First-Year Research in Earth Sciences: Dunes

The Effects of Two Fall Storms on a Lake Michigan Foredune

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ABSTRACT

Storms contribute to the shape of a beach-dune system but few studies describe specific effects of storms on a foredune environment. We studied changes that autumn storms made to a foredune located in P.J. Hoffmaster State Park on the east coast of Lake Michigan. We used a number of methods including on-site anemometers and a wind vane, erosion pins, GPS, photos, observations, and storm data from the National Weather Service. Two storms were observed during our study period with a week of lower wind speeds between them. The first storm, remnants of Hurricane Sandy, lasted five days with very strong winds and little precipitation. The second storm had more precipitation, was shorter in duration, and had higher maximum wind speeds. During the storms, high waves reduced the wind's access to loose sand on the beach. Nevertheless, there were large amounts of sand transport from the backbeach to the foredune with deposition occurring on the windward slope of the dune. Both storms were responsible for a significant amount of dune change, whereas very little change took place in the week between the storms.

INTRODUCTION

Previous studies suggest that storms are influential in shaping the beach-dune system (Davidson-Arnott *et al.* 2012; Mathew *et al.* 2010; van Dijk 2004). However, not many studies have been conducted on mid-latitude storms and what effects they have on foredunes. Therefore, we studied the effect of storms on the development of a foredune in P.J. Hoffmaster State Park on the east coast of Lake Michigan. Our objectives for our study were to (1) describe what happens during a storm event, (2) compare wind patterns to sand transport, and (3) compare differences in foredune changes during individual storm events.

BACKGROUND

Although there has not been much investigation of storm influences on coastal dunes, a few key studies have demonstrated the importance of storms in shaping dunes (Davidson-Arnott *et al.* 2012; Mathew *et al.* 2010) and other studies have identified the importance of storm-related variables (Bauer *et al.* 2009; Davidson-Arnott *et al.* 2005; Hesp *et al.* 2005). Foredunes are particularly suited to being affected by storm activity because they occupy a coastal position (immediately landward of the beach) that is exposed to coastal winds as well as storm surge and wave influences. Mathew *et al.* (2010) describe how a large storm severely damaged a foredune on the Atlantic coast of Prince Edward Island by overwashing the foredune, eroding vegetation, and redistributing the dune sediments. Storms also have the potential to destroy a foredune system when a storm surge carries the sediments back out to sea (Olivier and Garland 2003). Foredune recovery depends on location, but foredunes can take as much as 70 years to rebuild and become stable again (Mathew *et al.* 2010).

Wind and surface characteristics during storms influence aeolian processes and foredune changes in a variety of ways. A study by Davidson-Arnott *et al.* (2012) suggests that the wind speed and direction had the largest impacts on foredune change during a storm from direct influences on sand transport as well as influences on wave run-up. The higher wind speeds that come with storms, often in wind gusts, causes more sand transport because potential sand transport rates are proportional to the cube of the wind speeds (Davidson-Arnott *et al.* 2005; Davidson-Arnott *et al.* 2012). Vegetation acts as a friction element that slows down the wind and causes deposition to occur (Davidson-Arnott *et al.* 2012). Both precipitation and waves washing over beach sediments increase the surface moisture content, which reduces the potential for sand to be moved by the wind (Bauer *et al.* 2009; Davidson-Arnott *et al.* 2005). Topography also affects sand transport because it shapes the wind speed and direction at ground level, such as causing wind to accelerate over dune crests (Davidson-Arnott *et al.* 2012; Hesp *et al.* 2005).

Wave run-up reduces the fetch distance on the backbeach and can cause scarping on the windward slope of the foredune (Davidson-Arnott *et al.* 2012). Scarping occurs when waves undercut the windward slope of the dune exposing the roots of the vegetation which may be holding the sand in place; scarping can cut the foredune off from saltating grains moving towards the dune's windward slope (Davidson-Arnott *et al.* 2012). Even if wave run-up does not reach the edge of the foredune, it affects sand transport amounts by reducing subaerial beach width and fetch: the distance over which wind interacts with the beach surface. A decreased fetch means a decreased supply of sediments that can be moved by wind to the foredune. Wind direction is an important variable in determining fetch distances, because an oblique wind angle relative to shoreline produces a much longer fetch than a wind that is perpendicular to the shoreline (Bauer *et al.* 2009; Davidson-Arnott *et al.* 2005).

Mid-latitude coastal dunes are influenced by the characteristics of the storms that occur at their locations. For Great Lakes dunes, there are seasonal patterns such as the number of storms increasing during the fall, with the greatest numbers recorded during November and December (Angel and Isard 1998). A previous study of the foredune in Hoffmaster State Park noted that sand transport rates and foredune changes increase during the fall (van Dijk 2004).

STUDY AREA

Our research site was located at P.J. Hoffmaster State Park in Muskegon and Ottawa Counties, Michigan, on the east coast of Lake Michigan (figure 1). We focused mainly on the foredune and backbeach at our site. The foredune was 54 m wide and 2.8m high. It was oriented north-south and roughly parallel to the shoreline. There is a saucer blowout on the dune ridge to the east of our site. Our section of the foredune is in a secluded park area that does not get a lot of visitors. An anemometer tower was already stationed at the site for another study. Several previous studies have been located at the same location including van Dijk (2004) and Koster and van Dijk (2008).

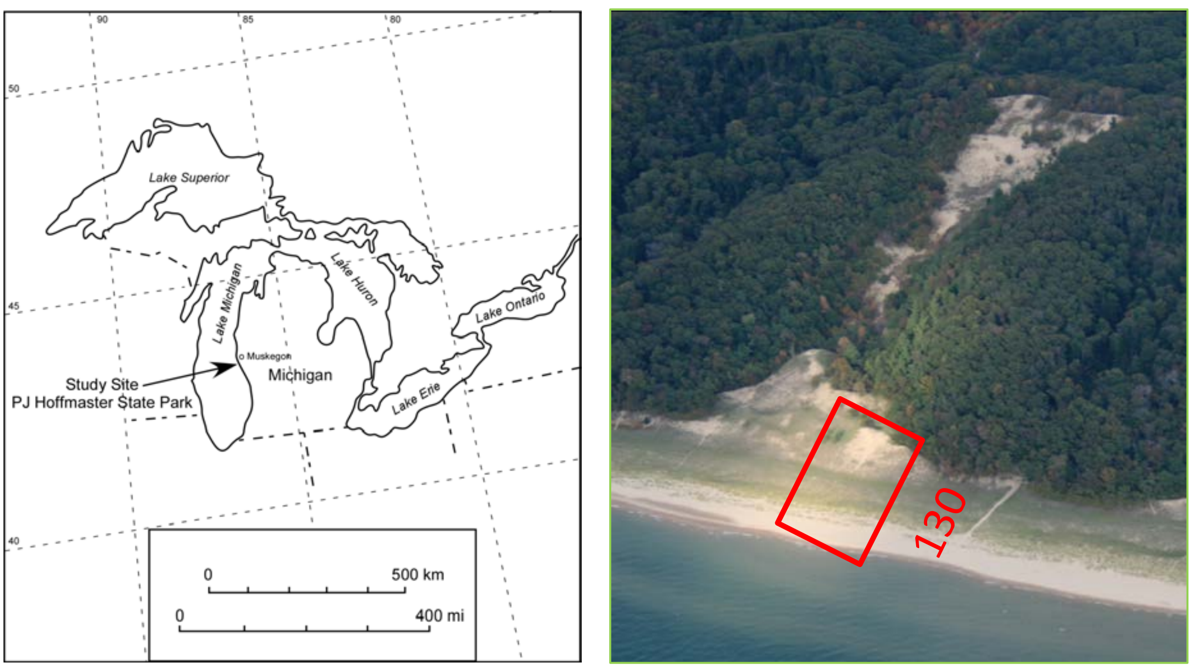

Figure1: The study site is located a) located in P.J. Hoffmaster State Park and b) encompasses a section of beach and foredune near a small blowout.

METHODS

We conducted research over a period of 3 weeks from October 25 to November 14, 2012. A number of methods were implemented in this study such as investigating surface change, investigating wind and storm patterns, and mapping observed surface changes.

We used on-site anemometers to record wind speeds at half hour intervals. We had a total of 4 anemometers set at heights of 0.5 m, 1 m, 2 m, and 4.55 m. We also had a wind vane at 4.55 m. In this study, wind speeds and directions will be reported from the 4.55 m high instruments. We analyzed the wind data to compare the direction of sand transport with erosion and deposition patterns.

To measure sand transport we used erosion pins set up in a grid pattern spaced 5 meters apart to record sediment erosion and deposition (figure 2). The pins were measured once a week. We compared wind patterns and surface changes to look for patterns and relationships.

During our site visit on November 1, 2012, we used a GPS to record locations of our erosion pins at our research site. We also plotted out the location of our anemometer tower and areas of visual erosion or deposition.

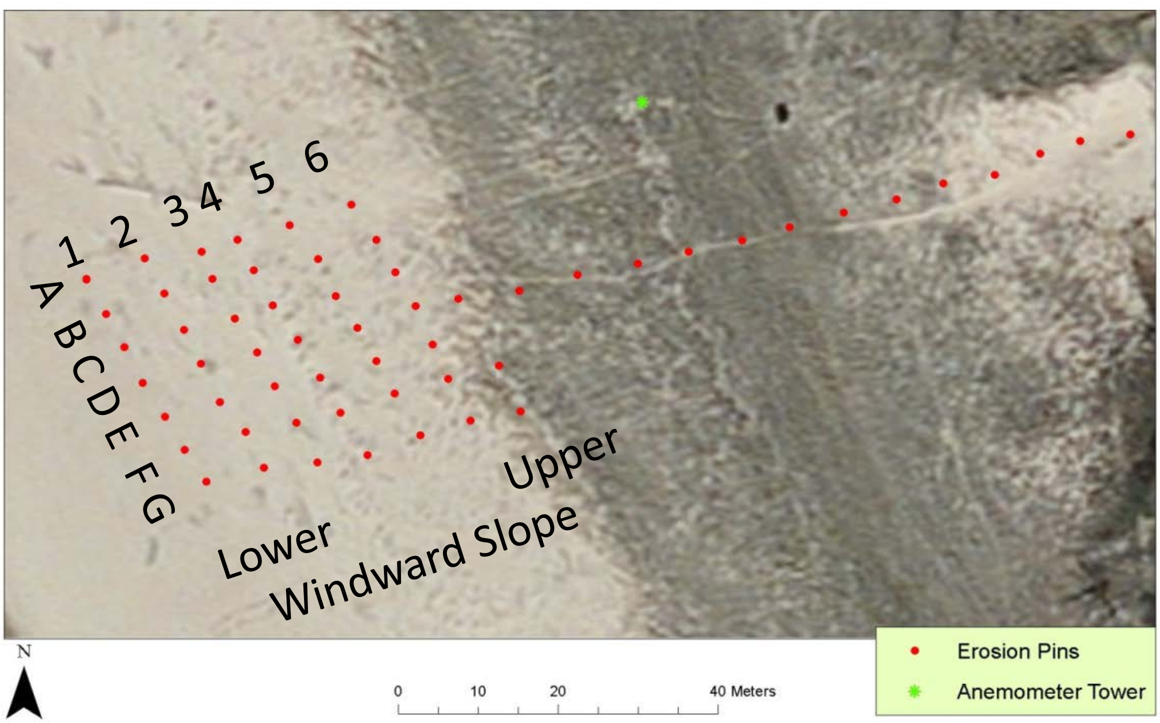

Figure 2: Erosion pin locations and labeling by W-E row number (1-6) and N-S positions (A-G). The background photo predates the study and does not correctly show the present foredune during our study which extended to the edge of the pins.

On each trip to our research site we took photos of areas of visible erosion and deposition. We used these pictures in combination with our erosion pin data to see areas of deposition and erosion. We also used them to study the overall form of the foredune. We also made beach observations such as beach shape, beach size, and unusual beach conditions.

We obtained information gathered from the National Weather Service (2012) to analyze precipitation data and overall storm characteristics for comparison with our wind and sand transport data. The station from which the data was gathered was located in Muskegon, MI about 5 km away from our research site. Storms were identified as having sustained wind speeds greater than 5 m/s. From the data, we identified specific storm traits such as maximum wind speeds, wind direction, and precipitation totals. We compared the storm conditions to the patterns of change measured on the foredune.

RESULTS

Wind Patterns and Storms

During our three-week study period, two storms were observed (figure 3). The first storm was caused by remnants of Hurricane Sandy (Storm 1). After Storm 1 there was a week of relatively calmer wind speeds that we called the Interstorm Period. Finally, towards the end of our study a second storm (Storm 2) passed through Hoffmaster.

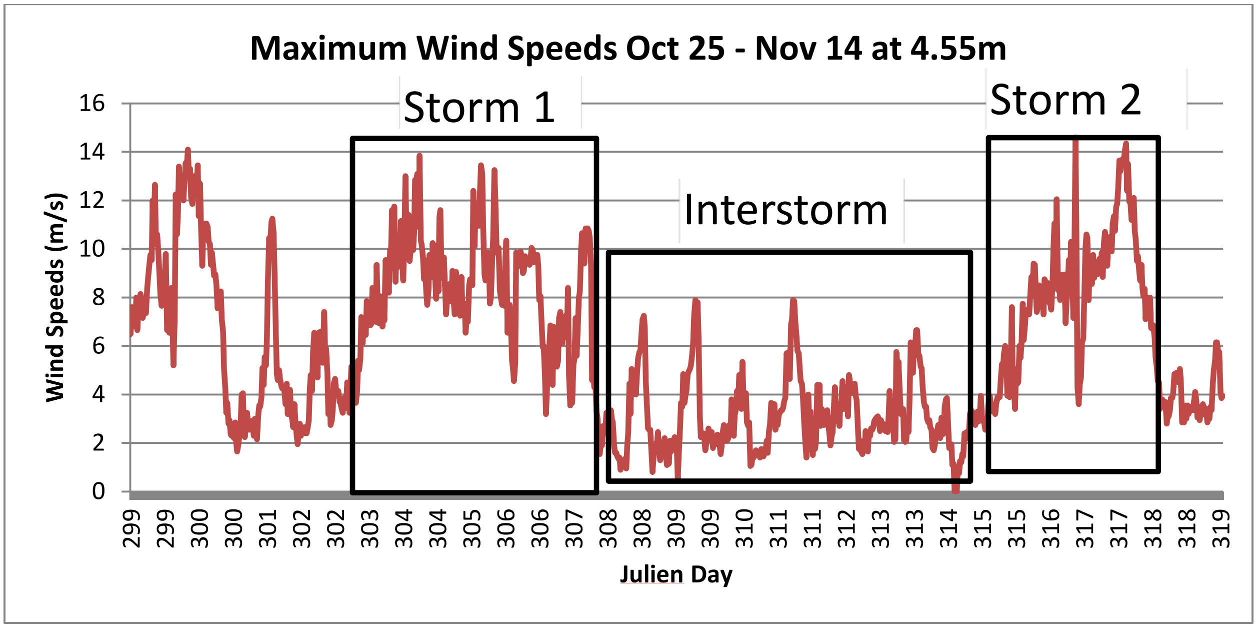

Figure 3: Maximum wind speeds recorded during 30-minute intervals at our research site.

Storm 1 lasted from October 28 until November 2 (5 day duration). Prior to this period, Hurricane Sandy had reached the east coast of the USA where it lost its hurricane status and became "post-tropical cyclone Sandy", although it still had hurricane force winds (Freedman 2013). Sandy then moved to the Midwest where it caused Lake Michigan locations to experience high winds and large wave heights (Milhouse 2012). Our on-site anemometer recorded average wind speeds ranged from 0.73-10.41 m/s during this storm. The maximum-recorded wind speed was 13.85 m/s. Wind directions during Storm 1 were primarily out of the NNW and N directions (figure 4). The highest recorded wind speeds from the NNW. Only 1mm of rain was recorded at Muskegon during Storm 1 (National Weather Service 2012).

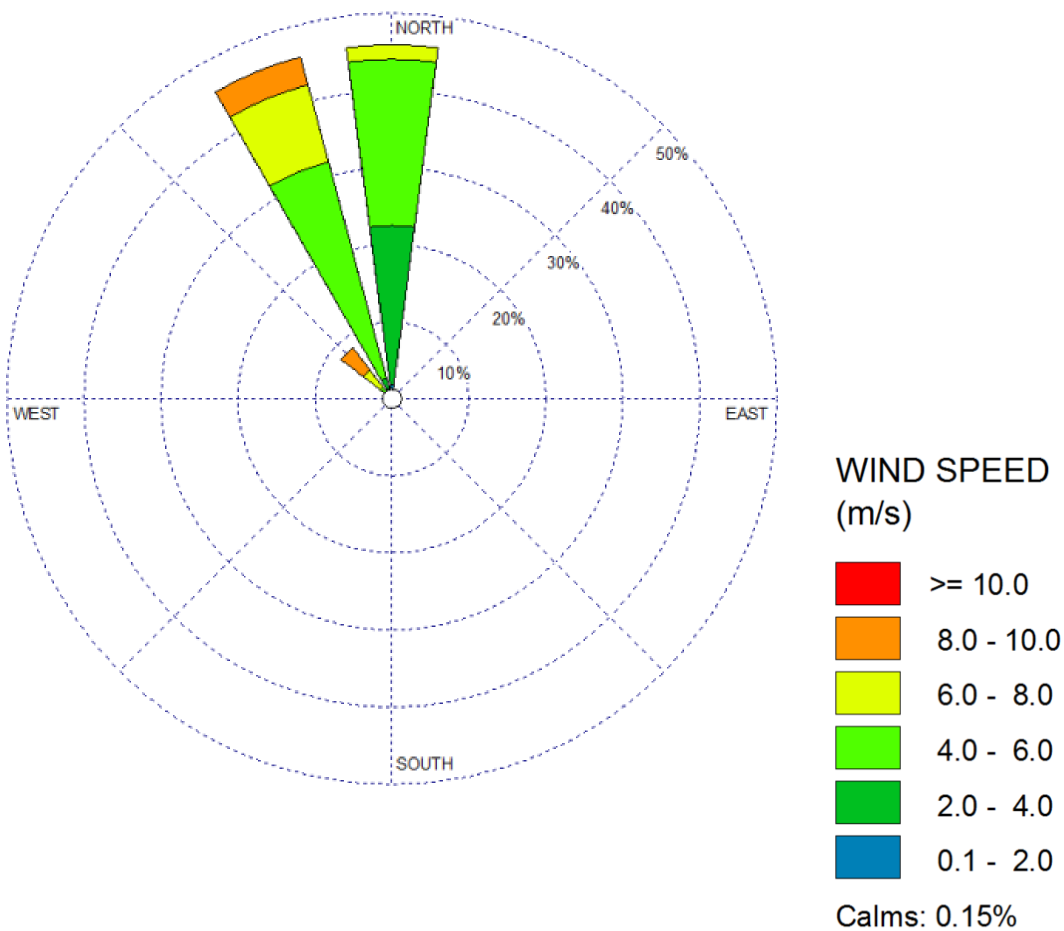

Figure 4: Frequency and direction of average wind speeds at the study site during Storm 1.

Storm 2 occurred on November 10 through 13 (4 day duration). The on-site anemometer recorded average wind speeds ranged from 1.1-11.4 m/s. The maximum-recorded wind speed was 14.6 m/s and it occurred on November 11. The wind during this storm came primarily out of the south. However, at 2:30pm on November 12 the wind direction switched to the west for the remainder of the storm (figure 5). The highest wind speeds were recorded during this part of the storm. During Storm 2, 17 mm of precipitation were recorded in Muskegon by the National Weather Service (2012).

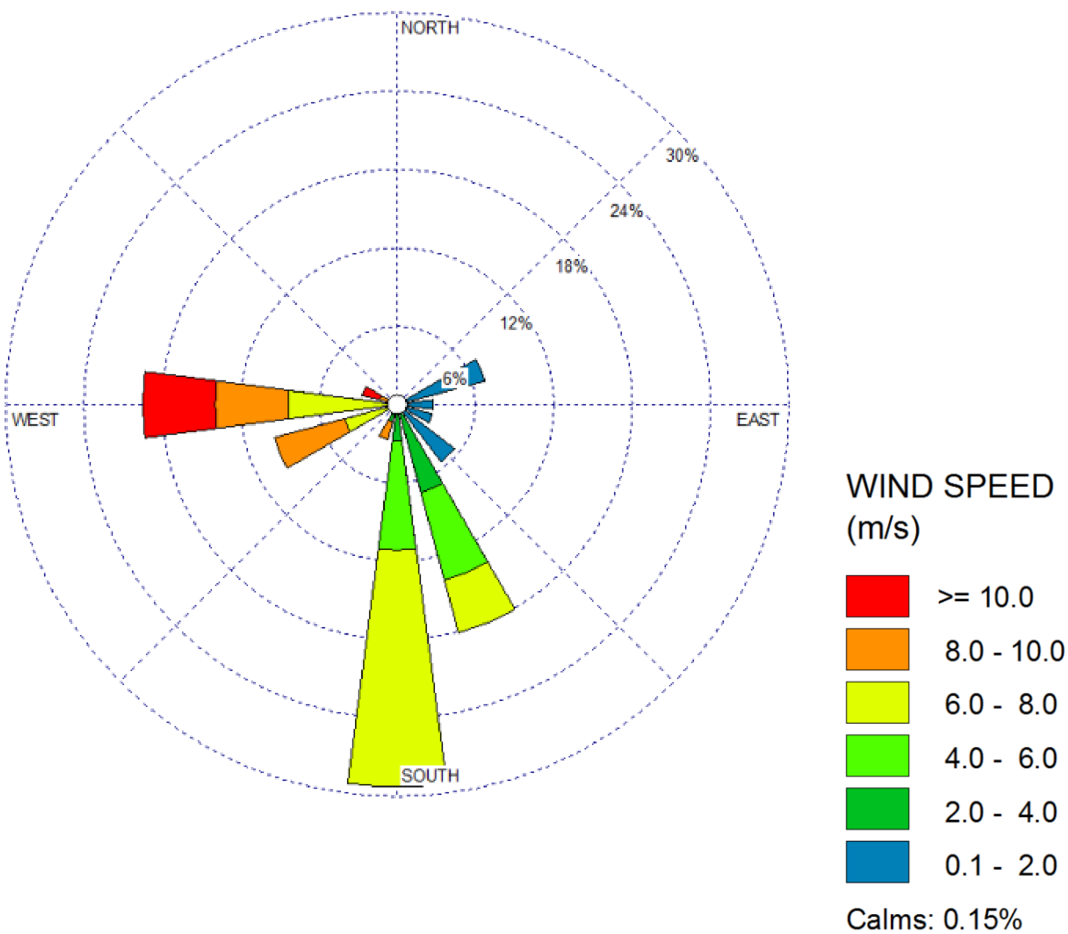

Figure 5: Frequency and directions of average wind speeds at the study site during Storm 2.

The Interstorm Period began on November 3 and ended on November 9. The average wind speeds ranged from 0-6.77 m/s and the wind direction was variable (figure 6). The strongest winds were those that came out of the south, southwest, north, and northwest directions. Scarping was observed on the beach after this period.

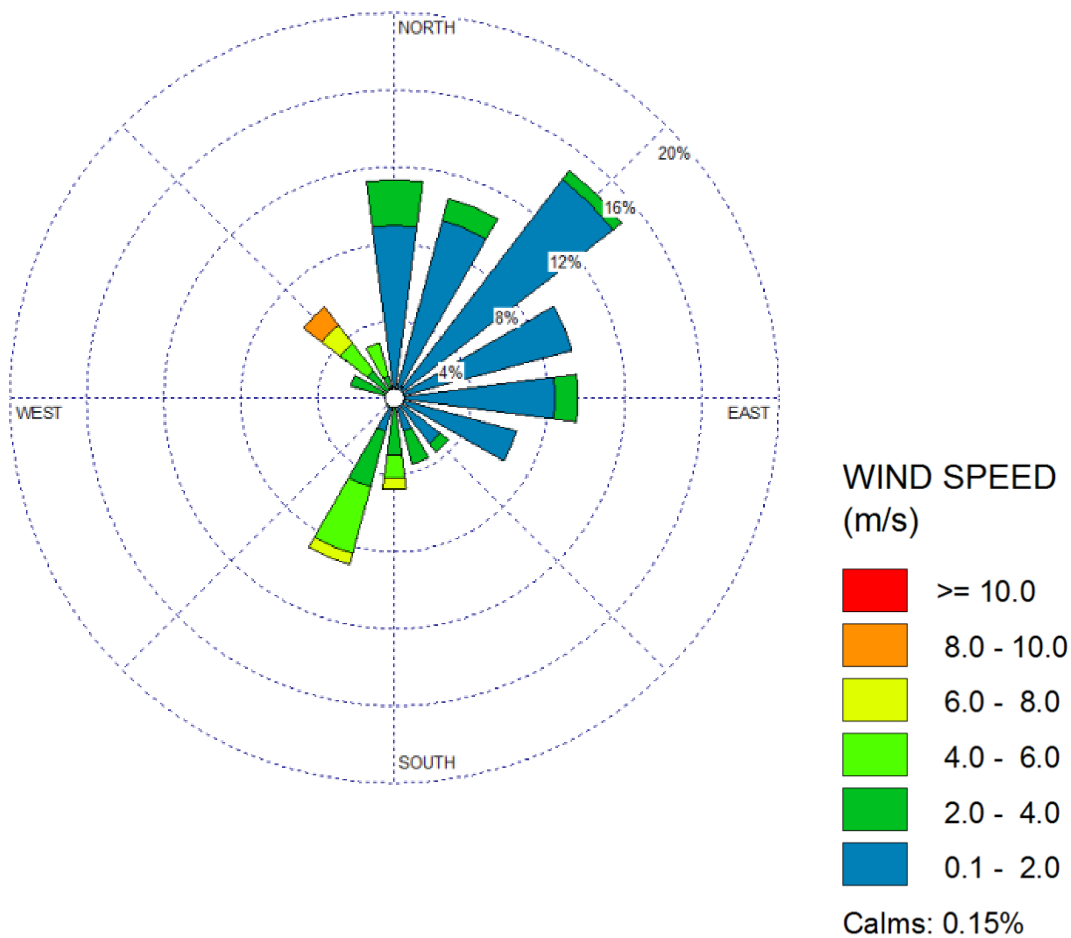

Figure 6: Frequency and direction of average wind speeds during the Interstorm Period.

Comparison of Storms

Storm 1 was a longer-duration storm than Storm 2, lasting for 5 days instead of 4. However, Storm 1 had very little precipitation compared to Storm 2. Storm 2 had higher wind speeds compared to Storm 1. Wind directions were different from Storm 1 (N to NNW) to Storm 2 (S to SSW shifting to W to WSW).

Foredune Changes

Figure 7 displays the erosion and deposition recorded at erosion pins during the first week of the study, which included Storm 1. The average amount of deposition was 3.4 cm and pin G6 recorded the highest amount of deposition at 8 cm. Spatially, erosion and deposition occurs in a patchy pattern across the study area, with the majority of deposition occurring on the middle windward slope.

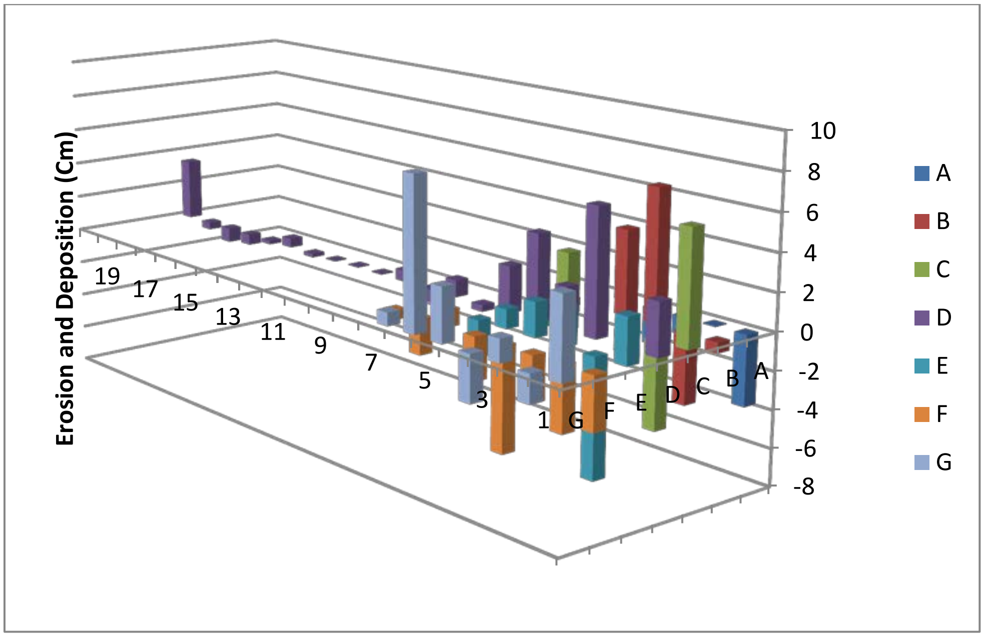

Figure 7: The erosion and deposition that occurred during the first week of our study (October 25 – November 1). The horizontal and depth axis display the pin identification number and letter.

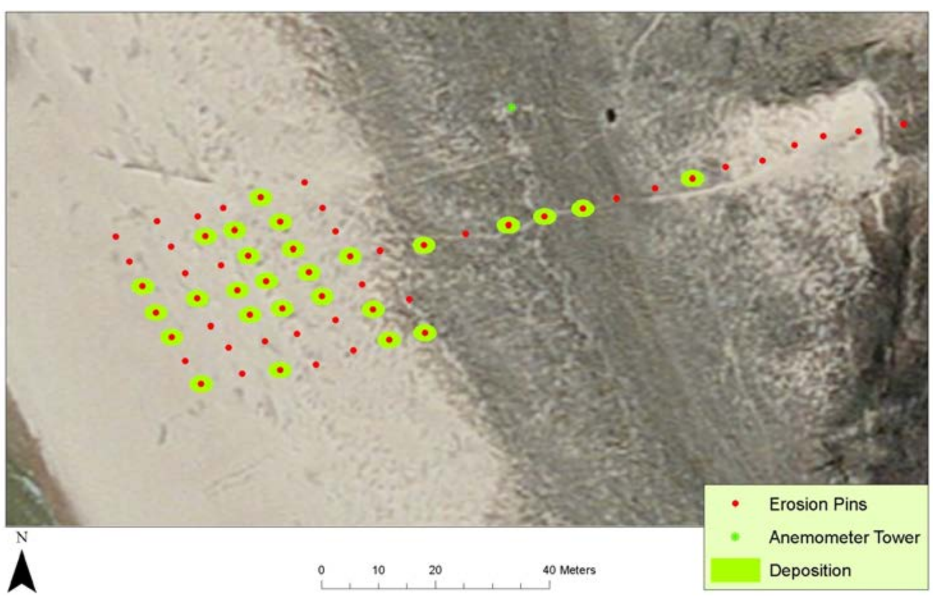

Figure 8: Spatial distribution of deposition recorded from October 25 - November 1.

During the Interstorm Period, small but significant amounts of deposition were recorded at the foredune erosion pins. The largest amount of deposition was recorded at pin B3 with a total of 3.4 cm (figure 9); average deposition was 1.5 cm. Spatially, deposition occurred over most of the windward slope of the foredune (figure 10).

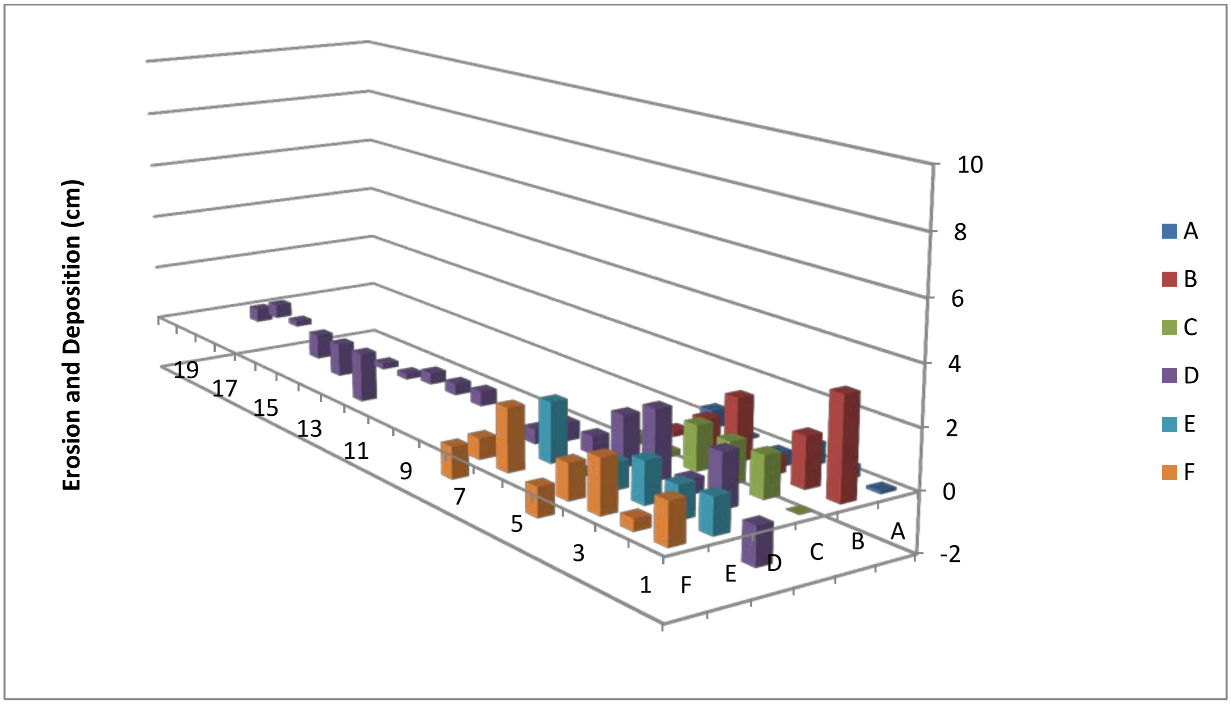

Figure 9: The erosion and deposition that occurred during the second week of our study (November 2-8). The horizontal and depth axis displays the pin identification number and letter.

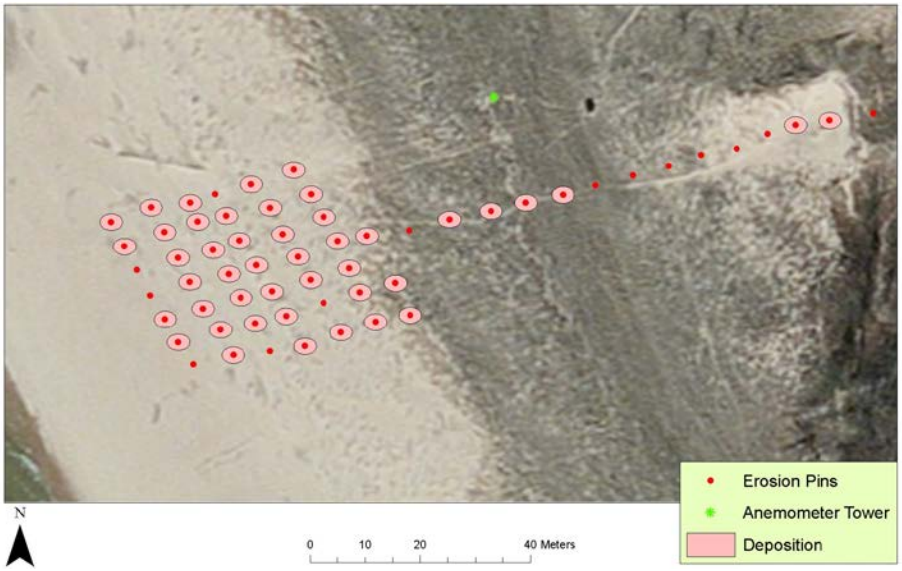

Figure10: Spatial distribution of deposition recorded from November 2-8.

During the third week of the study, which included Storm 2, a maximum of 9.6 cm deposition was recorded at pin D5 (figure 11). Spatially, erosion took place on the lower and middle windward slope as well as the backbeach (figure 12), with patches of deposition occurring in areas with patchy vegetation (figure 13). Deposition occurred in the upper windward slope around erosion pins in rows 5 and 6 (figure 12).

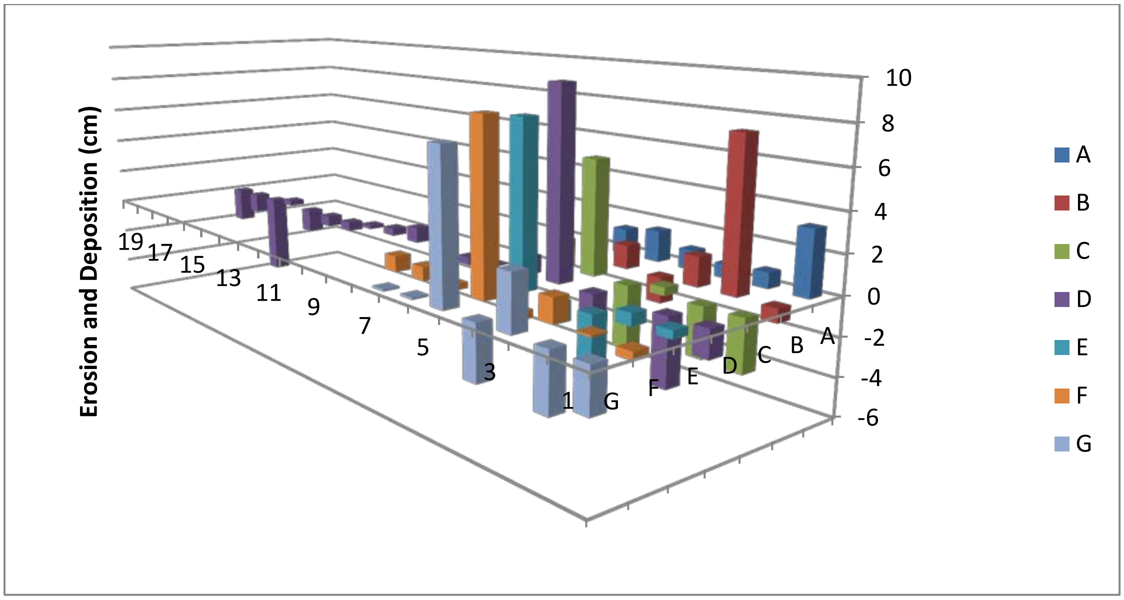

Figure 11: The erosion and deposition that occurred during the third week of our study (November 8-14). The horizontal and depth axis display the pin identification number and letter.

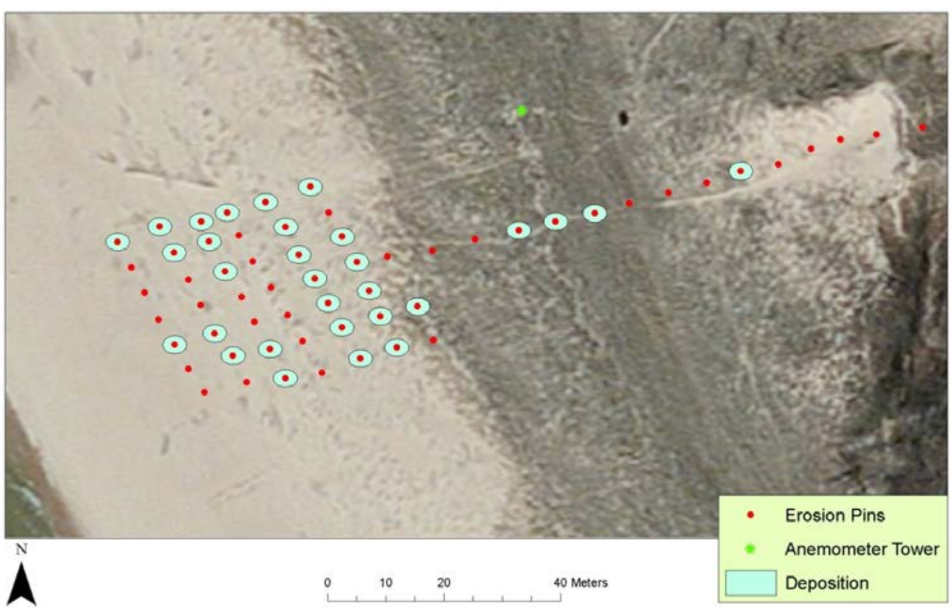

Figure 12: Spatial patterns of deposition during week three (November 8-14).

Figure 13: Deposition in the form of a shadow dune downwind from vegetation.

Cumulative surface change results (figure 14) from October 25 to November 14 reveal that the majority of deposition occurred on the upper windward slope, whereas the majority of erosion occurred on the low and mid windward slopes. The maximum amount of deposition was 15.8 cm at pin D5.

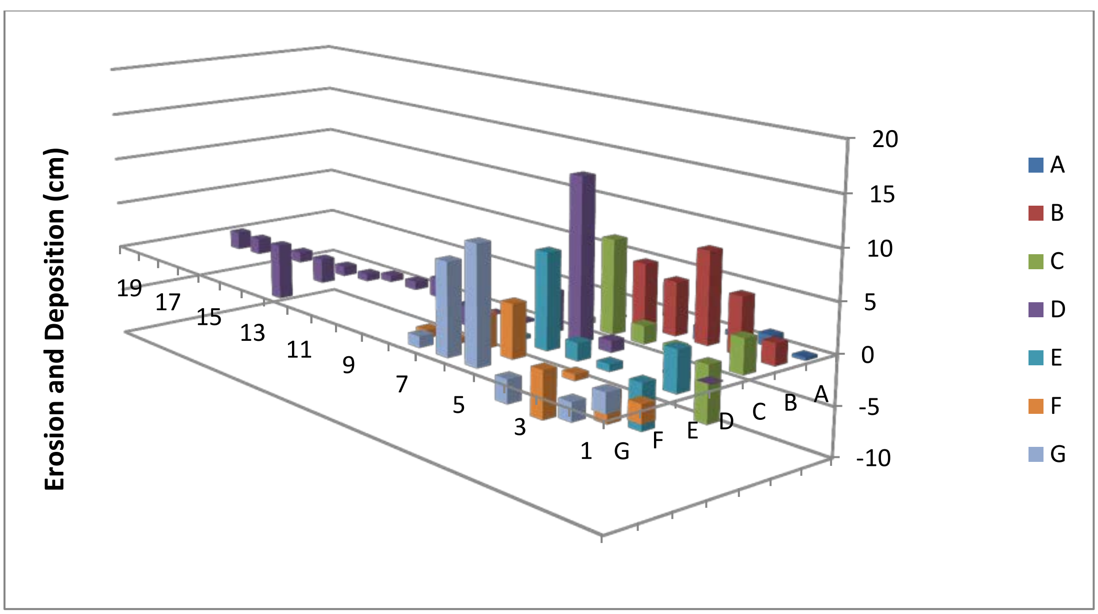

Figure 14: Cumulative (3-week) surface changes at erosion pins from October 25 to November 14, 2012.

Changing Vegetation and Beach Conditions

Vegetation on the foredune was almost entirely *Ammophila breviligulata* (American beach grass) occurring in different densities by dune location and time of study. The grasses were concentrated in higher densities on the upper windward slope of the foredune throughout the study. During the first two weeks of the study, we observed considerable amounts of vegetation (in patches) on the lower and middle windward slopes of the foredune. During the third week of the study, we observed less vegetation in these areas because of sand deposition.

Beach width varied during the study because of changing wave conditions. Maximum beach width was approximately 25 meters measured at the beginning of the study. On November 1, we observed wave run-up reducing the beach width to 20 meters on day 4 of Storm 1 (figure 15). We saw wrack lines as evidence that wave run-up had been further up the beach than pictured here. We also observed evidence of wave run-up occurring during Storm 2.

Figure 15: Wave run-up reaching the 4th pin in a line of 5; pins are spaced 5 meters apart.

DISCUSSION

Throughout the study period, the locations of sand movement and deposition progressed up the windward slope of the foredune (figure 16). This progression of sand movement likely occurred because the vegetation on the lower and middle windward slope was progressively buried during Storm 1 and the Interstorm Period.

During Storm 1, sand was likely eroded from the backbeach and lower windward slope of the foredune, and moved southeastward (under the influence of N-NNW winds). During this time the vegetation on the lower and middle windward slope was still present and able to locally decrease wind speeds. Therefore, sand was deposited on the lower and middle windward slopes.

During the Interstorm Period, some winds did exceed the threshold for sand movement (approximately 5 m/s for the sand sizes in the study area), but these winds were not sustained for long periods of time. Small amounts of foredune deposition during this period are evidence of the occasional occurrence of sand moving winds. Most likely the wind eroded sand from the backbeach and deposited it on the lower and middle foredune slope.

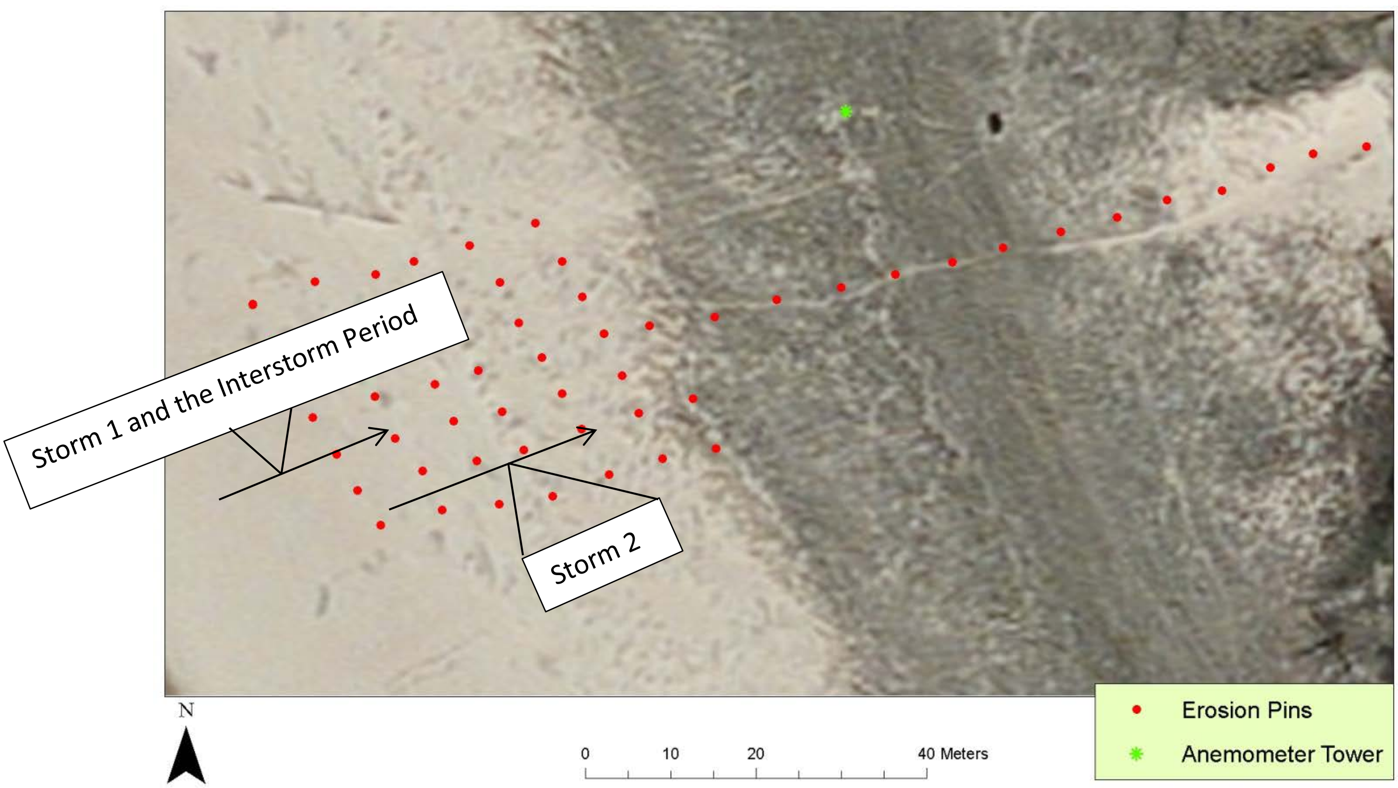

Figure 16: The progression of sand movement/deposition areas throughout the study period.

During Storm 2, sand was eroded off the lower and middle windward slopes and deposited onto the upper windward slope. The stronger west winds at the end of the storm would have been more effective than the earlier winds from the south which may have caused sand to move along the beach and bypass the foredune. The dense vegetation on the upper windward slope would have effectively trapped wind-blown sand.

Sand movement was also influenced by wave run-up during the storms. Wave run-up has the potential to cut off the sand supply to the foredune if waves cover the entire subaerial beach. Waves covering part of the beach reduce the sediment supply area for transport by wind. Wind directions during both storms would interact with supply decreases in different ways (figure 17). During Storm 1, the winds the NW would provide a longer fetch distance for sand entrainment by wind than if the winds were directly from the west. The pattern becomes more complicated during Storm 2, in which the winds were from the SW and the W. The winds from the SW had a longer distance for wind to pick up sand, but the winds from the W were stronger and had the potential to move more sand even over the shorter distance.

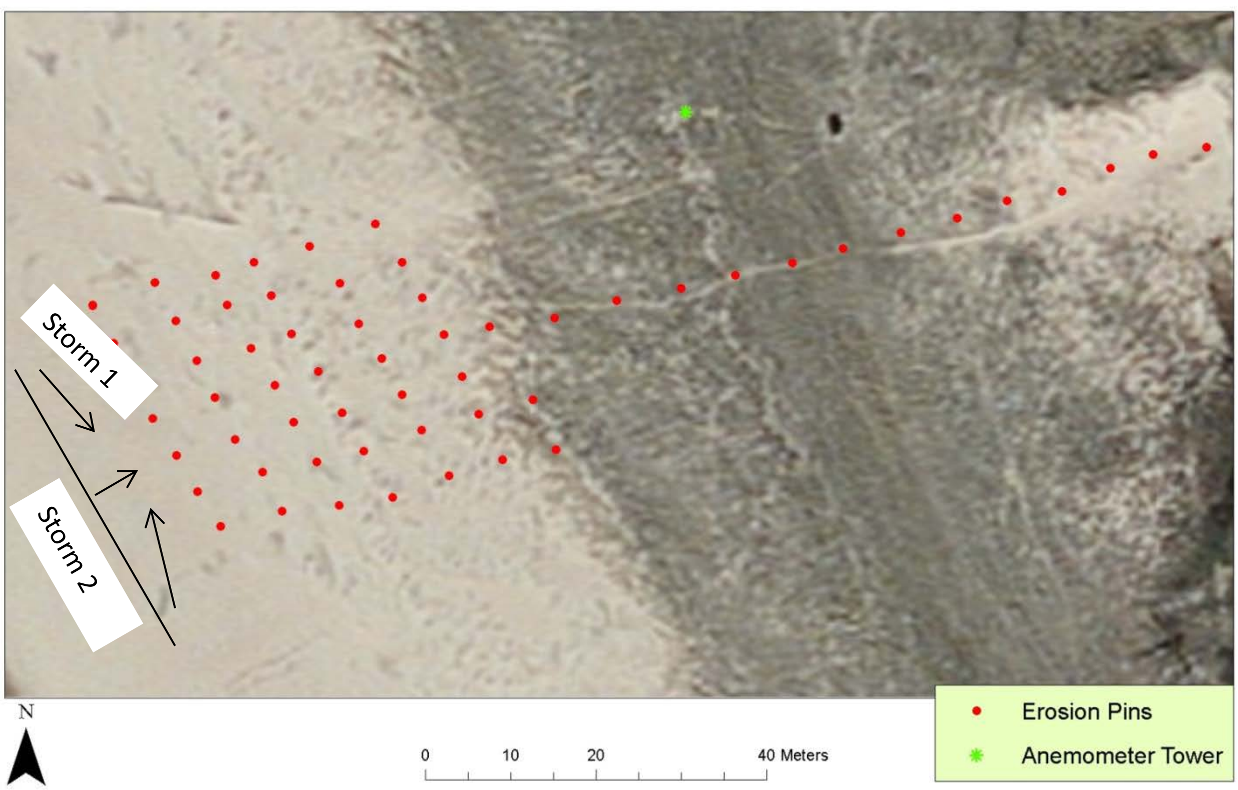

Figure 17: Wind directions observed during both storms; the solid line represents the potential decrease in subaerial beach area and fetch distance because of wave run-up.

CONCLUSIONS

During the 3-week study in autumn 2012, significant erosion and deposition took place on the foredune culminating in maximum foredune surface change of 15.8cm of deposition in the center of our study area on the upper windward slope. The majority of sand transport took place during the two storms, despite reductions in sand supply because of wave run-up. Finally, the patterns of foredune change were influenced by the topography and influence of roughness elements, such as vegetation. Storm characteristics, including high winds, limited precipitation, and wind directions that moved sand from beach to foredune also had large influences on foredune changes.

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