The Emerging Science of Coastal Sand Dune Age and Dynamics: Implications for Regulation and Risk Management in Michigan

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Coastal sand dunes are found in many places along the shores of the Great Lakes. They are particularly common along the western coast of Lower Michigan and the northern shore of Upper Michigan due to three reasons, including 1) the very high supply of fine sand (1-2mm in size) initially deposited during the ice age, 2) the orientation of the shore as it relates to prevailing westerly winds, and 3) the long fetch resulting in unencumbered air flow across Lake Michigan and Lake Superior. The interaction of these variables has resulted in spectacular dune fields that collectively embody the largest complex of freshwater dunes in the world. In fact, they rival any coastal dune systems in the world as far as their size and grandeur is concerned, including those in northern Europe, Australia, New Zealand, and South Africa, to name a few places where prominent coastal dunes occur.

Recent Research Challenge Dune Age and Formation Assumptions

Given the high profile of the dunes, they have been a source of geological and geographical interest for over a century. Early studies (e.g., Cowles, 1899; Dow, 1937; Scott, 1942; Olson, 1958a, b) were largely descriptive in their character and focused on the general physical geography of the dune systems, including the relationship to hypothesized lake levels and the interactions of wind and vegetation.

As a result of this collective body of work, it was generally assumed in the scientific community by the 1970s that the dunes had largely formed during the “Nipissing phase” of the ancestral Great Lake. This high lake stage, which occurred ~5,500 years ago, occurred due to the complex interactions related to climate and crustal rebound following the most recent ice age. The upper Great Lakes (Huron, Michigan, and Superior) shared the same water plane at this time and were about 15’ to 20’ higher than present during the peak part of the high stand. As far as the dunes are concerned, it was assumed that they formed during or shortly after this time, largely because high amounts of sand were presumably eroded from lake bluffs and then blown by the wind to the nearshore environment.

Following a ~ 20-year hiatus in research, investigations focusing on the physical geography and geomorphology of the coastal dunes began again in the late 1990s. This shift occurred in large part because dating techniques, such as radiocarbon (^{14}C) dating and optical stimulated luminescence (OSL) dating now existed that could confidently estimate the age of the dunes. Another reason for the renewed interest in the evolution of the dunes was the discovery that many of the lake-fronting dunes contain a variety of buried soils (paleosols), which represent the ground position in the past for an extended time as the dunes formed. This discovery was significant because it meant that the dunes did not form during a single period of time as had been generally assumed, but rather grew in distinct stages that were separated in time by periods of landscape stability when relatively little wind-blown sand accumulated. Given the buried organic matter in these ancient soils, it was possible to estimate via radiocarbon dating when these intervals of time occurred. In places where paleosols were not present or exposed, OSL dating was employed to estimate the most recent time when sand grains were exposed to light shortly before they were buried by additional deposits of sand.

Currently, more than twenty peer-reviewed studies have been conducted by various research teams (e.g., Loope and Arbogast, 1999; Arbogast et al., 2002; Arbogast et al., 2004; Hansen et el., 2010; Blumer et al., 2012; Lovis et al., 2012), with the collective acquisition of more than 250 age estimates from the coastal dunes. This suite of ages appears to represent the largest such data inventory from a complex of coastal dunes in the world.

Revising Dune History

Results from this systematic dating program suggest that an early pulse of coastal-dune growth in Michigan indeed occurred during the Nipissing high stand ~ 5,500 years ago. Contrary to earlier assumptions, however, this period of dune growth was not the primary event in the history of the dunes. Instead, it very much appears that most dune growth occurred during two distinct periods of time (Figure 1).

The first of these cycles occurred between ~ 3500 and 2000 years ago. Subsequently a distinct episode of coastal stability occurred over much of the Michigan shoreline for about a 1,000 years that resulted in the addition of little wind-blown sand to the dune system. Following this episode of extended stability, the second episode of dune growth took place between 1000 and 500 years ago. Some additional accumulations of wind-blown sand have even occurred in the past ~300 years into the historic period.

Although we have an excellent understanding of when the dunes formed, *why* they grew during these episodes of time is still poorly understood. Dune growth and stability is likely related to some combination of lake-level fluctuations, climate changes, and the incidence of strong storms (e.g., Arbogast and Loope, 1999; Loope and Arbogast, 2000; Arbogast et al., 2002; Arbogast et al., 2004; Hansen et el., 2010; Blumer et al., 2012; Lovis et al., 2012). Lake-level fluctuations may be important because they could have directly impacted the supply of sand that could be moved by the wind to form dunes.

In contrast, the impact of climate may be best exemplified by the most recent period of extensive dune growth, which occurred between ~1,000 and 500 years ago. This interval of time corresponds very well with the *Medieval Warm Period*, which is well documented in the Northern Hemisphere. This climate interval, which was likely somewhat drier in the Great Lakes region than the modern environment, could have changed the supply of sand in the dune system by reducing vegetation.

Additional evidence suggests that El Niño cycles could possibly play a role, with periods of stability occurring in centuries with relatively high occurrence of El Niño (Monaghan et al., 2013) because fewer strong storms may have occurred due to the configuration of the mid-latitude jet stream during those intervals. The precise interaction of these variables, *if* they occurred, and their response time(s), currently remains a mystery and thus a focal point for further research.

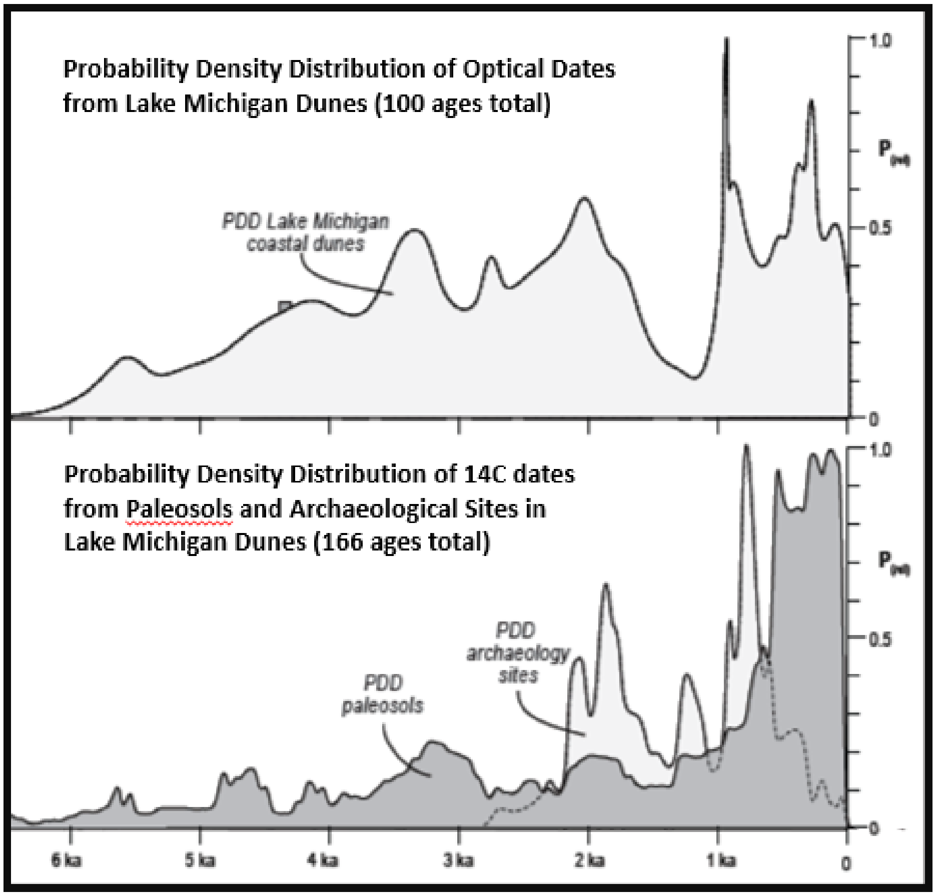

Figure 1. Probably density distribution (PDD) of ages derived from sand dunes along the shore of Lake Michigan in Michigan. Peaks on the graph represent periods of time when the probability of a certain age is greater. Note that the peak occurrence of dune growth occurs between 3.5 and 2.0 ka (thousands of years ago) and from 1.0 to ~ .5 ka. A distinct period of stability occurs from about 2.0 and 1.0 ka (source: Monaghan et al, 2013).

Regional Variations in Dune Position and Stability

In addition to the reconstructed history of dune growth and stability, it is now understood that dune systems in the northern part of Michigan differ from their counterparts in the southern part of the basin as far as their position on the landscape is concerned. Dunes in the southern end of the basin tend to consist of large, overlapping parabolic dunes with active blowouts in many places. These dunes line the shore for many miles and also contain several paleosols, indicating that they have grown upward in an episodic fashion through time.

In contrast, northern coastal dunes tend to occur in distinct embayments, such as Little Traverse Bay, and consist largely of distinct ridges that contain relatively few parabolic forms. In addition, buried soils are rare in this area. This lack of parabolic dunes and buried soils in the north suggests that dunes in this part of the basin formed quickly, whereas those in the south grew vertically and have been reworked frequently through blowout formation. The central part of the lakeshore, between approximately Muskegon and Ludington, appears to be a transition zone, with a combination of ridges and overlapping parabolic dunes present (Hansen et al., 2010).

This geographical variation in dune form is likely related to the differential effects of crustal rebound following the most recent ice age. It is well understood that the landscape in northern Michigan continues to rebound slowly from the weight of the most recent glacier that covered the region between ~ 30,000 and 10,000 years ago. In contrast, the southern end of the basin may be slowly subsiding. As a result, dunes have in the north have grown outward as new coastal surfaces rebounded above the water plane (Lovis et al., 2012). In the south, however, coastal dunes have been heavily eroded, resulting in their "cliffed" appearance.

Implications for Dune Management

The new understanding of coastal dune evolution in Michigan that has emerged in the past two decades could have significant implications for their management. In particular, this collective body of work clearly demonstrates that the coastal dune system should not be viewed as a singular body that formed largely during one interval of time thousands of years ago, but instead be should be viewed as a complex system that is dynamic.

Coastal sand dunes have long been portrayed and often managed as fragile features to be preserved, rather than as dynamic systems to be accommodated. The legislative findings section of the Sand Dune Management statute (Part 353), in fact, finds that "the critical dune areas of this state are a unique, irreplaceable, and fragile resource." National news coverage during the run-up to passage of Michigan's controversial 1989 dune management law similarly reflected the view of the day, saying this of the soon-to-be designated critical dunes: "Formed by the interplay of wind and water, sand dunes are particularly fragile and sensitive. Removal of vegetation for construction of a home, for instance, frequently results in a "blowout," in which the sand blows away down the shore - and often onto someone else's property."

While technically true – human and other impacts can and often do destabilize individual dunes, with the result often a suddenly more unpredictable and frustrating landscape of actively blowing, drifting and migrating sand – the image of the dunes as a discrete and largely static feature in need only of careful handling fails to capture the full, dynamic and diverse nature of the dune system overall. Emerging information about the age ranges and dynamic nature of the full coastal dune complex suggests that other influences – changing lake levels, climatic variations, weather patterns – have a much larger impact on the dunes as a system.

This should not be taken as a recommendation to ignore or downplay human activities and development approaches that clearly can and do destabilize individual dunes and create costly challenges for communities and neighboring homeowners. Rather, the science suggests that our management programs should be revisited with a greater appreciation for relative dynamism and diversity of the system—particularly the role of large-scale dune destabilization, migration and alteration, which has and will happen within much shorter time frames than previously understood, and which is driven by factors not entirely understood yet. A dune management approach that took this view would likely treat dune development with an eye toward hazard risk mitigation, in addition to slope, environmental or aesthetic concerns.

At present, the dunes are managed as if all dunes are essentially the same from a geomorphic perspective and that singular variables such as slope attributes can be used as a simple and effective surrogate for dune management. Research demonstrates, however, that dunes should likely be viewed individually when it comes to their management, with consideration of variables such as landscape position, geography, and growth history in mind. By using such a holistic view of the dunes, it is then possible to understand that comparative dunes with similar slopes may or may not be very different with respect to their overall stability. Such an understanding, in turn, can lead to better decisions about the impact that development may have in the immediate area.

The most recent changes to Michigan's dune management law, Public Act 297 of 2012 recognized the importance of science for effective dune management, specifically calling for the application of "the most comprehensive, accurate, and reliable information and scientific data available." To accomplish its stated purpose, one of Part 353 intentions is to: "Ensure and enhance the diversity, quality, functions, and values of the critical dunes in a manner that is compatible with private property rights."

Given the emerging understanding of dune age and dynamism, the *function* of a particularly younger dune, formed in the most recent period of extensive dune growth between ~1,000 and 500 years ago, may be to destabilize entirely, form large blowouts, and migrate or change dramatically in a relatively short time—a storm, a season or over a few years or decades. The *function* of an older dune formed in a growth phase 3,500 or 5,500 years ago, may be to continue growing a very stable and very inactive backdune forest with little risk of destabilization.

Development within a young dune system, perhaps more likely to destabilize during a warm period or a cycle of high lake levels, would need to be managed in such a way that risk is acknowledged and accommodated in order to avoid costs to the individual landowner and society.

Recommendations for Future Efforts

In addition to Michigan's Sand Dune Management program, dealing specifically with designated critical dunes, Michigan uses several different regulatory programs to manage development in the shoreline environment. Given the emerging science of dune age and dynamics, the authors believe a thoughtful look at both the Shorelands Protection for High Risk Erosion Areas (Part 323), and the Sand Dunes Management Program (Part 353) could prove interesting.

The purpose of the High Risk Erosion Area program is to "prevent structural property loss in an area of the shoreland that is determined by the department, on the basis of studies and surveys, to be subject to erosion" High risk erosion areas are defined as shorelands "where recession of the landward edge of active erosion has been occurring at a long-term average rate of one foot or more per year, over a minimum period of 15 years." Updating and modifying these recession rates, which were first created between 1980 and 1986 and which fluctuate with lake levels and other variables, remains a challenge for both DEQ and landowners. High Risk Erosion Area designation, unlike in the Critical Dunes program, applies to the entire parcel rather than existing as a separately mapped area or designation. Thus, a DEQ permit is required prior to construction on a parcel in a high risk erosion area regardless of where the structure is proposed on the parcel. Construction setbacks on each parcel are determined for the projected recession of the shoreline 30 years and 60 years into the future.

In addition several high profile initiatives are underway to better assess the hazards of shoreline areas of the Great Lakes, and to help communities deal with the dynamics of the coastal environmental in terms of risk and resiliency. For example, the Water Resources Center at the University of Michigan recently undertook a program called "Restoring, Retrofitting, and Recoupling Michigan's Great Lakes Shorelands," with a focus on assisting communities in planning for coastal resiliency, and learning from them how best to approach this emerging challenge. The Land Information Access Association's "Resilient Michigan" program also works with communities – often in partnership with the University of Michigan's efforts – to support comprehensive, risk-based planning. We believe it may be useful for such initiatives to also incorporate emerging research into the age and dynamic nature of coastal sand dunes.

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Additional resources:

Part 353: Sand Dunes Protection and Management (Critical Dunes), Natural Resources and Environmental Protection, Public Act 451 of 1994. (http://www.legislature.mi.gov/%28S%28llbzuckaviw2yai255mhikah%29%29/mileg.aspx?page=GetObject&objectname=mcl-451-1994-III-1-LAND-HABITATS-353)

Michigan Sand Dunes Management Program – Critical Dunes (Part 353) (http://www.michigan.gov/deq/0,4561,7-135-3311_4114_4236-9832--,00.html)

Part 323: Shorelands Protection and Management (High Risk Erosion Areas), Natural Resources and Environmental Protection, Public Act 451 of 1994. (http://www.legislature.mi.gov/%28S%28jeedgbyzxmjfddxnm2kwc42x%29%29/mileg.aspx?page=getobject&objectname=mcl-451-1994-iii-1-the-great-lakes-323)

Michigan Shorelands Protection for High Risk Erosion Areas (Part 323) (http://www.michigan.gov/deq/0,4561,7-135-3313_3677_3700_3995-344443--,00.html)

U-M Water Resources Center, “Restoring, Retrofitting, and Recoupling Michigan’s Great Lakes Shorelands” Program Fact Sheet (http://graham.umich.edu/media/files/watercenter-tier2-norton.pdf).

U-M/LIAA Resilient Michigan Planning Efforts in Coastal Communities:

- Grand Haven (http://www.resilientmichigan.org/grand_haven.asp)
- St. Joseph: (http://www.resilientmichigan.org/st_joe.asp)
- Ludington: (http://www.resilientmichigan.org/ludington_about.asp)