First-Year Research in Earth Sciences: Dunes

Measurement of Alongshore Dune Sediment Budgets and Movement

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Abstract

Studies investigating the relationship of dune interactions with beach sediment budgets along Lake Michigan have been sparse. This study examines the characteristics and sediment exchanges of the foredune-beach system at three locations along the east Lake Michigan coast: Rosy Mound Natural Area, P.J. Hoffmaster State Park, and Muskegon State Park. In Nov-Dec 2017, roughly 800 meters of beach in each location were mapped using GPS units; mapped features included the shoreline and beach-foredune boundary. The beach-foredune boundary was delineated into stretches of no, low, medium, and high scarp, and mapped as such. Measurements taken at each beach-foredune section included beach width, scarp height, and scarp slope angle. Results showed that Rosy Mound Natural Area primarily had high scarps, while the two other parks showed a distinct mix of scarp heights. This, along with other measurements, suggests that Rosy Mound is experiencing more dune erosion than the other two study locations, where several cases of wave deposition of sediments onto the foredune were identified. While results varied throughout the three locations, overall more sand was being contributed to the beach from the foredune than the converse.

Introduction

A full understanding of Lake Michigan dune systems requires insight into the sediment exchanges between the dunes and the beach. Here, the concept of sediment budgets is helpful—where net gains and losses of sediment are identified, as well as directions of movement. However, such studies have been sparse, particularly with respect to the foredune-beach system along Lake Michigan. In this research we investigate the characteristics and trends of the interactions between the foredune and beach, using the framework of sediment budgets. This study has four primary objectives:

- To map the foredune-beach boundary and the shoreline,
- To measure characteristics of the foredune-beach system,
- To observe amounts of erosion or deposition on the foredune, and
- To categorize the observed types of foredune-beach boundaries.

Background

Foredune-Beach Relationships

Dunes, and specifically foredunes, have been shown in past studies to have a distinct relationship with beaches. Foredunes, here defined as the shore-parallel dune ridges immediately adjacent to the beach (van Dijk 2004), are significant elements of the coastal system. They provide protection for backshore regions and act as a buffer against coastal processes, preserving the health of the dune system as a whole (Ruz *et al.* 2009). Beach sediment constitutes a sediment supply to foredunes, and it is also the origin of dune systems as a whole (Davidson-Arnott and Law 1996). While the interactions of beach sediment and foredunes have been well studied in other dune systems (van der Wal 2004; Anthony *et al.* 2006; Ruz *et al.* 2009), the dunes of Lake Michigan have had very little research into that relationship.

Foredune-Beach Sediment Budgets

Past studies suggested that foredune-beach interactions are most heavily influenced by the availability of sand, wind conditions, beach morphology, vegetation cover, and storms (Anthony *et al.* 2006). All of the aforementioned features are variable, making predictions of sediment budgets for these features complicated and requiring *in situ* regular monitoring of study sites. Past studies have utilized photographs, field studies, and even some levels of remote sensing to interpret foredune-beach sediment budgets (Davidson-Arnott and Law 1996; Saye *et al.* 2005; Anthony *et al.* 2006).

Sediment budgets for the foredune-beach boundary can be expressed in two primary directions. First, the beach can transfer sediment to the foredune, such as by waves or wind moving sediment onto the foredune where it is caught by the vegetation and builds up the dune (Darke *et al.* 2016). The reverse can also be seen, in the form of erosion of the foredune by waves and other sources, in which the foredune transfers sediment to the beach (Davidson-Arnott and Law 1996).

The most relevant factors impacting the sediment budget of the foredune-beach system for this study are wave and wind influences. Wave energy has been shown to have a significant impact on the beach and foredune (Short 1988). Foredune stability has a tendency to decrease and foredune height to increase with increased wave energy, leading to a sediment budget that tends to deposit sediment back into the water body rather than onto the dune. While the reverse is

not precisely true for areas of low wave energy, the erosive aspects of wave impacts are significantly lessened (Short 1988). Aeolian transport is deeply significant in the foredune-building process as sediment is transferred from the beach to the foredune and is caught in vegetation (Psuty 2005). However, this process does require a sufficiently large beach surface and sufficiently strong winds for transport to occur from the beach to the foredune; either beach size or wind strength may limit its occurrence in some regions (Psuty 2005).

Study Areas

This research was conducted at three sites along the eastern coast of Lake Michigan: Rosy Mound Natural Area (an Ottawa County park), P.J. Hoffmaster State Park, and Muskegon State Park (Figure 1). At each of these three locations, approximately 800 meters along the shoreline was selected for study. This included almost the entire shoreline of Rosy Mound Natural Area. All three parks have extensive dune systems—including foredunes, blowouts, large parabolic dunes, and wooded dunes—bordered to the west by Lake Michigan.

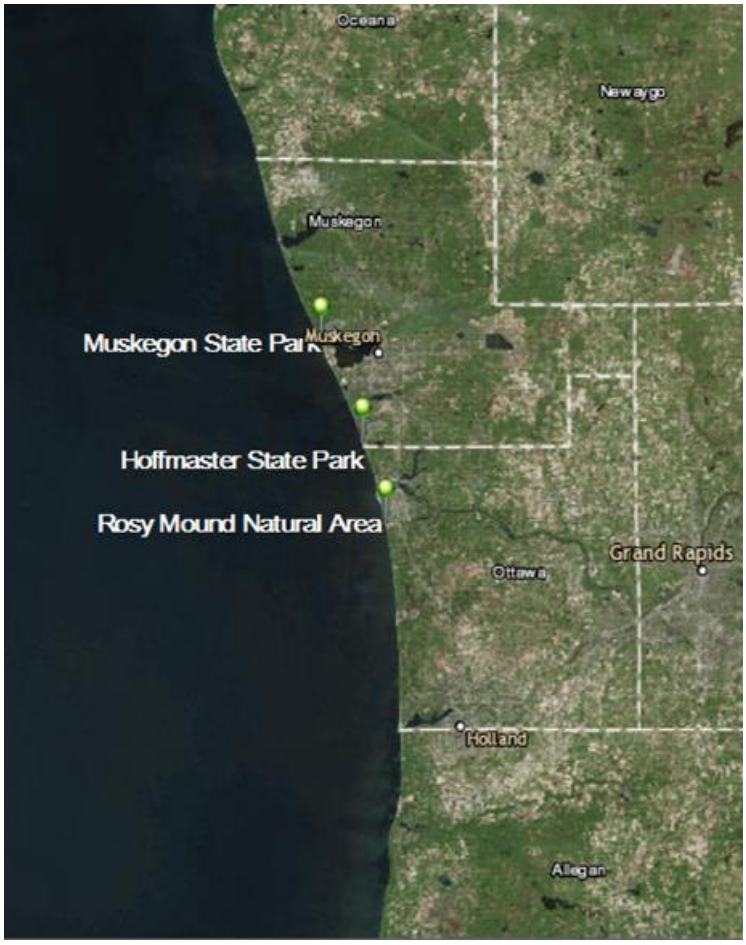


Figure 1. Study area locations in the regional context.

Methods

Field Data Collection

Field data were collected during late October and early November 2017. At each study location, we mapped the foredune-beach boundary as a line feature using GPS Trimble units. The GPS units were used to measure the length of the line to constrain the study area to approximately 800 meters. We also mapped the shoreline, which was defined as the highest visible extent of the water at the particular time measurements were being taken.

In the field, scarp heights along the foredune-beach boundary were delineated into sections according to the categories of no scarp, low scarp, medium scarp, and high scarp (Table 1 and Figure 2). After identifying the ends of each scarp section, a random point was selected from each section for additional measurements which were taken to be characteristic of the section as a whole. The measurements included beach width (from foredune-beach boundary to shoreline) measured with a tape measure and scarp height (from bottom to top of scarp) measured with a stadia rod. Scarp slope angle was measured with an abney level set on a clipboard held against the slope to provide a base that was not affected by small surface irregularities.

Category	Scarp Height Range	Comments
No Scarp	0 m	Beach-dune boundary shows no visible scarp.
Low Scarp	0-0.8 m	Scarp is visible but does not rise above 0.8 m.
Medium Scarp	0.8-1.4 m	Intermediate category between low and high scarp.
High Scarp	>1.4 m	Scarp exceeds 1.4 m in height.

Table 1. Scarp classification

Figure 2. Examples of scarp categories include no scarp (P.J. Hoffmaster State Park), low scarp (P.J. Hoffmaster State Park), medium scarp (Muskegon State Park), and high scarp (Muskegon State Park).

At all three study locations, two reference points were also established and mapped. These reference points were permanent features, such as trees, signposts, or in one case a research station, at which all the above measurements were taken, as well as the distance from the reference point to the scarp edge. The intent for these reference points was to provide comparison points so that in future years researchers will be able to return and take measurements to establish any changes in these locations. In PJ Hoffmaster State Park and Rosy Mound Natural Area, reference points were also used to identify any changes during a two-week study period. Measurements at these reference points were taken on the first day of the study (26 October 2017) and the last day of the study (9 November 2017). The measurements were compared to see whether changes had occurred. Muskegon was not included in these measurements due to time restraints and its distance from the other study areas.

Mapping Spatial Data

Mapping was done using ArcGIS and data captured using the GPS Trimble units. This data was imported into ArcGIS and projected using the WGS 1984 projection. A map was then developed showing the shoreline and foredune-beach boundary of each study area. Different scarp types were also mapped in ArcGIS. From the mapped data, the percentage of each scarp type within each study section was calculated. Total scarp distances were also calculated from the mapped data.

Results

Scarping at the Foredune-Beach Boundary

Our measured shorelines included scarp heights in all categories (Figure 3). The most common type was medium scarp, which comprised 41% of the 2400-m total distance of the foredune-beach boundary that we mapped. Rosy Mound Natural Area had mostly high scarp (more than 75%) along its foredune-beach boundary. The P. J. Hoffmaster State Park study location had the highest percentage of no scarp boundary (43%), whereas the Muskegon State Park study location had scarps ranging from low to high along all of its foredune-beach boundary. Measured slope angles of the scarps ranged from 30 to 90 degrees. The 30-degree slope measurements were often accompanied by observations of slope failure near the scarp.

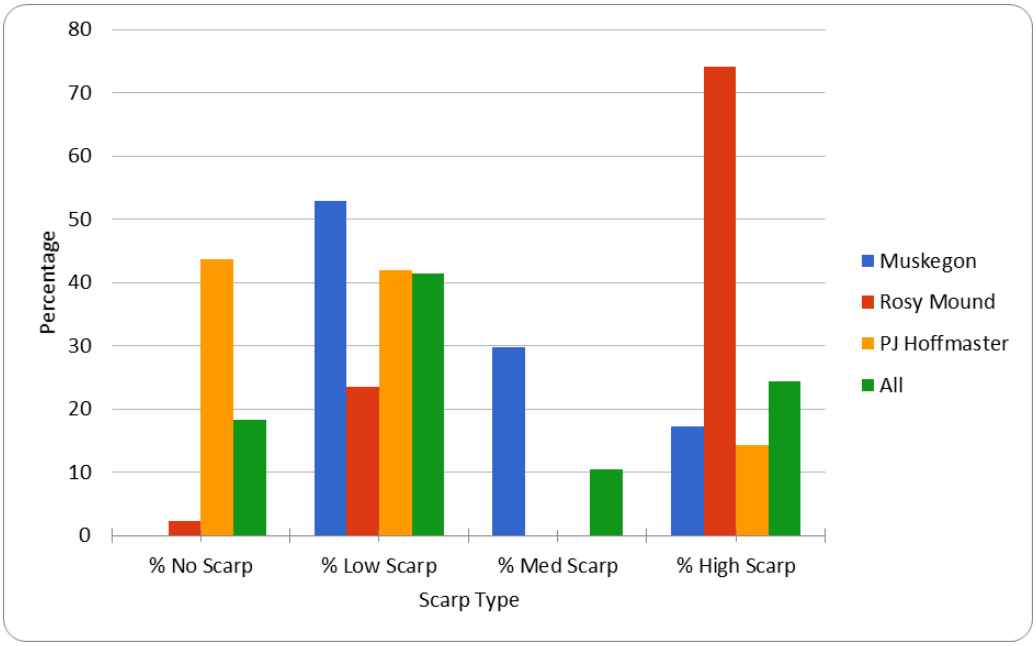
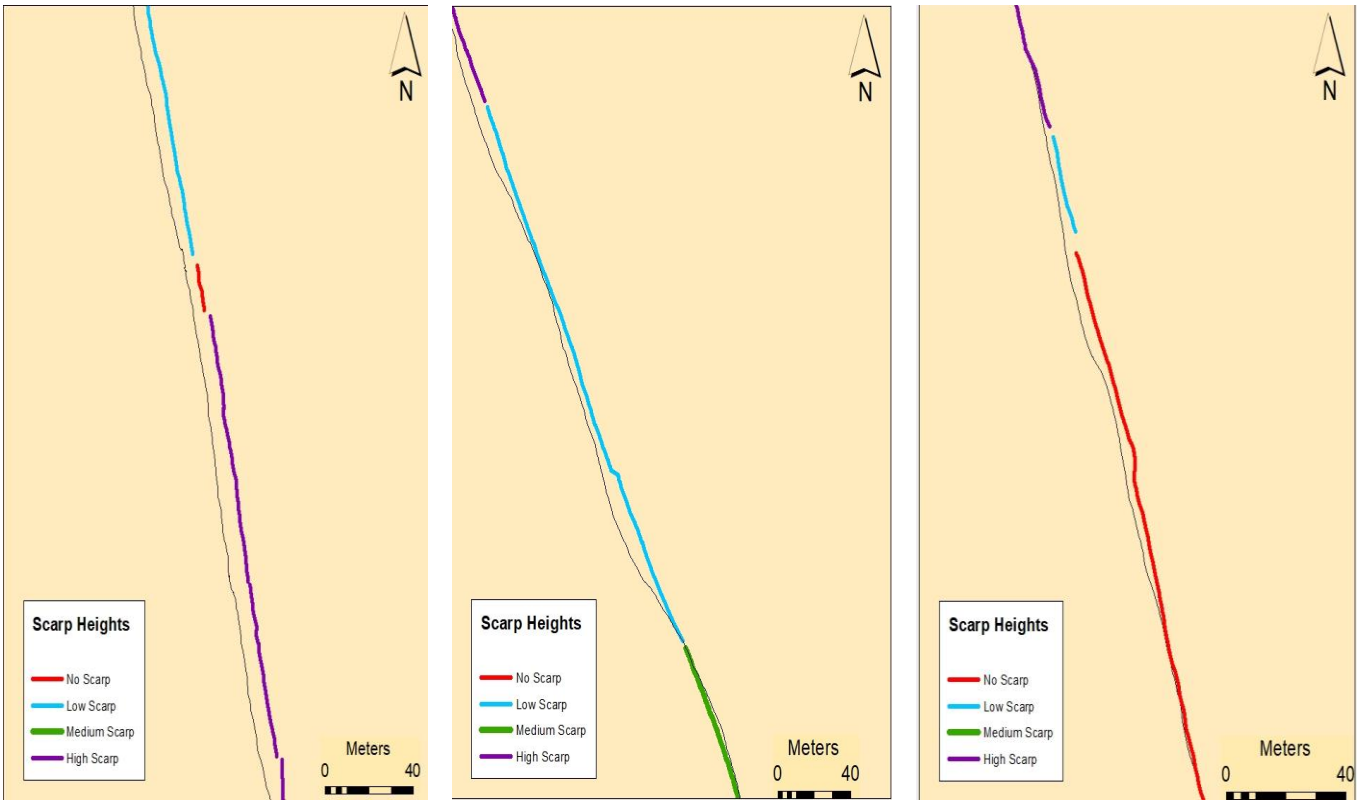


Figure 3. Percent of scarp type along the foredune-beach boundary at each study location.

Spatial Patterns of Beach Width and Foredune-Beach Boundary Types

Spatial patterns of boundary types and beach widths are visible from the mapped data (Figure 4). Beach widths ranged from 0 m (the shoreline was at the foredune-beach boundary) to nearly 10 meters. Transitions between foredune-beach boundary types could be abrupt; in other words, the boundary type could change from one category to another over a very short distance. The mapped scarp heights show that any of the types can be adjacent to any other type, including high scarp adjacent to no scarp or low scarp.



Rosy Mound Natural Area Muskegon State Park P.J. Hoffmaster State Park

Figure 4. Mapped shorelines and beach-dune boundaries for representative portions of the three study areas.

Changes at Reference Points

At least two reference points were established in each park, including sign-posts, distinctive trees, and corners of structures such as boardwalks (Table 2). Second measurements were taken at four of the seven reference points, with the results showing 0.3m or less change in beach-foredune boundary location between the measurements.

Park	Reference Point Description	Measurement (and Date)	Second Measurement (and Date)
Rosy Mound Natural Area	RMNA-1 – Sign	2.5 m (2017-10-26)	2.3 m (2017-11-09)
	RMNA-2 – South leg of boardwalk	10.58 m (2017-10-26)	10.65 m (2017-11-09)
Muskegon State Park	MSP-1 – Tree	24.1 m (2017-11-02)	
	MSP-2 – Sign (No Parking) at road	13.25 m (2017-11-02)	
Hoffmaster State Park	HSP-1 – Black stick box	2.8 m (2017-11-09)	
	HSP-2 – Tree	23.75 m (2017-11-01)	24 m (2017-11-09)
	HSP-3 – Post (for timelapse camera)	13.8 m (2017-10-26)	13.5 m (2017-11-01)

Table 2. Reference point descriptions and measurements of distances between reference point and beach-foredune boundary.

Discussion

Based on our results, we propose the following categories for foredune-beach boundaries: eroded (human impact), eroded (wave impact), deposition (wave), deposition (wind), and stable. These boundary categories take into account only what was observed in the field, and they might not represent all possible boundary types.

Erosion by waves is characterized by slumping, scarping, and collapsing vegetation (Figure 5). The category represents the movement of sediment from dune to beach. This was the dominant type of scarp present during our study, particularly in Rosy Mound Natural Area. The time of year could have influenced this result, as autumn storms were common. Each field work day had a storm occurring either before or during the fieldwork. Rising lake levels (discussed later) could also be responsible for the large percentage of shoreline that fit in the “erosion by waves” category.

Figure 5. Wave erosion at scarps in Rosy Mound Natural Area (top photos) and Muskegon State Park (bottom photos).

Erosion by humans is categorized by slumping (Figure 6), but unlike wave erosion, human erosion does not lead to scarping. Rather, blowouts and visibly-disturbed areas with less vegetation were present on the lakeward slope of the dune. Sediment displacement may be either from the dune to the beach when sand gets pushed downslope by human trampling or from the dune further into the dune system when the disturbance allows wind to pick up sand grains and

Figure 6. Human impact erosion at Rosy Mound Natural Area.

move them inland. The category of "erosion by humans" was seen in significant sections (> 3 m distance along the foredune-beach boundary) only in Rosy Mound Natural Area and may be an indicator of the amount of foot traffic at the location. Elsewhere, there were small point locations of this category where trails crossed the foredune to meet up with the beach.

Deposition by waves is characterized by no scarp and evidence of sand and other debris on top of vegetation at the foredune-beach boundary (Figure 7). Partial or complete burial of vegetation by sand/debris were also possible. This boundary category represented sediment movement from beach to dune. Only Hoffmaster State Park had areas with this type of boundary condition, where the deposition comprised a fairly significant section of the mapped "no scarp" boundary in that area. Although these areas showed current deposition, they are vulnerable to future erosion due to the vegetation loss.

Figure 7. Evidence of wave deposition at beach-foredune boundary in Hoffmaster State Park.

We also propose two categories that we did not encounter at any of our sites: *deposition by wind* and *stable*. While wind deposition on the foredune has been observed in Hoffmaster State Park in the past by previous studies (van Dijk 2004; van Dijk 2014), none was observed during this study. A likely reason is the significant rise in lake levels over the several years leading up to this study (Figure 8). With a higher lake level than previous years, the beach is more likely to be narrow, there is less beach supply area for aeolian transport, and there is a greater likelihood that storm waves will reach the foredune-beach boundary. In addition, high scarps could be a barrier to sand moving from the beach to the foredune, because sand transport processes would not lift the sand high enough to go over the scarp and be deposited on the dune.

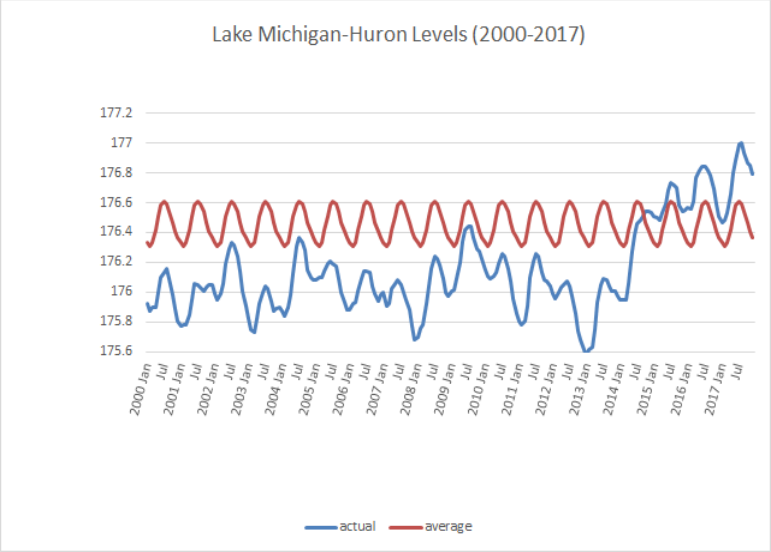


Figure 8. Lake Michigan-Huron levels from 2000-2017 (Data source: US Army Corps of Engineers 2018)

Stable foredune-beach boundaries were also not observed. Our proposal of this category is based on theorizing that there should be some locations where neither significant deposition or erosion is occurring. Some of the same factors leading to no wind deposition of sand on the foredune might lead to no sediment-budget-neutral locations. Measurements at other times of year are needed to see whether there are seasonal influences on the patterns we saw.

Conclusions

Overall, significant variety did exist in scarp height and foredune-beach boundary conditions. Rosy Mound Natural Area showed the most erosion in alongshore distance and scarp height, with both waves and humans contributing to moving sediment from dune to beach. P.J. Hoffmaster State Park showed the largest amount of deposition on the foredune in alongshore distance. Muskegon State Park showed the greatest variety in scarp heights. The variations in foredune-beach boundary conditions shown by this study at three locations suggest that further study would be helpful.

Five foredune-beach boundary categorizations were proposed in this study, but only three were present at the study locations: wave-influenced erosion, human-influenced erosion, and wave deposition. The other proposed categories of wind deposition and stable boundaries were not observed in this study. They may be more common during lower lake levels, other seasons, or perhaps in areas along the shoreline that we did not map. Future studies that expand the spatial

extent and time-period for measurements would be helpful. Future research will also be able to utilize the reference points established in this study, with the goal of understanding changes at the foredune-beach boundary over longer time periods.

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