Bars denoted with different letters are statistically significant from each other.

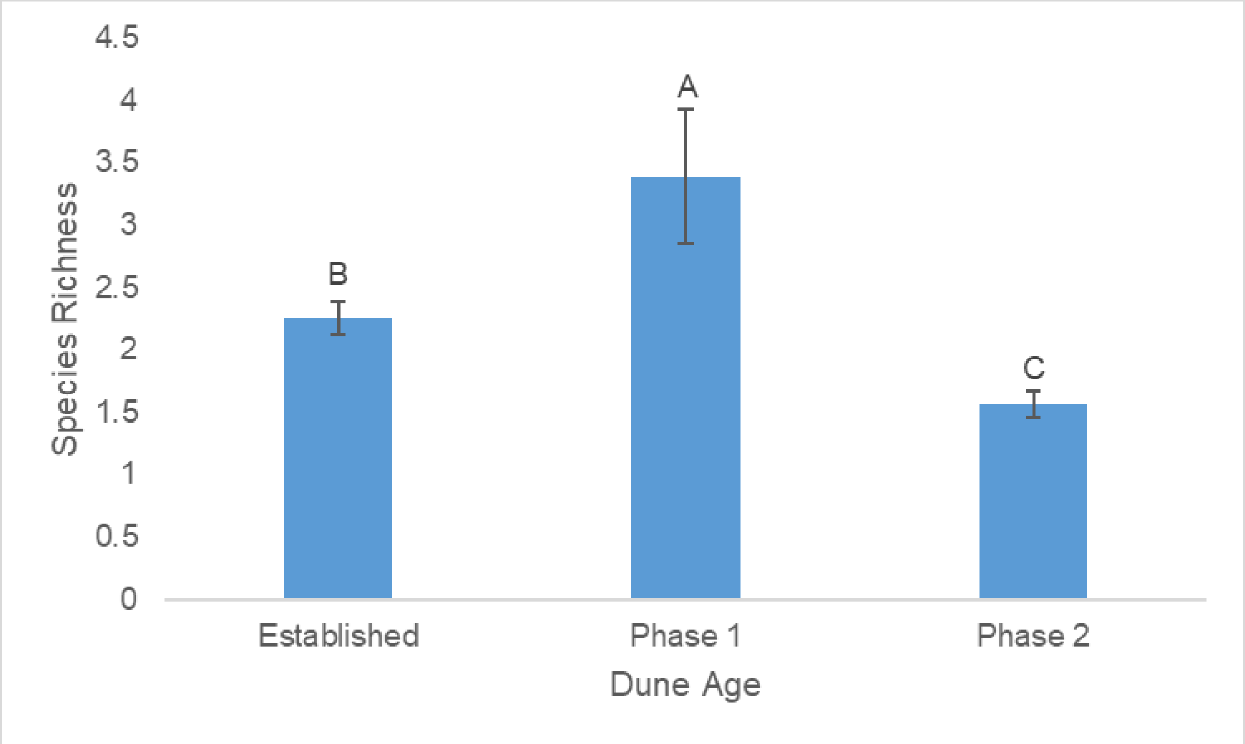

Figure 13. Average total species richness of dune vegetation for all sites in each different dune age, measured from September to March. Bars denoted with different letters are statistically significant from each other.

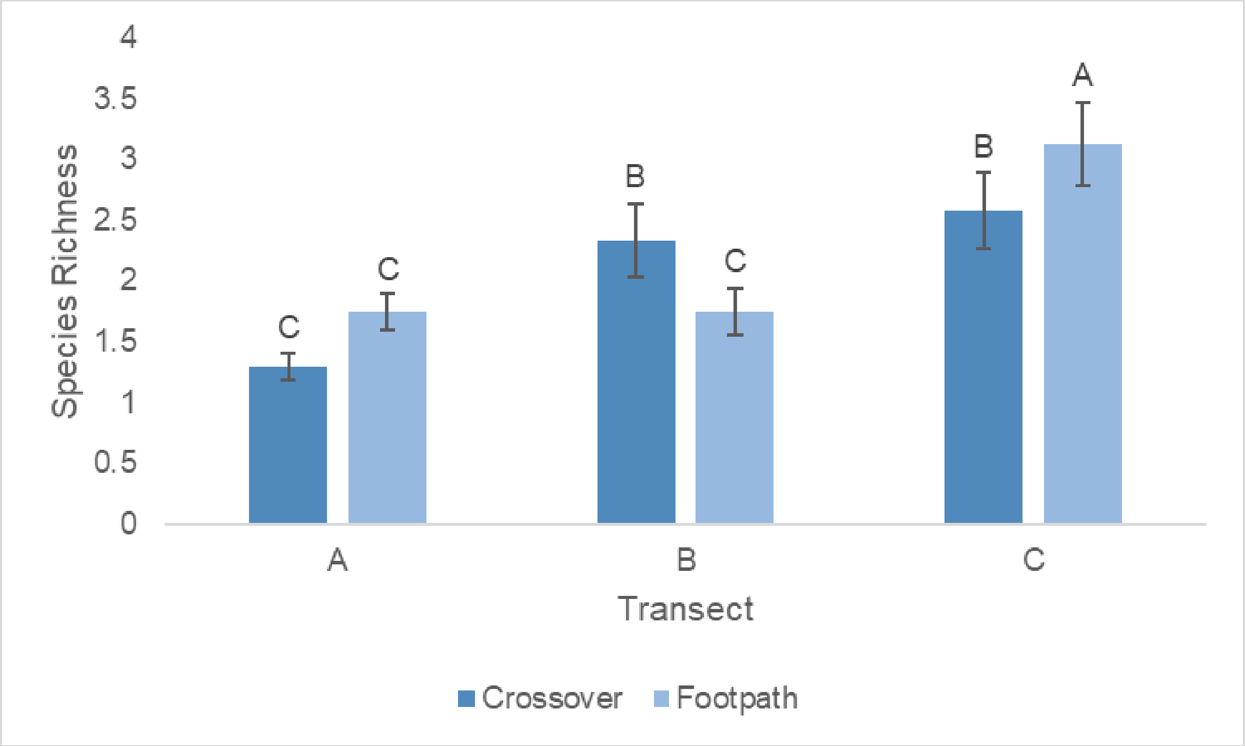

Figure 14. Average total species richness of dune vegetation for all sites at each transect, measured from September to March. Bars denoted with different letters are statistically significant from each other.

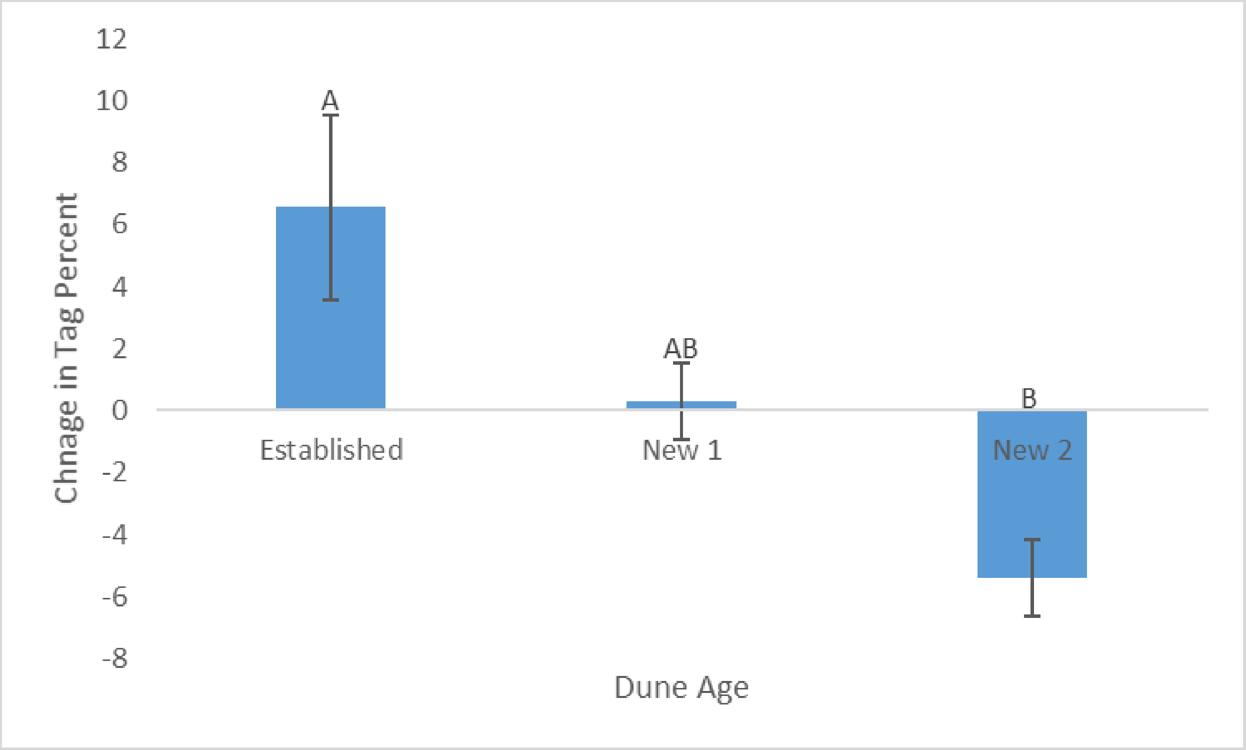

Figure 15. Change in percent cover of tagged plants in each dune age, measured from September to March. Bars denoted with different letters are statistically significant from each other.

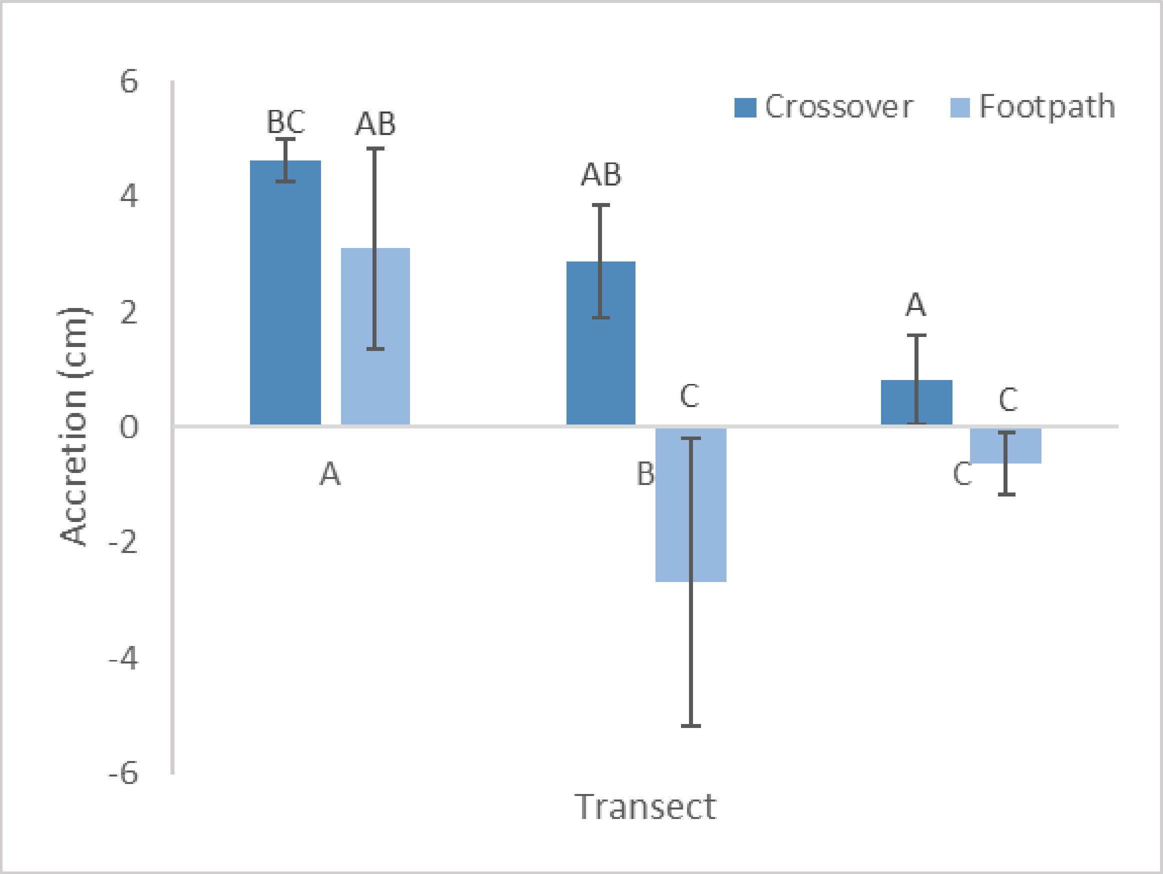

Figure 16: Average sand accumulation of each site type between the three transects, measured from September to March. Bars denoted with different letters are statistically significant from each other.

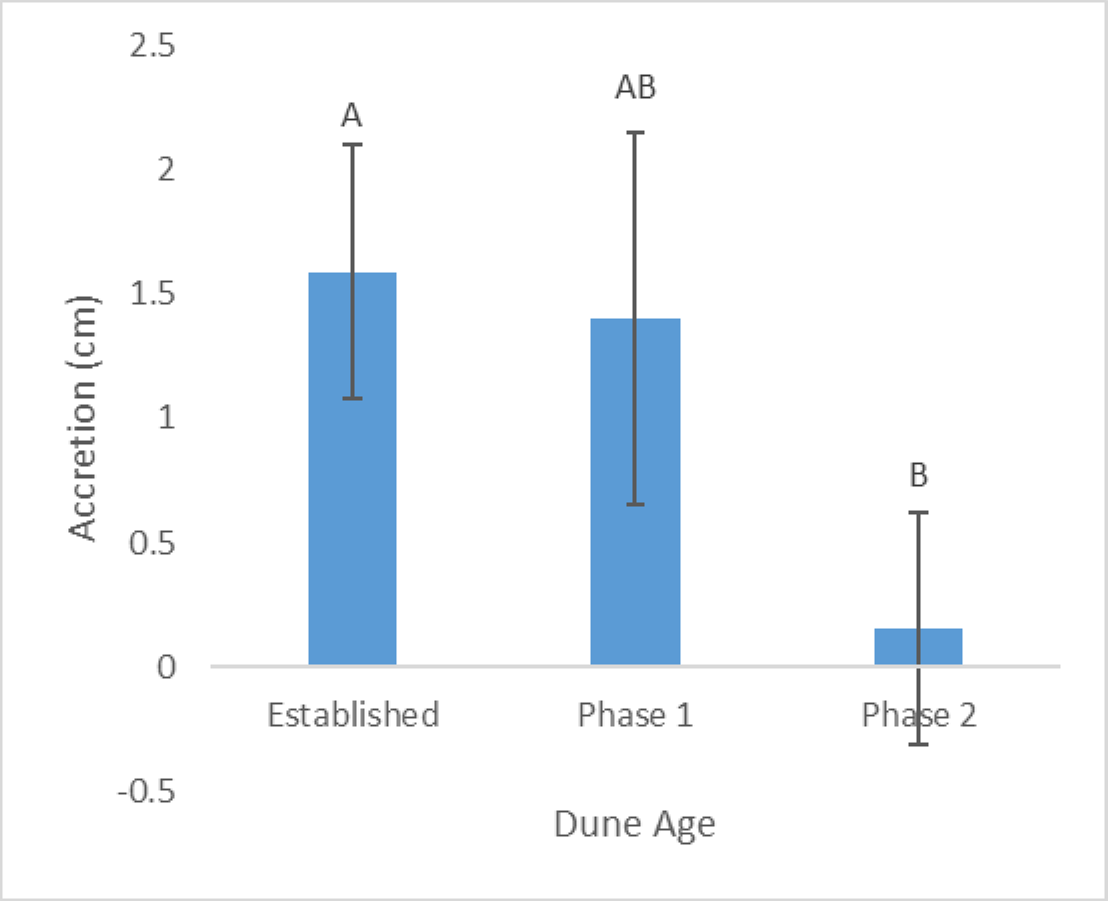

Figure 17: Average sand accumulation of all sites between the three dune ages, measured from September to March. Bars denoted with different letters are statistically significant from each other.

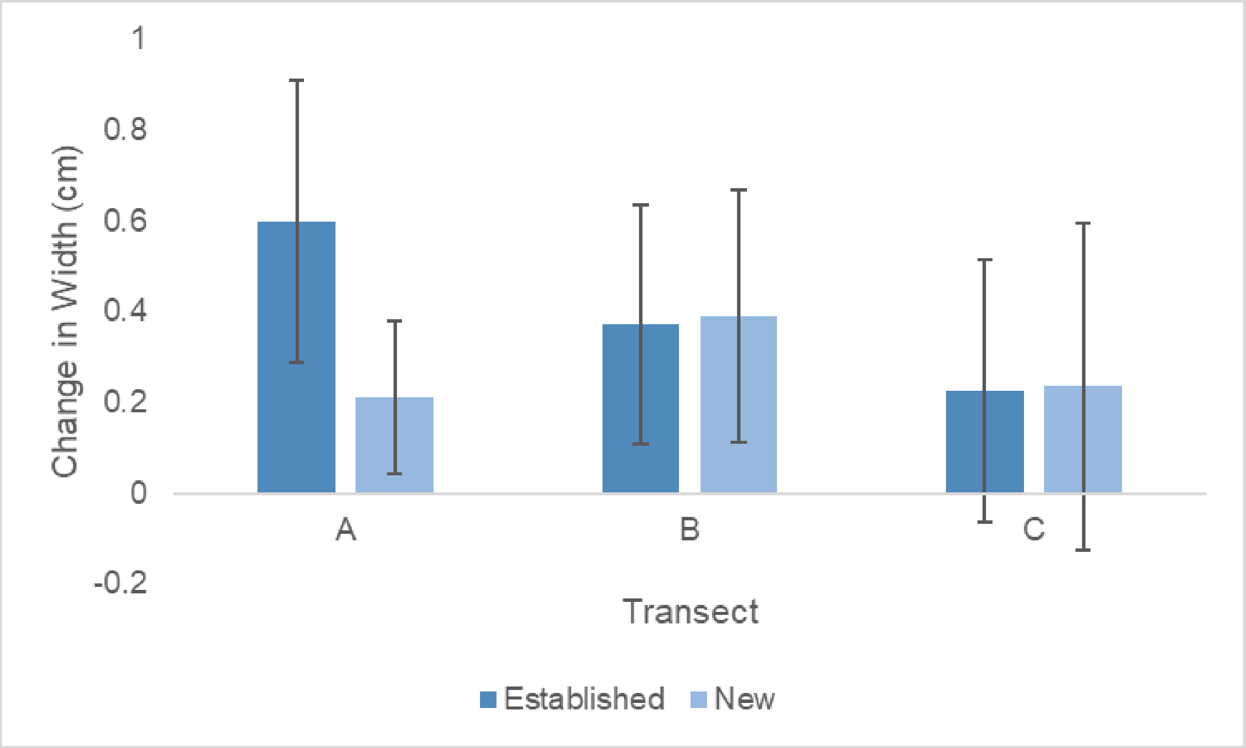

Figure 18. Average change in path width at each transect for in the new versus established footpath, measured from August to March.

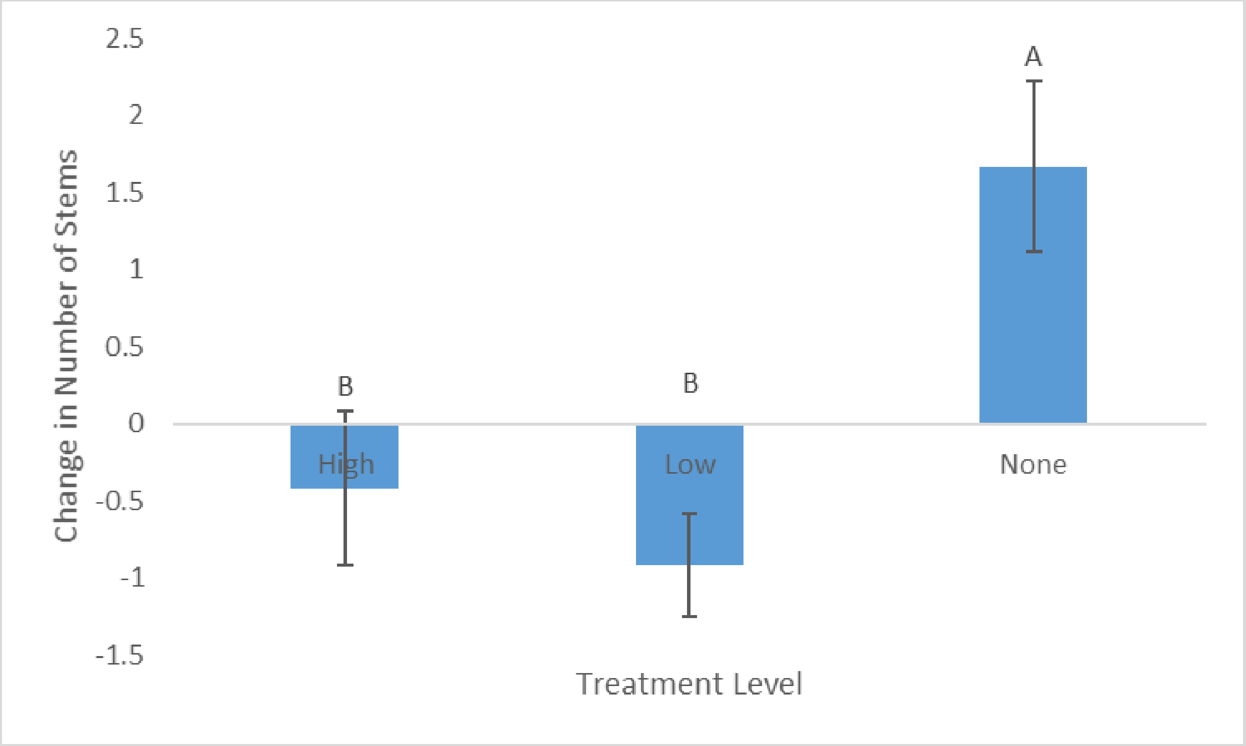

Figure 19. Average change in the number of stems for *Uniola paniculata* at various levels of trampling conducted under controlled conditions in a greenhouse, measured from February 25 to April 3. Bars denoted with different letters are statistically significant from each other.

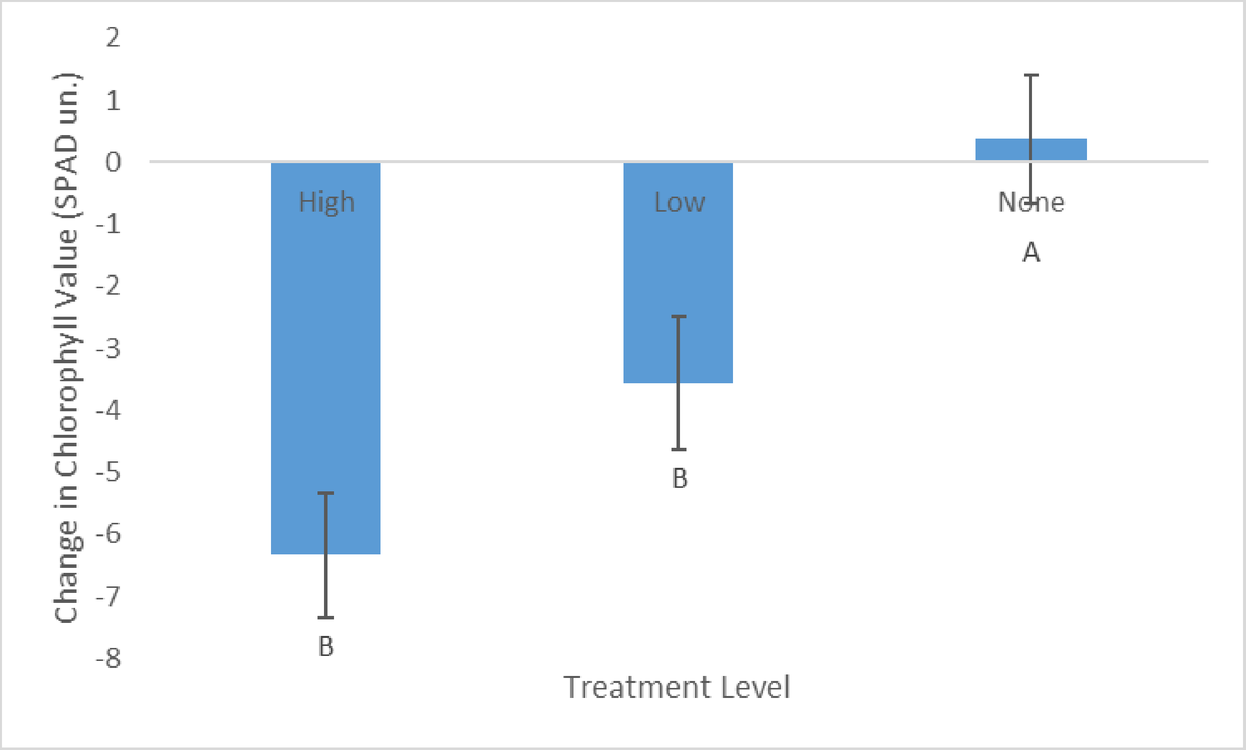

Figure 20. Average change in chlorophyll concentration for *Uniola paniculata* at various levels of trampling conducted under controlled conditions in a greenhouse, measured from February 25 to April 3. Bars denoted with different letters are statistically significant from each other.

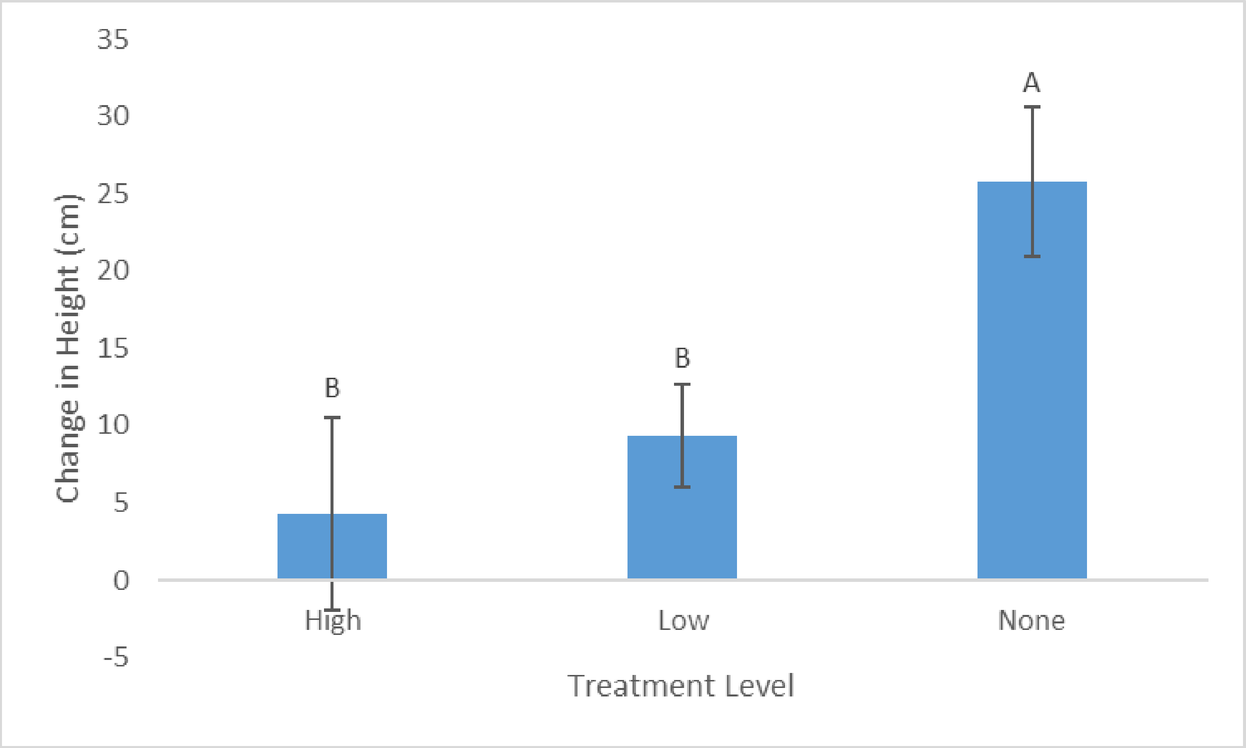

Figure 21. Average change in height for *Uniola paniculata* at various levels of trampling conducted under controlled conditions in a greenhouse, measured February 25 to April 3. Bars denoted with different letters are statistically significant from each other.

Figure 22. Image of Phase 2 dunes following a tropical storm on November 6, 2021, depicting debris and storm that rose to the base of the dunes, destroying *Ipomoeae* vines that had colonized the bare regions by the site 15 crossover.

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