First-Year Research in Earth Sciences: Dunes

Wrack's Influence on the Foredunes of Lake Michigan

**by Stephanie A. Praamsma, Olivia J. den Dulk, Kyle R. Post,
Hudson R. Siegers, and Ben J. VanderWindt**

**FYRES: Dunes Research Report #29
June 2017**

Department of Geology, Geography and Environmental Studies
Calvin College
Grand Rapids, Michigan

Abstract

Natural and anthropogenic debris on beaches influences sand transport and consequently the formation of the critical buffer against high energy waves—foredunes. When this debris is deposited by waves, it is known as wrack. Our study investigated the locations and characteristics of wrack relative to the rate of sand transport and deposition near the foredune at P.J. Hoffmaster State Park, Michigan. We utilized GPS units to map the areas of wrack along the beach and we used photos to document the appearance of wrack and the sand activity around it. We removed wrack from half of a designated study area and comparatively measured sand movement with sand traps and erosion pins over two weeks in fall of 2016. Observations revealed abundant wrack along the beach in varying amounts, containing organic as well as inorganic debris. The presence of wrack decreased the sand transport across the beach. Wrack also increased sand deposition on the lakeward side of the wrack and within the wrack compared to the area of beach where wrack was cleared. With this research we can better understand wrack's relationship to sand transport and the foredune, which aids in effective management of the foredune as a natural barrier to wave erosion.

Introduction

On the shores of Lake Michigan the beach is fed and remodeled with sand from the lake, which supplies the sand to the foredune, and the subsequent dunes after that, creating an essential beach-dune relationship (Olson 1958; Houser 2009). The transport of sand from the beach to the foredune creates variation in habitats and forms a protective barrier against eroding waves, and is critical to the natural balance of erosion and deposition on the beach (Houser *et al.* 2008). Obstacles on the beach affect this movement of sand, due to their effect on wind patterns. Wrack is one of these obstacles—a form of roughness that is deposited naturally on the beach, influencing the movement of wind and sand. Our study investigated how the presence of wrack on the shores of Lake Michigan affect the patterns of sand transportation and deposition. Our objectives were to:

(1) record locations and characteristics of wrack,
(2) record beach and foredune characteristics relative to wrack,
(3) compare sand transport and deposition on areas of beach with wrack and without wrack, and
(4) analyze collected data for relationships between wrack and sand transport.

Background

The movement of sand on coastal dunes has been studied extensively in order to comprehend how these complex systems function. In order to better understand how the dunes are formed and how they change over time, it is important to study the interactions between wind and sand, as well as between anthropogenic influences and sand. Many different types of factors have been found to influence how sand moves and forms into dunes, such as wind, temperature, precipitation patterns, vegetation, houses, dune topography, sand fences, wrack, and others (Hesp 1989; van Dijk 2004; Nordstrom *et al.* 2006). Each of these factors must be considered in order to obtain a comprehensive understanding of the dune system as a whole.

One of these elements, wrack, has largely been studied on marine coasts for a variety of reasons. Wrack is defined as the beach litter that accumulates in swash lines and consists of algae, grasses, driftwood, fruits, seeds, and carrion, along with cultural litter (Colombini and Chelazzi 2003). The content of the wrack varies considerably depending on location. It has been studied for its ecological role (Dugan *et al.* 2003; Feagin and Williams 2003; Deidun *et al.* 2009;

Harris *et al.* 2014), as well as its geomorphological role (Olson 1958; Nordstrom *et al.* 2006; Nordstrom *et al.* 2011c). Wrack deposits on the beach are primarily dependent on the action of the water, as that is the agent of formation and deposition of wrack. The action of the waves depends on many factors, including wind patterns (Beletsky and Schwab 2001). The presence of wrack is highly variable, can change very quickly, and is a very dynamic part of the beach system (Orr *et al.* 2005). However, when wrack is deposited far enough onto the beach, sometimes even onto the foredune itself, the wrack can stay present for weeks at a time or longer.

Wrack is a natural part of the coastal dune system, which begins at the beach and continues landward to include the foredune and subsequent dunes after that (Table 1). The beach is the primary source of sediment to the coastal dunes, and critically links the beach with the dune system (Houser 2009). Obstacles that act as a form of surface roughness affect the flow of wind, which affects the quantity and placement of sand transport, causing influences on the dune systems inland (Arens *et al.* 1995). Beach wrack is one of the most common types of surface roughness (Nordstrom *et al.* 2011a) and has been seen to be a key factor in trapping wind-blown sand and initiating dune development (Hesp 1989; Nordstrom *et al.* 2000). The formation of incipient foredunes at the back of the beach is an important aspect of the protective nature of coastal dunes, as foredunes have been seen to be predictors of what will happen to the coastal dunes as a whole (Hesp 2002).

Location	**Description**
swash zone	Area of beach where waves move onto the beach (swash) and water returns to the lake (backwash).
foreshore	Area of beach affected by wave action during non-storm conditions*
backshore	Area of beach affected by wave action during storm conditions. For recreational users, this area is often known as “the beach”.*
foredune toe	Lakeward edge of foredune, usually distinguished by the presence of vegetation on foredune and a change in topography.*
foredune	An elongated dune ridge parallel to the shoreline just inland from the beach.

Table 1. Definition of significant beach-dune locations relevant to this study. *Definition adapted from Davidson-Arnott (2010).

Direct studies of the impact of wrack on rates of sand transport have been limited, and even fewer have looked at the impact of wrack on rates of transport on the Great Lake's coasts. Defining the role of freshwater wrack is important for managing wrack itself, understanding freshwater coastal dynamics, and for management, conservation, and restoration of the coast. Freshwater wrack has been studied in its amount, mobility, decomposition, and ecology (Harris *et al.* 2014), but rarely on its interaction with wind, wind-blown sand, and foredune morphology.

Study Area

The study site was located in P.J. Hoffmaster State Park, Muskegon, Michigan on the east coast of Lake Michigan (Figure 1). The park covers about 4.9 square kilometers (1200 acres) and contains entire dune systems, beginning at the beach and including foredunes, active parabolic dunes, blowouts, and stable dunes farther inland (MDNR 2017). The park is managed by the Michigan Department of Natural Resources and has a series of trails and boardwalks.

Within Hoffmaster State Park, the beach at 43°07'05.1''N 86°16'16.4''W was chosen as the study site, based on the presence of a foredune and a wide backshore, with enough room to set up for our equipment. Deposits of wrack was already present on the beach at the start of the study. Our study site included a portion of the beach, the foredune toe, and part of the foredune. The foredune was roughly parallel to the shoreline and about 1.5m high.

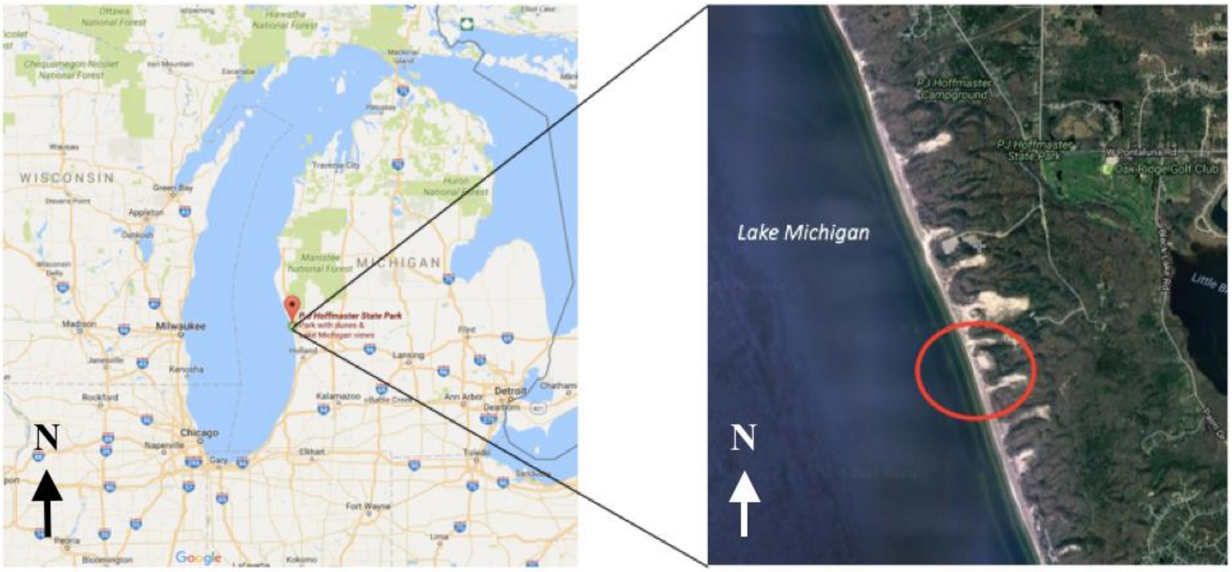


Figure 1. The study location (circled in red) in P.J. Hoffmaster State Park, Michigan.

Methods

Measurements were taken on 3 subsequent Thursdays over the course of 2 weeks, from October 27 to November 10, 2016. The study site was set up during the first visit and taken down during the third visit, with measurements of sand moisture, sand deposition/erosion, and sand transport taken during each of the 3 visits. Observations of wrack locations, amounts, and characteristics as well as foredune and beach characteristics were noted during each visit as well.

A 20m (N-S) section of the beach/foredune area was marked off with corner posts, rope, flagging tape, and signs. Ropes were placed high enough so as not to interfere with wave action. The site was split in half with flags in order to separate the two sides to receive different treatments (Figure 2). Very little foot traffic was expected in the area of the study site, as it was the recreational off-season. A metal gardening rake was used to carefully remove the wrack from the northern side of the study site each site visit, with measures being taken to disturb the sand as little as possible. The removed wrack was then massed together and photographed, with the same team member in the picture each time for scale. This was done in order to compare how much wrack washed onto the shore over the course of a week.

A. Raked area B. Unraked area

Figure 2. The two sides of the study area are A) the raked side (shown after raking) and B) the unraked side. Erosion pins are flagged in red and in a line perpendicular to the beach. Sand traps are white and staggered on the beach.

Locations of wrack were measured using a handheld GPS Trimble each day we went out to the site. The GPS user would identity wrack lines and accumulations, and either map the wrack as a line feature or a point feature. This was done on our study site as well as south of our site up until the southern boundary of P.J. Hoffmaster State Park. The foredune toe, water's edge, and scarp (if present) were mapped in a similar fashion, utilizing the line feature in the GPS. The data was later downloaded, post-processed, and analyzed with Esri ArcGIS 10 where it was superimposed upon a base map.

Characteristics of wrack and the beach were observed by photo-documentation using a digital camera and notetaking in a field notebook. Observations taken in the field noted the amount and composition of the wrack found on the study site and south along the beach.

The moisture content of the sand on the beach was measured by collecting sand samples from the backshore (landward of the wrack on the unraked side) and the middle of the shore (lakeward of the wrack on the unraked side) on both sides of the study site, as well as beneath the wrack on the raked side, before the wrack was removed. The samples were taken from the top of the sand, about 3cm deep. The samples were stored in air-tight tins and transported to the lab. Each sample was then weighed, dried in an oven for over 24 hours, and weighed again to determine the percent moisture. Sand samples were collected each site visit.

Sand erosion and deposition on our study site was measured using 8 erosion pins, 4 on each side, placed in a line perpendicular to the shore. The pins were placed on the middle of the shore, on the backshore, on the foredune toe, and on the foredune itself. Height of the pin from where it emerged from the sand to its top was measured using a meter stick. Measurements were taken each site visit.

Sand transport was gathered using 4 vertical cylindrical traps of Leatherman (1979) design, 2 placed on each side. Traps were placed in a staggered pattern, one near the middle of the shore, the other on the backshore. During each site visit the collection tubes were removed and replaced with empty tubes. The collection tubes with sand accumulated from the past week were emptied into tins, dried, and weighed. The amount of sand collected per paired sand trap was compared, measured in kilograms per meter-width per week. During the first sand collection, data from the sand trap on the raked side was lost due to a broken sand trap.

Weather data, including wind speeds and wind direction, was obtained from an ongoing monitoring of a foredune in P.J. Hoffmaster State Park, as part of a study being conducted by

Professor Deanna van Dijk of Calvin College. Wind speeds were analyzed to observe the relationship between wind conditions and the amount of wrack accumulation on the raked side of the study area.

Results

Wrack Locations and Characteristics

Wrack was observed to be washed up onto the beach by waves and formed into a variety of configurations. Along the beach, long wrack lines of loose material formed as well as balls of densely packed material that had been tumbled around by the waves (Figure 3). The wrack contained a range of material including: dead beach grass, driftwood, feathers, zebra mussels, cattails, cultural debris such as Styrofoam, bottle caps, and ribbons, and living organisms such as beetles.

A. B.

Figure 3. Wrack on the beach (photographed south of study area), included A) lines of wrack along the swash line, and B) a dense ball of wrack sitting on the beach.

The majority of the wrack was spread out in lines along the backshore, where the highest energy waves had reached (Figure 4). Larger, heaver pieces of wrack stayed closer to the water's edge. Areas of beach with an extreme scarp (>1m) appeared to have less wrack than areas without scarping present (Figure 5). Wrack was also observed on top of the foredune in one area.

Figure 4. Wrack locations as mapped by GPS during a site visit. The study site is in the top left corner of the map.

A. B.

Figure 5. Areas of beach A) with a large scarp (~1.5 meters) and B) without a scarp. Both photos were taken south of the study site.

Over the two-week period of our study, the amount of wrack that was washed up onto our raked study site varied considerably. During the first site visit we observed the most amount of wrack (Figure 6). One week later, we observed some wrack accumulation on the side of the site we had raked. A week after that, on our third and final site visit, we found no significant amount of wrack had washed up onto our study site.

A. Site visit 1 B. Site visit 2 C. Site visit 3

Figure 6. Wrack amounts collected from the raked side of the study area during each site visit. In photos A and B, the pile of collected wrack is shown beside a researcher posing for scale. During the last site visit (photo C), no wrack had accumulated on the raked side which is visible beyond the unraked side in the photo foreground.

Moisture Content

The moisture of the sand on the raked side of the study area increased over the course of the study, except for the sand sample taken ‘behind the wrack’, referring to the backshore (Figure 7). The moisture of the sand on the unraked side of the study area decreased over the course of the study (Figure 8).

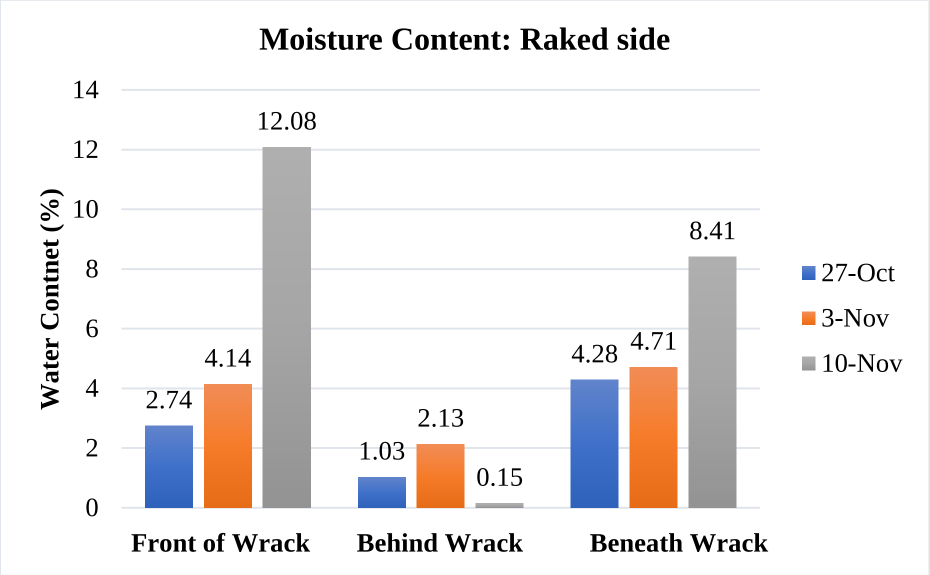


Figure 7. Sand moisture contents measured on the raked side of the study area. Three areas were sampled during each site visit.

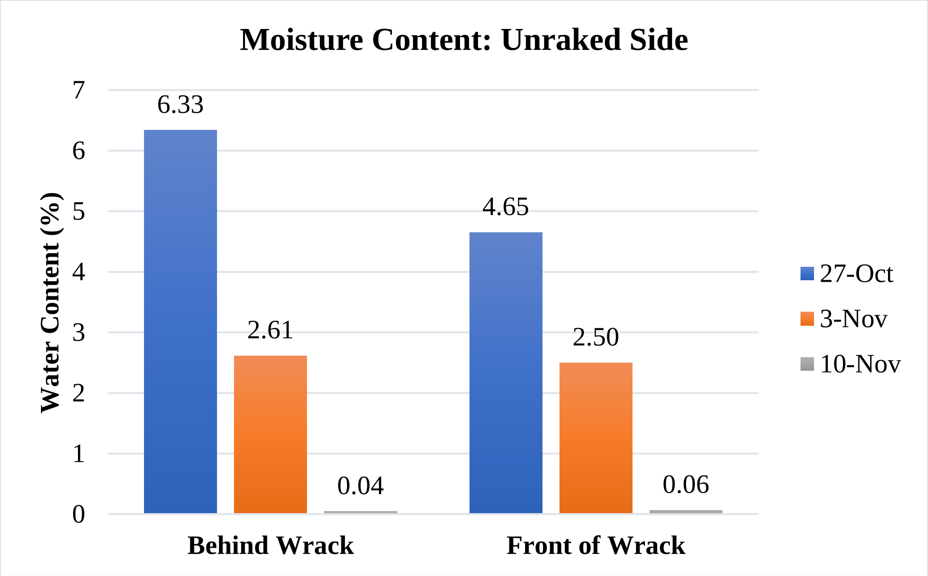


Figure 8. Sand moisture contents measured on the unraked side of the study area. Two areas were sampled during each site visit.

Sand Erosion and Deposition

Surface change differed considerably between the two sides of the study site (Figure 9). On the raked side, erosion occurred during both weeks, mainly in the middle of the shore (pin R1), where 21 mm of sand had eroded, and on top of the foredune (pin R4) where 12 mm of sand had eroded. Some deposition occurred on the raked side, ranging from 3 mm on the foredune toe and foredune to 9 mm on the backshore.

On the unraked side of the study site, more deposition occurred than erosion. Erosion over a one-week period occurred on the foredune toe and foredune by 5 mm and 2 mm respectively. Besides those two data points, the rest of the surface change recorded was deposition. The middle of the shore (pin UN1) received the highest deposition of 27 mm the first week, and 3 mm the following week. The pin on the backshore (pin UN2) received 15 mm of sand deposition the first week, and 10 mm the next week. The foredune toe and foredune received the least deposition.

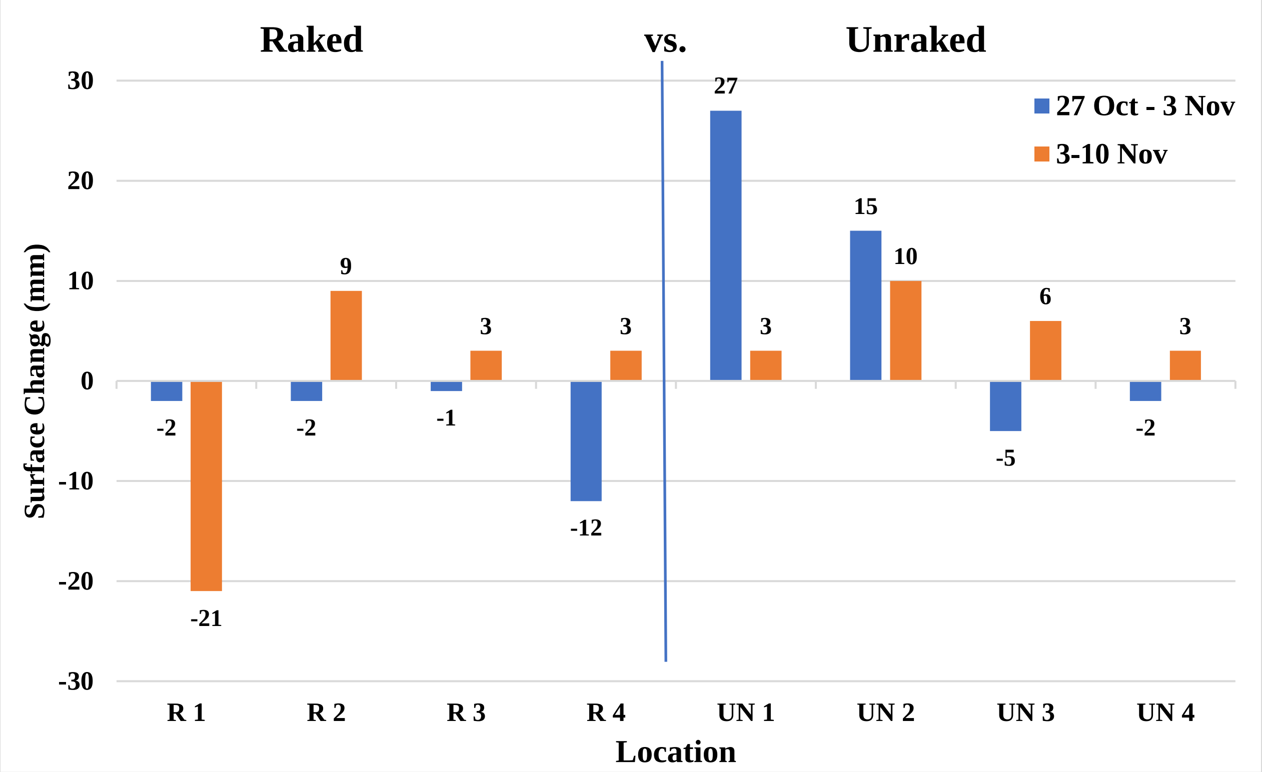


Figure 9. Erosion and deposition that occurred over the two weeks of the study. On the left side of the blue line are measurements from the raked side of the study area; on the right side of the blue line are measurements from the unraked side of the study area.

Sand Transport

Sand transport was recorded at all four sand traps during both weeks of the study, with rates ranging from 0.044 to 14.8 kg m-width^{-1} week^{-1}. More sand movement was observed during the first week of collection compared to the second week of collection, especially on the foredune toe on both sides of our study site.

When paired sand transport rates were compared across the two sides of the study site, the raked side showed consistently higher amounts of sand transport (Figure 10). The first week we observed 14.8 kg m-width^{-1} week^{-1} of sand transport on the foredune toe of the raked side, compared to 4.3 kg m-width^{-1} week^{-1} on the foredune toe of the unraked side. Similar patterns were observed the next week as well, on both the beach and the foredune toe.

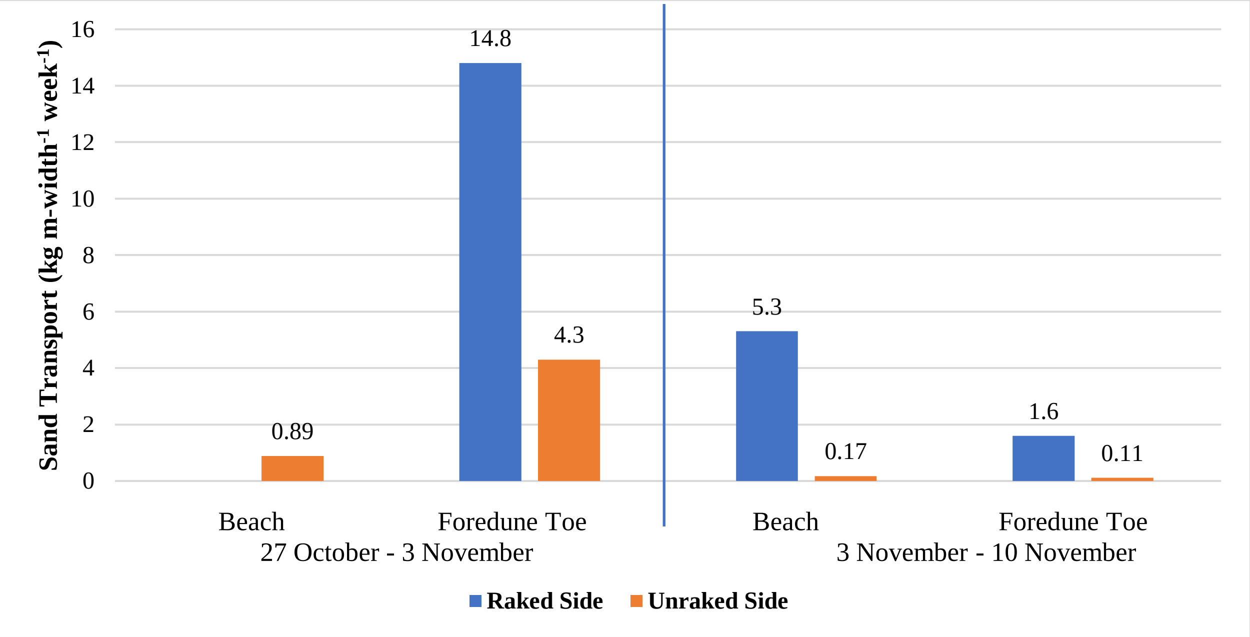


Figure 10. Amount of sand transport per week measured at the four sand traps over the course of the two-week study. The blue line separates the values collected for each subsequent week.

Wind Patterns

Over the course of the study weekly average wind speeds were not significantly different (Appendix 1). The highest wind speed recorded for the first week, October 27 to November 3, was 14.0 meters per second. The highest wind speed for the second week, November 4 to November 10, was 14.6 meters per second. Wind directions did not differ significantly from week to week. The first week of the study wind direction varied. The second week of the study wind direction varied, but tended towards the west.

Discussion

Wrack Locations and Characteristics

The abundance of wrack found on the beach gave support to the hypothesis of wrack acting as an influence on the beach in areas such as sand transport and wind flow (Nordstrom *et al.* 2011a). Wrack formed into mounds and strands, becoming a topographic obstacle on the beach, directly where sand begins to saltate and move in the direction of the oncoming wind. Roughness elements such as wrack have been seen to affect small-scale differences in sediment transport (Jackson *et al.* 2006). Wrack composition was in conformity with previous literature (Colombini and Chelazzi 2003; Nordstrom *et al.* 2011a), except that the wrack we observed was freshwater wrack, leading to a slightly different composition of organism species.

Where scarping had occurred along the foredune, wrack was found less frequently. The presence of a scarp signifies that waves are reaching to the foredune itself and beginning to erode it away. With no backshore, wrack is pushed against the scarp and washed away by the waves, without being deposited. This leaves wrack lines primarily on areas of the beach where a gradual incline is present, and where the waves do not reach the foredune.

Wrack is continually resupplied to the beach, as was seen over the course of our study, but it is not easy to predict when and in how much quantity. Interestingly, wrack was deposited on the raked half of the study site while the wrack on the unraked half was left undisturbed. This suggests that wrack patterns can be very different on the same stretch of beach, even within an area as small as 5 meters. Previous studies on wrack deposits on oceanic coasts have shown beach debris accumulation being regulated by season, lunar, and tidal phases (Colombini and Chelazzi 2003). Further study is needed of the same regulatory mechanisms of wrack on lacustrine shores.

Moisture Content

Moisture content variations at the site may be influencing sand movement. The percent water content of sand can greatly influence sand movement, and have a direct effect on the amount of sand being transported from the beach. Even moisture values of 4-8% can greatly reduce the likelihood of sand transport (Nordstrom *et al.* 2011a). On the raked side of the study site, the areas of mid- and back-shore were within this range, or above it, the majority of the time. Farther back on the shore, however, the surface of the sand was below this range consistently. This is consistent with previous studies which determined that moisture decreases with increasing distance inland (Nordstrom *et al.* 2011a; Nordstrom *et al.* 2011b; Jackson and Nordstrom 2012). The increase of moisture over time on the raked side seems counterintuitive, but may have been due to the absence of a damping effect on wave action caused by wrack (Colombini and Chelazzi 2003). With higher moisture content of the sand, sand transport will be affected and hindered.

The unraked side of the study site, 5 meters away from the collection sites on the raked side, showed opposite trends. With the wrack present, the sand was of similar moisture in front of and behind the wrack, suggesting that the wrack was causing an increase in moisture around the area of the beach it was deposited. As the weeks progressed, that moisture decreased to less than 1%. The damping effect could be the cause of these results, but further study would be needed. Less moisture on the unraked side would result in higher sand transport rates, as the dried sand is more likely to be moved by the wind.

Sand Erosion and Deposition

The change in surface topography on the beach is accounted for by the movement of sand, of which wrack is an effective trap (Hesp 1989; Dugan and Hubbard 2010; Nordstrom *et al.* 2011a; Nordstrom *et al.* 2012). Deposition occurred before the wrack and within the wrack, confirming previous studies which found that wrack acts as a barrier to sediment movement (Figure 11). With the buildup of sand due to this topographic obstacle, incipient foredunes begin to form. This can extend

Figure 11. Accumulation of sand around a clump of wrack. The picture was taken on the beach south of the study area, during one of the site visits.

the foredune lakeward with some scour seen behind the wrack due to the flow of the wind (Arens *et al.* 1995). With slightly porous obstacles (such as wrack), a vortex is created immediately behind the object, causing sand to be blown away and some small erosion to occur (Liu *et al*. 2014). Flat areas without a form of roughness, such as the area of beach that was raked, showed much less deposition, due to the absence of a barrier to slow the wind and cause sand to be deposited. Erosion was seen in greater amounts, as the wind was able to easily pick up the sand and transport it away from the beach and foredune. Although wrack that is not spatially close enough to the foredune toe may not have a direct impact on the formation of the foredune toe or foredune itself, wrack has the potential to begin shadow dunes which can turn into incipient dunes if colonized by vegetation (Hesp 1989). Many studies have observed the presence of seeds in wrack, suggesting that once sand begins to build up around wrack stabilization by vegetation is a great possibility (Leatherman 1979; Colombini and Chelazzi 2003; Nordstrom *et al.* 2011a).

Sand Transport

Our results confirm that sand transport across the beach is affected by the presence of wrack. The sand traps placed behind the wrack on the unraked side of the study site received much less sand, as the wrack acted as an obstruction in the path of the sand-driving wind (Bagnold 1941). Wrack is an effective local trap for aeolian sand transport (Nordstrom *et al.* 2011a), by slowing wind flow velocities within and behind the wrack (Hesp 1989). Not all aeolian sand movement is blocked by wrack, as the sand traps behind the wrack did gather some sand, although a very minimal amount. The effect is only local, however, and does not affect the transport of sand by wind on areas of beach next to it, such as the raked side of the study site less than 5 meters away. The size and amount of wrack did not appear to affect a change in the amount of sand transport hindered over the course of our study. Sand transport behind a larger amount of wrack received similar amounts of sand as the sand trap located behind a smaller amount of wrack. Further study is needed to understand this relationship better.

Wind Patterns

Wind patterns revealed very little about the differences in the amount of wrack washed up on the shore. Although great differences between wrack amounts were seen, no extreme differences between wind speed data was observed. According to MacMillan and Quijón (2012), on an ocean coast, wrack input is variable and depends on tides, wave exposure, wind, storms, erosion levels, and even beach substratum types. It is likely that similar influences act upon the spatial variation of wrack deposits on the coast of Lake Michigan, but these factors have not been determined and will require further research.

Our study suggests that wrack is an important component of the Great Lake coastal system, especially in regards to foredune formation and the natural movement of sand. Wrack has local influences on sand transport and surface moisture, both of which affect the amount of sand that is moving to the foredune from the beach, and the amounts of erosion and deposition on the backshore. Therefore, variations in patterns of wrack along the shoreline affect how dunes, particularly foredunes, develop and change. Managers who value natural connections between beach processes and dunes, as well as the health of the dune systems, should avoid removing wrack from beaches. Raking beaches of wrack is harmful to the natural ecology and morphology of the dunes, and should be done sparingly and only when necessary in order to preserve the natural functioning of the coast.

Conclusions

During this two-week study, wrack was found to be located along the swash line in varying amounts, and formed a topographic obstacle on the beach. Wrack may have an impact on sand moisture, causing implications for sand movement, but further study would be required. Wrack increased sand deposition on the windward side of the wrack and within the wrack, and prevented erosion of sand from the area of beach landward from the wrack. The presence of wrack on the backshore decreased sand transport from the beach to the foredune as well. The influence of wrack on sand movement may aid in the formation of small dunes and help to stabilize the foredune.

Acknowledgements

This study was made possible by many people who we would like to thank: Calvin College and the Michigan Space Grant Consortium for funding, P.J. Hoffmaster State Park and the Department of Natural Resources for allowing us to carry out the study in their park, and Dr. Deanna van Dijk for her support, guidance, and mentoring through this research process.

Works Cited

Arens, S.M., H. M. E. van Kaam-Peters, and J. H. Van Boxel. 1995. "Air flow over foredunes and implications for sand transport." *Earth Surface Processes and Landforms* 20: 315-332.

Bagnold, R. A. 1954. *The Physics of Blown Sand and Desert Dunes.* Second edition. Methuen (London, UK). 265 p.

Beletsky, D., and D. J. Schwab. 2001. "Modeling circulation and thermal structure in Lake Michigan: Annual cycle and interannual variability." *Journal of Geophysical Research* 106 (C9): 19,745-19,771.

Colombini, I., and L. Chelazzi. 2003. "Influence of marine allochthonous input on sandy beach assemblages." *Oceanography and Marine Biology: an Annual Review* 41: 115-159.

Davidson-Arnott, R. 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge University Press (Cambridge, UK). 442 p.

Deidun, A., S. Saliba, and P. J. Schembri. 2009. "Consideration on the ecological role of wrack accumulations on sandy beaches in the Maltese Islands and recommendations for their conservation management." *Journal of Coastal Research* SI 56:410-414.

Dugan, J. E., D. M. Hubbard, M. D. McCrary, and M. O. Pierson. (2003). "The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California." *Estuarine, Coastal and Shelf Science* 58(S): 25-40.

Dugan, J. E., and D. M. Hubbard. 2010. "Loss of coastal strand habitat in Southern California: The role of beach grooming." *Estuaries and Coasts* 33:67-77.

Feagin, R. A., and A. M. Williams. 2003. "Final Report: Sargassum: Erosion and Biodiversity on the Beach." *Coastal Coordination Council Report.* http://ssl.tamu.edu/media/1828/07_005_10_final_report.pdf

Harris, C., D. L. Strayer, and S. Findlay. 2014. "The ecology of freshwater wrack along natural and engineered Hudson River shorelines." *Hydrobiologia* 722: 233-245.

Hesp, P. 1989. "A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes." *Proceedings of the Royal Society of Edinburgh* 96B: 181-201.

Hesp, P. 2002. "Foredunes and blowouts: initiation, geomorphology and dynamics." *Geomorphology* 48: 245-268.

Houser, C., C. Hapke, and S. Hamilton. 2008. "Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms." *Geomorphology* 100: 223-240.

Houser, C. 2009. "Synchronization of transport and supply in beach-dune interaction." *Progress in Physical Geography* 33(6): 733-746.

Houser, C. 2013. "Alongshore variation in the morphology of coastal dunes: Implications for storm response." *Geomorphology* 199: 48-61.

Jackson, N. L., D. J. Sherman, P. A. Hesp, A. H. F. Klein, F.Ballasteros, Jr., and K. F. Nordstrom. 2006. "Small-scale spatial variations in aeolian sediment transport on a fine-sand beach." *Journal of Coastal Research* SI 39 (Proceedings of the 8th International Coastal Symposium): 379-383.

Jackson, N. L., and K. F. Nordstrom. 2012. "Aeolian sediment transport and morphologic change on a managed and an unmanaged foredune." *Earth Surface Processes and Landforms* 38: 413-420.

Leatherman, S.P. 1979. "A new eolian sand trap design." *Sedimentology* 25:303-306.

Liu, B., J. Qu, W. Zhang, L. Tan, and Y. Gao. 2014. “Numerical evaluation of the scale problem on the wind flow of a windbreak.” *Scientific Reports* 4(6619): 1-5.

MacMillan, M. R., and P. A. Quijón. 2012. “Wrack patches and their influence on upper-shore macrofaunal abundance in an Atlantic Canada sandy beach system.” *Journal of Sea Research* 72: 28-37.

MDNR. 2017. “Hoffmaster State Park.” Michigan Department of Natural Resources. http://www.michigandnr.com/parksandtrails/Details.aspx?type=SPRK&id=457. Accessed on 9 July 2017.

Nordstrom, K. F., R. Lampe, and L. M. Vandemark. 2000. “Reestablishing naturally functioning dunes on developed coasts.” *Environmental Management* 25(1):37-51.

Nordstrom, K. F., N. L. Jackson, A. H. F. Klein, D. J. Sherman, and P. A. Hesp. 2006. “Offshore aeolian transport across a low foredune on a developed barrier island.” *Journal of Coastal Research* 22(5):1260-1267.

Nordstrom K. F., N. L. Jackson, and K. H. Korotky. 2011a. “Aeolian sediment transport across beach wrack.” *Journal of Coastal Research* SI 59:211-217.

Nordstrom, K. F., N. L. Jackson, K. H. Korotky, and J. A. Puleo. 2011b. “Aeolian transport rates across raked and unraked beaches on a developed coast.” *Earth Surface Processes and Landforms* 36:779-789.

Nordstrom, K. F., N. L. Jackson, N. C. Kraus, T. W. Kana, R. Bearce, L. M. Bocamazo, D. R. Young, and H. A. De Butts. 2011c. “Enhancing geomorphic and biologic functions and values on backshores and dunes of developed shores: A review of opportunities and constraints.” *Environmental Conservation* 38: 288-302.

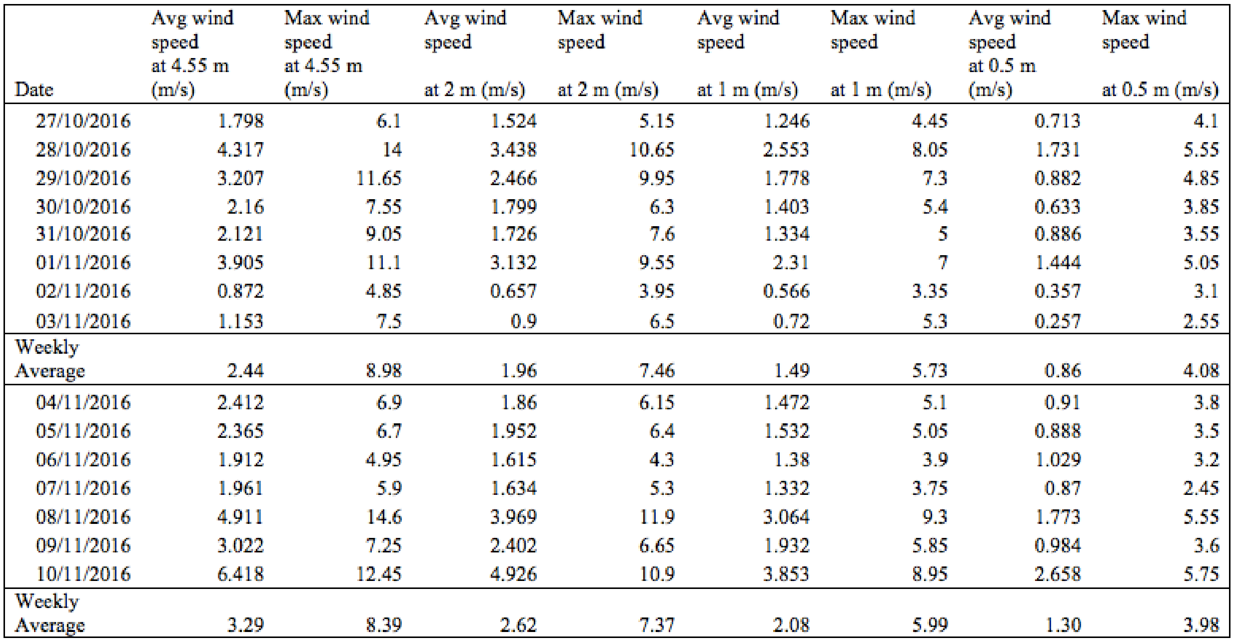
Nordstrom, K. F., N. L. Jackson, A. L. Freestone, K. H. Korotky, and J. A. Puleo. 2012. “Effects of beach raking and sand fences on dune dimensions and morphology.” *Geomorphology* 179: 106-115.

Olson, J. S. 1958. “Lake Michigan dune development. 3. Lake-level, beach, and dune oscillations.” *The Journal of Geology* 66 (5): 473-483.

Orr, M., M. Zimmer, D. E. Jelinski, and M. Mews. 2005. “Wrack deposition on different beach types: Spatial and temporal variation in the pattern of subsidy.” *Ecology* 86(6): 1496-1507.

van Dijk, D. 2004. “Contemporary geomorphic processes and change on Lake Michigan coastal dunes: An example from Hoffmaster State Park, Michigan.” *Michigan Academician* 35: 425-453.

Appendix A. Wind speed measurements over the course of the study from 4 anemometers at different heights above the foredune.



Date	Avg wind speed at 4.55 m (m/s)	Max wind speed at 4.55 m (m/s)	Avg wind speed at 2 m (m/s)	Max wind speed at 2 m (m/s)	Avg wind speed at 1 m (m/s)	Max wind speed at 1 m (m/s)	Avg wind speed at 0.5 m (m/s)	Max wind speed at 0.5 m (m/s)
27/10/2016	1.798	6.1	1.524	5.15	1.246	4.45	0.713	4.1
28/10/2016	4.317	14	3.438	10.65	2.553	8.05	1.731	5.55
29/10/2016	3.207	11.65	2.466	9.95	1.778	7.3	0.882	4.85
30/10/2016	2.16	7.55	1.799	6.3	1.403	5.4	0.633	3.85
31/10/2016	2.121	9.05	1.726	7.6	1.334	5	0.886	3.55
01/11/2016	3.905	11.1	3.132	9.55	2.31	7	1.444	5.05
02/11/2016	0.872	4.85	0.657	3.95	0.566	3.35	0.357	3.1
03/11/2016	1.153	7.5	0.9	6.5	0.72	5.3	0.257	2.55
Weekly Average	2.44	8.98	1.96	7.46	1.49	5.73	0.86	4.08
04/11/2016	2.412	6.9	1.86	6.15	1.472	5.1	0.91	3.8
05/11/2016	2.365	6.7	1.952	6.4	1.532	5.05	0.888	3.5
06/11/2016	1.912	4.95	1.615	4.3	1.38	3.9	1.029	3.2
07/11/2016	1.961	5.9	1.634	5.3	1.332	3.75	0.87	2.45
08/11/2016	4.911	14.6	3.969	11.9	3.064	9.3	1.773	5.55
09/11/2016	3.022	7.25	2.402	6.65	1.932	5.85	0.984	3.6
10/11/2016	6.418	12.45	4.926	10.9	3.853	8.95	2.658	5.75
Weekly Average	3.29	8.39	2.62	7.37	2.08	5.99	1.30	3.98