VOLUMETRIC ESTIMATES OF COASTAL SAND DUNES IN LOWER MICHIGAN: EXPLAINING THE GEOGRAPHY OF DUNE FIELDS

Alan F. Arbogast, Ashton M. Shortridge, and Michael E. Bigsby
Department of Geography
121 Geography
Michigan State University
East Lansing, Michigan 48824

Abstract: This study assesses the geography and volume of coastal dune sand along Lakes Huron and Michigan in Lower Michigan. Dune field extents were obtained from digital maps of critical dune area and soil parent material. Volumetric estimates were determined by establishing basal surface elevations and then calculating the average height of overlying dune deposits using digital elevation model (DEM) data within a raster GIS framework. Results indicate that ~1.8 km^3 of coastal dune sand occurs in Lower Michigan, with ~95% located along Lake Michigan due to prevailing westerlies. Most (~80%) of eolian sand is contained within 10 dune fields. Six of these fields are along the northeastern coast of Lake Michigan where they are associated with embayments and headlands, suggesting that changing shore angles and sandy bluffs are important geographical variables. Dune fields along the southeastern shore generally line the coast for greater distances and contain smaller concentrations of eolian sand that may be partially derived from debouching streams. Differences in sand volumes between the northeastern and southeastern coasts of Lake Michigan may occur, in part, because (1) northern coastal surfaces continue to rebound isostatically, resulting in progressively younger surfaces for dune growth, and (2) erosion in the southern end of the basin has removed dune deposits. [Key words: Michigan, coastal sand dunes, volume, digital elevation model, GIS.]

INTRODUCTION

Sand dunes are very common along the shores of Lower Michigan (Fig. 1). They are especially numerous along the eastern shore of Lake Michigan where they may represent the largest body of freshwater coastal dunes in the world (Peterson and Dersch, 1981). These dunes have a very high public profile in the state of Michigan for a variety of reasons. From a recreational perspective, millions of people visit the numerous state and county parks (as well as two national lakeshores) that are centered in dune landscapes. The dunes are also heavily utilized for foundry sand (Santer, 1993) because the deposits are extremely well sorted and have distinctive physical and chemical properties that are particularly well suited for casting purposes. Michigan's coastal sand dunes also contain a sensitive flora, including the threatened Pitcher's thistle (*Cirisium pitcheri*), and are thus ecologically important. Finally, the dunes are very popular sites for home construction because of their coastal location.

As a result of these various demands, Michigan's coastal dunes are heavily managed by the Departments of Natural Resources (MDNR) and Environmental Quality (MDEQ). Along the east coast of Lake Michigan, where the majority of

Physical Geography, 2009, **30**, 6, pp. 479–500.
 DOI: 10.2747/0272-3646.30.6.479

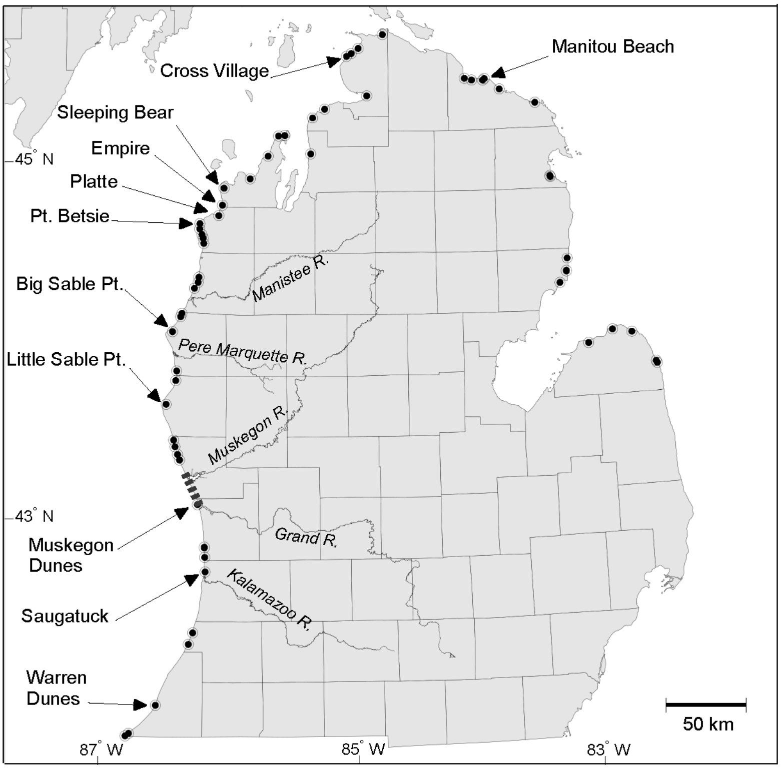

Fig. 1. Dune fields of Michigan's Lower Peninsula.

dunes occur, this management largely occurs within the framework of the Sand Dune Protection and Management Act (Michigan State Legislature, 1976), which was subsequently amended (Michigan State Legislature, 1994) to increase the regulatory authority of MDEQ through the establishment of numerous "critical dune" areas. These areas generally consist of the most spectacular dune landscapes and collectively encompass about 32,000 hectares of the coastline. Critical dune areas have particular properties, including (1) they consist of eolian sand, (2) they contain dunes at least 6.1 m (20 ft) in height, (3) they include exemplary dune-associated plant communities, and (4) they are within 3.22 km (2 mi) of a Great Lake. Initial work by MDNR to identify Michigan's CDAs resulted in an atlas published in the late 1980s (Michigan Department of Natural Resources, 1989). The maps associated with the atlas were subsequently evaluated and revised in 1996 using USGS topographic quadrangle sheets, aerial photography, and field surveys (Lusch et al., 1996). The vast majority of the critical dune areas are located along the eastern shore of Lake Michigan, with the remainder on islands in Lake Michigan, along Lake Michigan's northern shore, or on Lake Superior (Michigan Department of Environmental Quality, 2008).

Given the high profile of the coastal dunes in Lower Michigan, important questions remain about their geomorphology. A number of scientists (e.g., Cowles, 1899; Dow, 1937; Scott, 1942) investigated the dunes along the eastern shore of Lake Michigan in the early 20th century, but their research, which focused on descriptions of sand transport and deposition in various settings, was largely qualitative in nature. Dow (1937), for example, proposed that dunes that mantle topographically high headlands should be called "perched dunes." He also reported that sand is most likely supplied to these dunes when lake level is high and the adjacent bluff (the source for eolian sand) is destabilized by wave erosion. Other significant work of this early period was conducted by Olson (1958a, 1958b, 1958c), who discovered that foredune development was cyclic with low lake phases and that vegetation expanded across dunes in a predictable succession. Another important study of the dunes was conducted by Buckler (1979), who mapped the various kinds of dune landscapes (e.g., high-relief parabolic dunes, low-relief linear dune ridge) and established the concept of "barrier dunes" for those areas where dunes are a prominent barrier between the coast and interior locations.

After Buckler's (1979) classification scheme was implemented, research on Lake Michigan coastal dunes was not pursued systematically again until the 1990s. At that time, interest turned toward reconstructing dune evolution by analyzing stratigraphic relationships in conjunction with dating techniques such as radiocarbon dating and optical stimulated luminescence dating (e.g., Arbogast and Loope, 1999; Van Oort et al., 2001; Arbogast et al., 2002, 2004; Lepczyk and Arbogast, 2005; Timmons et al., 2007). The goal of this research has been to link periods of dune growth and stability with lake-level fluctuations (e.g., Baedke and Thompson, 2000). These studies demonstrate that Lake Michigan coastal dunes have a complex history. Periods of dune stability and soil formation tend to align in time with low lake stages, whereas episodes of dune growth generally appear to have most often occurred during high lake stages when beach erosion was common and landscapes were geomorphically active.

With a growing understanding of coastal dune evolution along Lake Michigan, attention has recently turned to relating geomorphic processes with larger scale classification schemes. In an effort to place Lake Michigan dunes in an international context, Arbogast (2009) proposed that large coastal dunes be broadly lumped into the category of *transgressive dunes*, which has been used by geomorphologists such as Hesp and Thom (1990) elsewhere in the world to refer to dunes that migrate across previously vegetated surfaces. Arbogast (2009) also proposed that transgressive dunes along Lake Michigan should be subdivided into two subcategories, (1) *high-perched dunes* and (2) *low-perched dunes*. High-perched dunes are those that mantle high headlands and bluffs, similar to those described by Dow (1937). Low-perched dunes, in contrast, are dunes that cover topographically lower pro-glacial lake plains. The common variable between high-perched and low-perched dunes is the apparent relationship of dune growth with high lake phases (e.g., Dow, 1937; Loope and Arbogast, 2000; Arbogast et al., 2002).

Although much has been learned about coastal dunes in Lower Michigan in the past 20 years, important questions remain. For example, coastal dunes along the western shores of Lake Huron and Lake Erie have yet to be studied at all. In addition, knowledge is lacking regarding the overall volume of eolian sand contained within coastal dunes and the geographical distribution of the sand. Understanding these patterns is important because it could shed light on sand source areas. In addition, it could provide insight into the factors (e.g., prevailing winds, littoral drift) that influence the deposition of eolian sand in certain areas and help explain why some locations are more favorable for the development of dunes than others. This study addresses some of these questions by analyzing the volume and geography of eolian sand along the coast of Lower Michigan.

STUDY AREA

The study area consists of the Lower Michigan coastline that includes the shores of Lake Michigan and Lake Huron (Fig. 1). Although these lakes are generally considered to be separate water bodies, they form a single hydrological unit because they connect at the Straits of Mackinac and have the same surface plane (Larson and Schaetzl, 2001). These lakes have evolved in a complex way since the end of the Wisconsin glaciation, with a major regression (Chippewa stage in Lake Michigan; Stanley stage, in Lake Huron) during the early Holocene that was following by a significant transgression (Nipissing in both basins) that peaked about 5,000 years ago at an elevation of about 185 m (Farrand and Drexler, 1985; Hansel et al., 1985). In response to downcutting of the North Bay outlet, the lakes subsequently fell and have been in a constant state of flux (Baedke and Thompson, 2000) since that time.

At present the water level in both lakes is about 177 m (Larson and Schaetzl, 2001). The configuration of the modern coast of western and northeastern Lower Michigan is highly variable with respect to the southern and northern parts of the peninsula. Both the northwestern and northeastern coasts of Lower Michigan have highly irregular coastlines with numerous well-defined embayments (Fig. 1). Aside from the very broad embayments centered on Saugatuck Dunes and Warren Dunes, the southwestern shore of Lower Michigan is much smoother. This variation in coastal configuration may occur because the northern part of the peninsula continues to rebound isostatically from the most recent ice age (Larsen, 1987), whereas the southwestern shore has been isostatically stable throughout the late Holocene. As a result, the southwestern shore may have been more prone to long-term erosion because coastal bluffs were impacted by waves more consistently.

The climate of the study area is classified as humid continental with a marine influence (Eichenlaub et al., 1990). Average high January temperature ranges from –1° C at St. Joseph in the southeastern part of the Lake Michigan shore to –4° C at the Straits of Mackinac. In contrast, the average high temperature in July at St. Joseph is 27° C, whereas it is 24° C at the Straits. Winds at both locations are multidirectional, with winter and summer winds being northwesterly and southwesterly, respectively (Eichenlaub et al., 1990). According to Chrzastowski and Thompson (1992), net sediment transport in Lake Michigan during the late Holocene has been toward the southern end of the basin. Lake Huron has probably exhibited a similar trend.

METHODS

Dune Area and Elevation Data

Two spatial datasets were used to estimate dune volume across this large geographic region, including (1) a representation of the spatial footprint for each dune field and (2) a digital elevation model covering these fields. It was also necessary to know the base height of each field. We employed two separate sources for identifying dune field areas along Lakes Michigan and Huron in Lower Michigan. On the west coast of the peninsula, we used digital GIS shapefiles of critical dune areas (CDAs) that were constructed by the Michigan Department of Environmental Quality (MDNR, 2001). Spatial coordinates were in the Michigan GeoRef coordinate system, which is an oblique Mercator projection with parameters that provide minimal distortion for the state. A total of 123 distinct areas, stored as polygons and covering 301 km^2, are included in this dataset. Although these polygons omit some dunes, it is clear that the vast majority of dunes, and certainly *all* major dune fields, are encompassed by the revised critical dune field's dataset (Lusch et al., 1996).

CDAs not located along Michigan's west coast and those that did not have apparent dune features on topographic maps were removed by the authors prior to analysis. Given that CDAs are not mapped along the Lake Huron shore of Lower Michigan, we used established dune areas on the east coast of Lower Michigan by digitizing soil survey data that identified soils formed in eolian sands. In addition to determining distinct dune areas, we gathered a variety of elevation data for volumetric calculations. One arc-second National Elevation Dataset (NED) data were obtained for the Lower Peninsula of Michigan. NED was developed by the US Geological Survey (USGS) from existing digital elevation data products (Gesch et al., 2002) and is available from the USGS seamless data server (U.S. Geological Survey, 2008). At the time of this study, 1 arc-second NED was the highest spatial resolution digital elevation model (DEM) available for the entire region. Source data for most NED data in Michigan were derived using 3.05 m (10 ft) interval contours from USGS 1:24,000 topographic quadrangles. Raster data were projected to the Michigan Georef coordinate system and resampled to a cell size of 30 m. Elevation in each raster cell had a precision of 1 m.

Finer resolution, 1/3 arc-second elevation data are available from the USGS for portions of the study region (United States Geological Survey, 2008). Due to concern that spatial resolution may affect our ability to detect the location and heights of coastal dunes, and therefore impact volume estimates of the dune fields, we obtained these data for four regions along the Lake Michigan shoreline. From south to north, these fields included northern Muskegon County, one at Point Sable in Mason County, the coast from the Platte River dune field to the Sleeping Bear field in Leelanau County, and one in Antrim County, on the eastern shore of Grand Traverse Bay. Each of these datasets was projected to Michigan GeoRef and resampled to a cell size of 10 m.

Identification of Dune Base Heights

After the dune area and elevation data were obtained, the next step was to estimate the elevation at the base of each dune field. This was accomplished using manual interpretation of USGS 1:24,000 topographic quadrangle maps and expert knowledge gleaned from numerous field visits to many of the dune fields. Although many dune fields had a consistent base height, several complexes exhibited substantial variation in base elevation. In these cases, dune field polygons were split into multiple sections, each with its own average base height.

Since the method for dune field identification differed between the Lake Michigan shoreline and the Lake Huron shoreline, separate polygon datasets were maintained. The final Lake Michigan dune area dataset consisted of 140 polygons covering 193 km^2. These polygons included 75 distinct fields. The largest section covered 16.9 km^2, while the area of the average polygon was 1.4 km^2. Base heights ranged from 181 m, about 4 m above the current level of Lake Michigan, to 275 m for perched dunes at Sleeping Bear National Lakeshore. Mean base height was 190 m, and the median base height was 186 m. The final Lake Huron dune area dataset consisted of 29 polygons covering 36 km^2. These polygons included 22 distinct fields. The largest polygon covered 9.7 km^2, while the average polygon area was 1.3 km^2. Dune field base heights ranged from 180 m to 206 m.

Volume Estimation

Calculations were conducted using ArcGIS 9.1 (ESRI, 2005), the open source Quantum GIS 0.91 (QGIS, 2008), and the statistical computing package R version 2.8 (R Development Core Team, 2008). The major steps of the process are summarized in Figure 2: (1) rasterize dune areas and extract the DEM elevations within those areas; (2) identify differences between each elevation in the dune fields and their associated base heights; (3) aggregate all positive height differences for each field; and (4) convert heights to volume. Dune area polygons were rasterized at 30 m cell size and expanded by 1 cell to ensure that areas within the polygons were not excluded from analysis. Each dune field could consist of more than one polygon, and therefore more than one contiguous block of cells. Each cell within a dune field had a code corresponding to that specific dune field, enabling subsequent aggregation of sand volumes by field.

Elevations within the dune areas were extracted from the DEM. For each cell, dune field base heights were subtracted from the cell's corresponding elevation. In a standard cut-fill analysis, both positive and negative differences between the height of the terrain surface and the base height surface may be of interest, but in the present case only positive differences were important. Consequently, negative values were removed from further analysis. In addition, cells in dune field areas with elevations below the base height were also removed from the field. We consequently employed revised dune field areas in which only cells corresponding to dune locations were used. The average positive difference was derived for each dune area section via a raster map algebra zonal calculation. The raster dune

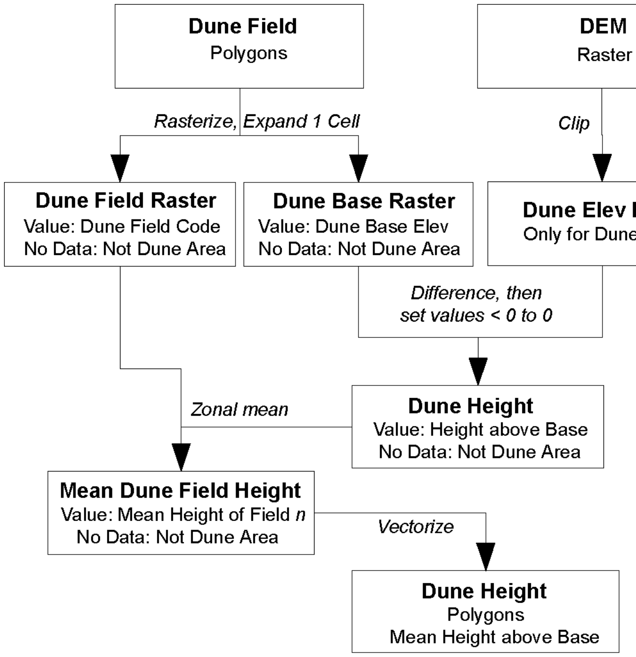

Fig. 2. GIS methodology for calculating dune field volume. Volume for each field = mean height × polygon area.

sections were converted back to polygons, and the average difference of each polygon was multiplied by its area to identify the sand volume, in cubic meters, of that section. Many distinct small areas in each critical dune area could be identified through this method; the dune volume dataset for Lake Michigan had over 1000 separate polygons. Dune volumes for all separate polygons falling within individual dune fields were added together to provide a final estimate of dune field volume.

The areal extents of dune area regions vary substantially, and it is possible that smaller fields might have greater concentrations of sand. To investigate the distribution of sand concentration, we divided the sand volume of each field by its post-processed area. This measure, which is average height of the dune field above its base, provides an intuitive and area-standardized estimate for sand concentration by dune field.

A major challenge in geographic analysis is that the results may depend very much upon the spatial resolution of the input data and how well that resolution is able to capture the landscape. To assess the magnitude of this challenge in the present work, we repeated the core methodology on four representative dune fields described in the previous section using 10 m resolution elevation data. We then compared volumetric estimates for these fields using the different resolution DEMs.

In addition to resolution-specific challenges, there may be substantial uncertainty in the volumetric estimates associated with our topographic map-based estimates of base dune height, as well as the positional quality of the critical dune area polygons. To assess the sensitivity of the results to these factors, the core methodology was repeated six times with varying inputs. In the first case, we shifted all base heights downward by 3 m, approximately one 3.05 m (10 ft) contour interval on the source topographic maps, simulating a systematic underestimation of the base height by a contour interval. In the second case, we shifted all base heights upward by 3 m, simulating a constant overestimation of the base height by one contour interval. In the third case, the critical dune area polygons were expanded outward 90 m via a spatial buffer operation to simulate a systematic dune classification bias toward larger fields. In the fourth case, critical dune area polygons were contracted inward by 90 m to simulate systematic bias toward smaller fields. The fifth case combined the lowered base height with the expanded dune polygons for a "largest dune" scenario, while the sixth case combined the raised base height with the contracted dune polygons for a "smallest dune" scenario. Volumes were calculated for all six cases.

RESULTS

A total of 61 dune fields had positive sand volume in at least one scenario. Of these dune fields 42 were located along the eastern shoreline of Lake Michigan. Table 1 presents sand volume estimates for the study area as a whole, and for the 10 largest dune fields. Our base estimate for total coastal dune sand volume in Michigan's Lower Peninsula is 1.84 km^3 in 57 distinct fields. Sand is not uniformly distributed between lake shores, or across dune fields. Coastal dunes along the west coast of Lower Michigan contain the vast majority (about 90%) of eolian sand on the peninsula. The only Lake Huron dune field appearing in this table is Manitou Beach, at #6. The joint dune sand estimate for the largest two dune areas in the state is greater than that of the smallest 51 dune areas combined. The largest five systems comprise about half of all sand volume in the study area. The next six systems contain about 26% of the total, and the remaining 50 fields hold about 24%. The spatial distribution of sand volume within the Lower Peninsula is shown in Figure 3. This distribution is not uniform; while many of the larger fields are distant from one another, a distinct concentration of intermediate to large fields occupies a short portion of the Lake Michigan coast in Leelanau County. Figure 4 presents the cumulative distribution of Lake Michigan dune volume from south to north. A perfectly uniform distribution would be linear; instead, very sharp increases are apparent in the north. The 50th percentile is reached only at Big Sable Point; one half the dune sand volume along the Lake Michigan Shore is located in fields at or north of this point.

Table 1 also reports results from the sensitivity analysis. Different scenarios resulted in a range of volume estimates from 0.98 to 2.38 km^3. Changing the base height and contracting the dune field polygons have substantial effects on volume estimates in the expected direction. Lowering the base height by a contour interval increases the total estimate by 30%, while raising the base height decreases the estimate by 24%. Contracting the dune area polygons by 90 m had an even larger impact, decreasing the estimate by 33%. Widening dune area polygons by 90 m has only a marginal effect on volume estimates. Scenarios that increase total sand

Table 1. Dune Sand Volume Estimates for Seven Scenarios

Field name	Base		High base		Low base		Wide poly		Thin poly		Low/wide		High/thin	
	km^3	%	km^3	%	km^3	%	km^3	%	km^3	%	km^3	%	km^3	%
Sleeping Bear	0.27	14.5	0.24	17.2	0.30	12.7	0.27	14.4	0.24	19.3	0.30	12.7	0.21	22.0
Warren Dunes	0.19	10.5	0.16	11.4	0.22	9.2	0.19	10.4	0.14	11.6	0.22	9.2	0.12	12.7
Muskegon	0.16	8.8	0.12	8.7	0.21	8.9	0.16	8.7	0.10	8.1	0.21	8.9	0.08	7.9
Little Sable Point	0.16	8.7	0.13	9.0	0.20	8.2	0.16	8.6	0.12	9.9	0.20	8.2	0.10	10.2
Cross Village	0.12	6.6	0.08	5.9	0.15	6.4	0.12	6.5	0.09	7.3	0.15	6.3	0.07	6.9
Manitou Beach	0.11	5.8	0.08	5.7	0.14	5.8	0.11	5.8	0.07	5.9	0.14	5.8	0.06	5.9
Saugatuck	0.10	5.6	0.08	5.8	0.13	5.3	0.10	5.6	0.07	5.5	0.13	5.3	0.05	5.6
Empire	0.09	4.9	0.08	6.0	0.10	4.1	0.09	4.9	0.06	4.8	0.10	4.1	0.06	5.8
Big Sable Point	0.08	4.5	0.06	4.3	0.11	4.8	0.08	4.5	0.06	4.8	0.11	4.8	0.04	4.5
Platte	0.06	3.2	0.03	1.8	0.11	4.8	0.06	3.2	0.04	3.6	0.11	4.8	0.02	1.8
Largest five	0.90	49.1	0.73	52.2	1.08	45.4	0.90	48.8	0.70	56.1	1.08	45.3	0.58	59.6
Largest ten	1.35	73.2	1.07	75.9	1.67	70.2	1.35	72.7	1.00	80.7	1.67	70.0	0.81	83.2
Lake Michigan	1.65	89.4	1.29	91.6	2.08	87.5	1.65	88.8	1.12	90.7	2.08	87.3	0.90	92.1
Lake Huron	0.20	10.6	0.12	8.4	0.30	12.5	0.21	11.2	0.12	9.3	0.30	12.7	0.08	7.9
All dunes	1.84	100.0	1.41	100.0	2.38	100.0	1.85	100.0	1.24	100.0	2.38	100.0	0.97	100.0

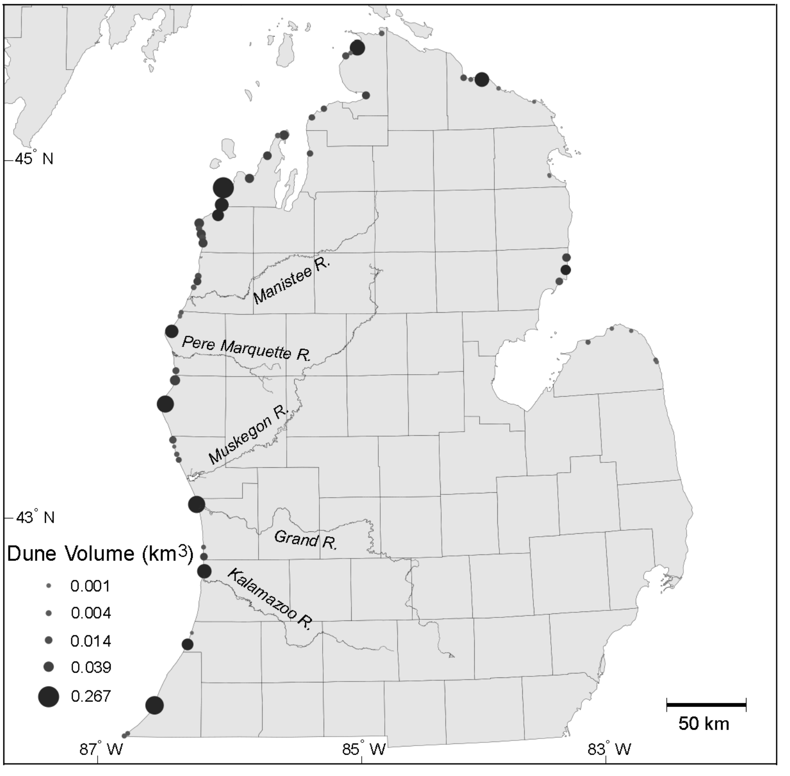

Fig. 3. Michigan Lower Peninsula dune field volume.

volume—those with lowered base heights—experience slightly more uniform sand distribution, with the top 10 fields containing 77% of the total. Scenarios that decrease total sand volume—those that raise base heights or contract the dune area polygons—experience greater concentration of sand in the largest fields. That is, the loss in sand volume is relatively greater for smaller dune fields. The high base scenario results in an increase of nearly 3% in the proportion of sand in the largest 10 fields, while the thin polygon scenario results in an increase of over 7%. Fully 83% of all sand is located in the largest 10 fields under the high-base/thin-poly scenario.

Most of the 10 greatest volume dune fields identified in Table 1 are also relatively large in area. Lower volume fields might nevertheless have greater concentrations of sand, given their size. Average height of the 10 highest dune fields above their bases, as determined following the removal of dune field areas below the dune base elevation, is shown in Table 2. There is some similarity with the largest volume fields. Eight of these highest average dune fields are in the top 10 in Table 1. However, the majority of fields documented in this table are much smaller. They contain great concentrations of sand relative to their spatial footprint. All but one of the 21 dune fields in this list occurs along the Lake Michigan shoreline, as portrayed in

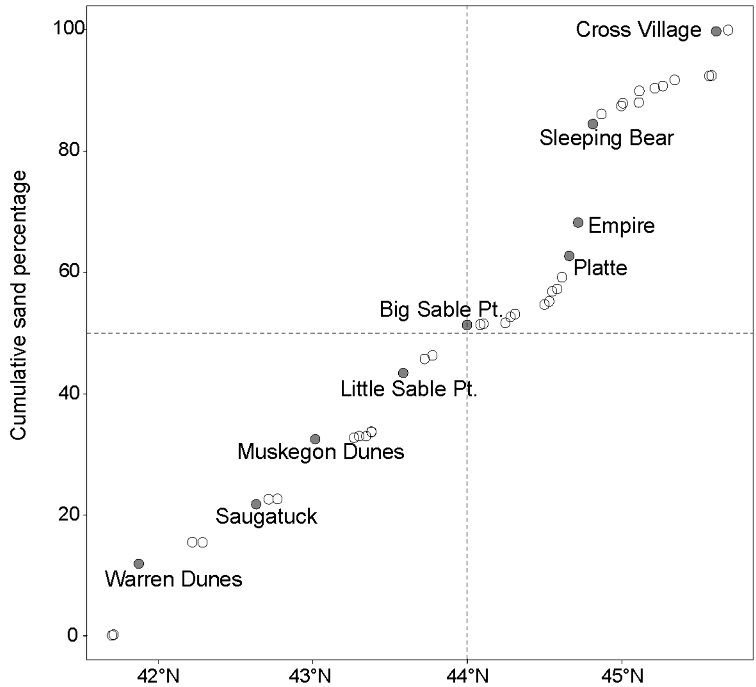

Fig. 4. Cumulative volume of eolian sand from south to north along Lake Michigan.

Figure 5, which shows the geographic distribution of average dune field height. There is a substantial spatial concentration of high sand dunes along the shoreline between Point Betsie and Sleeping Bear.

Dune volumes were estimated for portions of the coast where 1 arc-second, roughly 10 m resolution elevation data were available using both 30 m and 10 m data. These results are presented in Table 3. By far the largest amount of sand of the four areas examined was in the Platte–Sleeping Bear section, where about 0.4 km^3 of sand was identified. Both large and small fields were sampled to reconcile the variability of the results due to resolution effects. The areal extent of dune areas above the base height is consistently higher using the 10 meter DEM, and often substantially so. In three out of the four regions, the number of distinct areas (polygons) also increases substantially when using the finer resolution data. However, sand volume estimates are not uniformly greater when using the 10 m DEM. Sand volume estimates range from more than +30% to –10% below the base 30 m estimate. Overall, the volume estimate was 3.2% higher for the combined four studies. A comparison of 10 and 30 m dune estimates for a portion of the Platte River dune field is shown in Figure 6. It is clear that the finer resolution product is able to identify finer scale features; however, the overall pattern and extent is not especially different between the two.

Table 2. Dune Heights and Proportions for Dune Fields with Average Heights Greater than 10 Meters

Name[a]	Average height	Volume
Empire	47.0	0.091
Frankfort	31.0	0.027
Elberta	30.0	0.009
Sleeping Bear	26.8	0.267
Watervale	23.7	0.025
South of Portage Lake	19.7	0.016
Warren Dunes	19.3	0.194
Point Betsie	16.5	0.032
Pilgrim	16.0	0.006
West of Cross Village	16.0	0.011
Little Sable Point	15.1	0.160
Bass Lake	14.0	0.010
Pentwater	13.7	0.038
Saugatuck	13.2	0.103
Burgess	13.0	0.006
Macatawa	12.3	0.014
Cross Village	12.0	0.121
Manitou Beach	11.2	0.107
Van Buren	11.0	0.058
Portage Lake	10.9	0.008
Muskegon	10.6	0.162

[a]Italicized names are among the 10 largest by volume.

DISCUSSION

This study demonstrates that ~1.8 km^3 of eolian sand occurs along the coasts of Lake Michigan and Lake Huron in Michigan. Approximately 95% of this sand is found on the eastern shore of Lake Michigan, and about 80% of this sand is contained within 10 dune fields. Results from this study shed light on the factors that influence the deposition of eolian sand along the coasts of Lake Michigan and Lake Huron in Lower Michigan. On a regional scale, the most important variable that explains the large volumetric dichotomy between the two coasts is clearly the direction of prevailing winds. Given that these winds are essentially westerly in this mid-latitude location, it is logical that the vast majority of coastal eolian sand on the peninsula is on the eastern shore of Lake Michigan (i.e., west coast of Lower Michigan). The one place (Manitou Beach) along Lake Huron where large, voluminous coastal eolian sand occurs has a northerly aspect available to northwest winds. This pattern has been observed elsewhere on the west-facing coasts of the Great Lakes region where large dune fields occur on the southeastern side of Lake

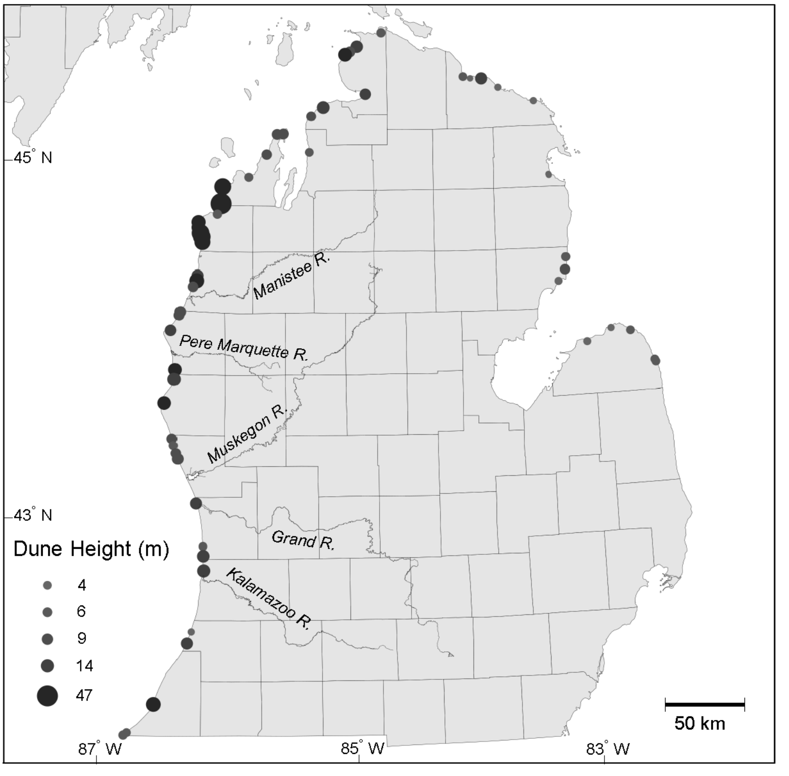

Fig. 5. Average field height (proxy for sand concentration).

Table 3. Comparison of Volume Estimates and Number of Individual Polygons Between 30 and 10 Meter DEMs for Selected Dune Fields

	30 m DEM			10 m DEM			
County	Area (m^2)	Volume (m^3)	Polygons	Area (m^2)	Volume (m^3)	Change (%)	Polygons
Antrim	1,398,600	0.006	13	1,825,700	0.007	30.5	13
Leelanau	21,334,500	0.399	43	23,119,300	0.417	4.3	55
Mason	6,193,200	0.060	50	6,708,800	0.053	–10.6	116
Muskegon	1,615,382	0.013	18	1,866,865	0.015	20.5	33
Total		0.478			0.493	3.2	

Huron (Dech et al., 2005) and the eastern side of Lake Ontario (Bonanno et al., 1998). Within North America, the largest coastal dune fields occur in the Pacific Northwest (Cooper, 1958; Hunter et al., 1983; Orme, 1992; Woxell, 1998), where westerly winds rework sands along the shore.

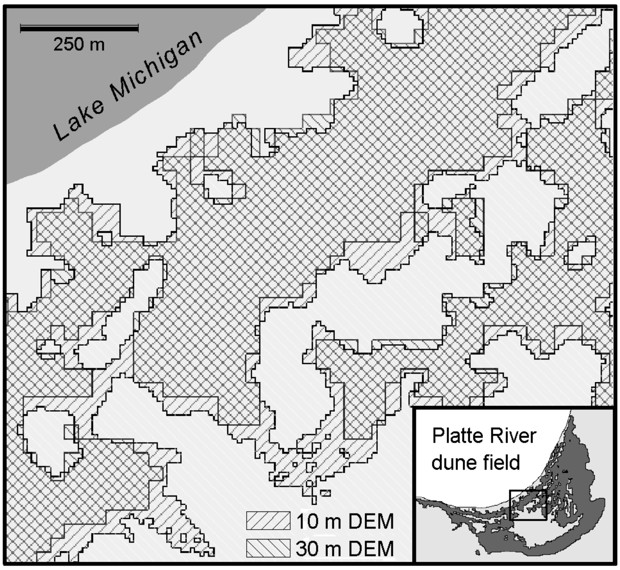

Fig. 6. Platte River: Differences in sand dune mapping using 10 m and 30 m. DEM sources.

This study also demonstrates the geographical patterns of dune formation at a subregional/local scale and thus suggests why certain locations are favored places of eolian sand. The most important of these secondary variables appears to be the configuration and aspect of the coastline at any given location. Most coastal dune fields in the north-central and northwestern part of the peninsula are clearly associated with some kind of an embayment or prominent headland that is a focal point for eolian sand deposition. According to Hesp (1999), such locations are favored because beach sand tends to be trapped by downdrift changes in shoreline angle and because headlands are bounding features.

An excellent example of this geographical association in northwestern Lower Michigan occurs where three (Sleeping Bear, Empire, Platte) of the top 10 dune fields (by volume) are located (Fig. 7). Although these dune fields are spread over only about 30 km of the coast, they collectively contain nearly 25% of the eolian sand on the peninsula. In addition to this concentrated area of coastal dunes, several distinct fields of eolian sand occur to the north. As shown in Figure 7, this portion of the Lake Michigan coast has several prominent embayments and headlands. Using Arbogast's (2009) terminology, a number of low-perched dunes are contained within the many arcuate embayments that mark this part of the coast. These locations are apparently a focal point of eolian sand deposition because sediment is funneled into them by littoral processes (e.g., Orme, 2002). These sands are likely derived from headlands that bound the embayments due to the concentrated effects of wave refraction. Most of the embayments contain well-defined pocket beaches that have likely formed due to the funneling effect of eroded headland sands into the embayments.

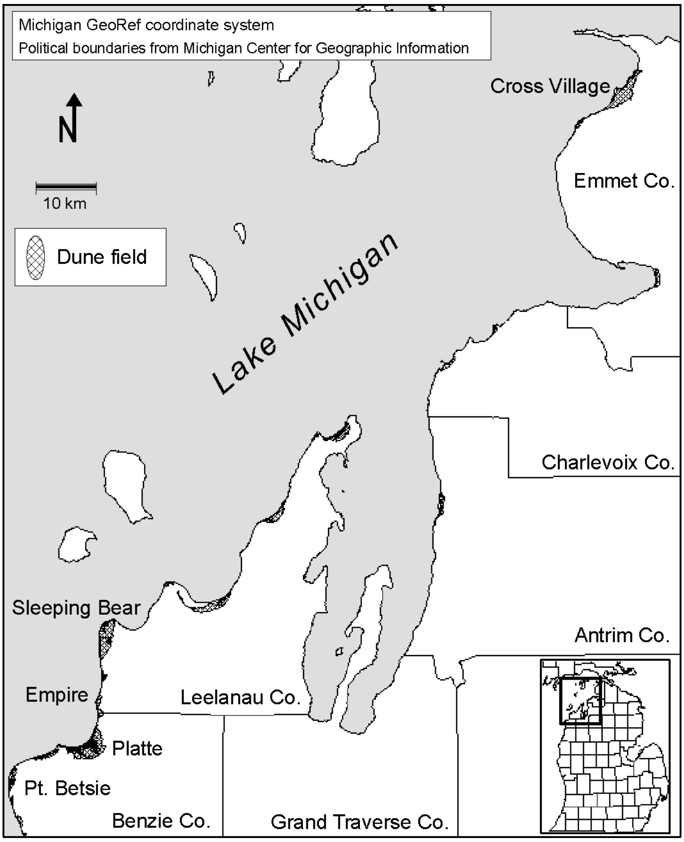

Fig. 7. Physical geography of coastal dune fields along the northwestern shore of Lower Michigan. Note the relationship of dune field location and coastal embayments.

Once these sands are deposited on the beach, they are free to be remobilized into the inland dune area. This remobilization of sand is enhanced in this part of Michigan because most of the embayments have a northwest aspect that faces the strongest onshore winds. The impact of these northwest winds is clearly visible along the coast of central Antrim County (Fig. 7), where only one notable dune field occurs. This dune field lies in the one area where an embayment is accessible by northwest winds. In contrast, areas to the south in the county are sheltered from the winds by the peninsulas to the west. Another factor that probably plays a role in dune growth in these northerly embayments is isostatic rebound from glacial unloading. This process has occurred throughout the Holocene in this part of Michigan (Larsen, 1987), which has provided progressively younger surfaces on which dune sand can accumulate.

In addition to embayments, headlands are also prime locations for dune growth in northwestern Lower Michigan because (1) they form topographic boundaries that trap littoral sediment (Hesp, 1999) and (2) they are associated with steep (~90 m high) bluffs composed of glacial sediment. This drift is part of the so-called "Manistee Moraine" (Dow, 1937) that is thought to have formed at the end of the Greatlakean readvance of the Lake Michigan lobe approximately 11,850 yrs B.P. (Evenson et al., 1976). Near Empire and Sleeping Bear Dunes, the drift exposed in the bluff faces is largely composed of sand that Dow (1937) argued is the dominant source for the high-perched dunes that mantle the adjacent plateau. Anderton and Loope (1995) demonstrated that eolian sand has been supplied to the Grand Sable dunes, a high-perched dune field along the southern coast of Lake Superior, in the past during high lake phases when the bluffs were destabilized by wave erosion. Such erosion would be intensified at headlands such as at Empire and the southern half of Sleeping Bear due to wave refraction. As a result, more sediment would presumably be liberated for eolian sand transport and deposition, especially since the strongest prevailing winds strike the bluffs directly. According to Snyder (1985), formation of high-perched dunes in the area began approximately 4500 years ago during the Nipissing high stand (Hansel et al., 1985), when coastal erosion would have been intense. Since that time, these sites have clearly been favored places for dune formation, as Sleeping Bear and Empire dunes contain the highest volume and concentration of eolian sand, respectively, along the Lake Michigan shore.

The effects of bounding headlands (Hesp, 1999) and aspect on dune formation can be seen in the north-central part of the Lake Michigan coast in Lower Michigan, specifically at Big and Little Sable points (Fig. 1). These locations are prominent headlands that are each over 15 km long and extend about 5 km into the lake. Aside from their large size, they fundamentally differ from the more northerly headlands because they are not fronted by high bluffs, but are instead underlain by late Holocene lacustrine surfaces that lie only 2 to 3 m above the lake. Nevertheless, they collectively contain over 13% of the total volume of eolian sand on the peninsula.

The large sand volume on Big and Little Sable points has apparently resulted because the changing shore angle associated with the headlands has trapped littoral and beach sediment (e.g., Hesp, 1999). It is possible that some of this sand is supplied to the area from the Pere Marquette and Manistee rivers, which debouch into Lake Michigan nearby (Fig. 1). These streams flow through sand-laden deposits in the northwestern part of Lower Michigan (Blewett et al., 2009). Given the extensive presence of dunes on both the northerly and southerly sides of these headlands, it appears that they are trapping sediment moving both north and south, probably on a seasonal basis. This hypothesis is supported by the orientation of parabolic dunes on the northwest- and southwest-facing shores of Big Sable Point (Fig. 8). Dunes on the northern part of the headland are oriented to the northwest, whereas those on the southern part of the headland are oriented toward the southwest. These respective orientations have likely resulted because the dominant winds in the fall and winter are northwesterly while those in the summer are southwesterly (Andresen and Winkler, 2009).

Although dunes in the north-central and northwestern coasts of Lower Michigan are clearly associated with major shoreline features, the geographic association of dunes along the peninsula's southwestern shore is less obvious because no prominent localized embayments or headlands occur in that subregion. Nevertheless, this

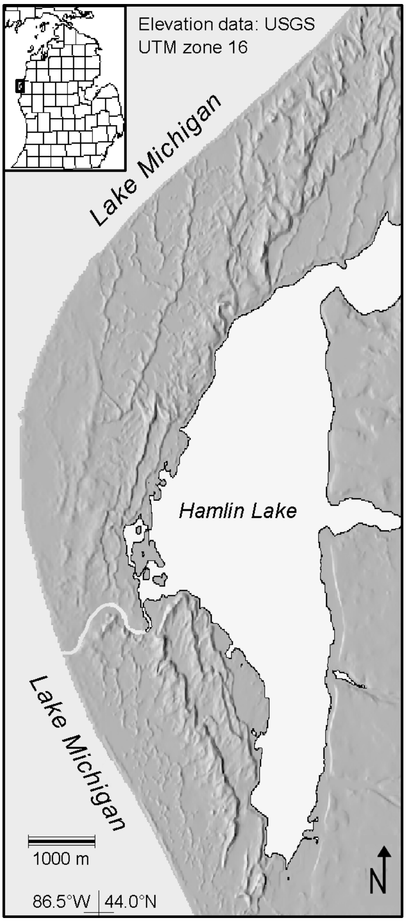

Fig. 8. Coastal dunes at Ludington State Park on Big Sable Point. The orientation of dunes on the north and south side of this bounding headland suggest that this coastal feature has trapped littoral sediment moving both from the north and south.

part of the coast contains nearly 25% of the total volume of eolian sand on the peninsula and the second (Warren Dunes) and third (Muskegon) largest dune fields. Warren Dunes is a distinct dune field, approximately 10 km long and 1 km deep, that contains about 10% of the total volume of eolian sand on the peninsula. Many of the dunes in this field are very large, reaching heights of about 60 m. In contrast, the Muskegon field consists of several localized dune clusters, such as those investigated by Arbogast and Loope (1999), between the city of Muskegon and Port Sheldon. Although this field contains almost 9% of the total volume of eolian sand in Lower Michigan, it is spread over about 50 km of shoreline and thus not particularly concentrated. Dunes in this field tend to be less than 15 m high and are thus significantly smaller than at Warren Dunes.

On a large scale, the extensive accumulation of eolian sand along Lower Michigan's southwestern coast may have resulted because the net transport of littoral sediment during the late Holocene was to the southern end of the Lake Michigan basin (Chrzastowski and Thompson, 1992). According to several studies (e.g., Arbogast and Loope, 1999; Arbogast et al., 2002; Hansen et al., 2002) dunes along this part of the shore began to grow about 5000 yrs B.P., with about 75% of the total volume deposited by 2000 yrs B.P. The onset of this depositional interval coincides with the Nipissing high stand (Hansel et al., 1985), when coastal erosion would have been extensive and the production of littoral sediment high. One hypothesis is that the sands within these sediments were slowly funneled on to beaches within the southern end of the basin over the course of about three millennia (Chrzastowki and Thompson, 1992), where they could be remobilized by eolian processes to progressively enlarge dunes. In this context, this portion of the Lake Michigan coast can be viewed as an enormous embayment (>150 km long) where sediment slowly accumulated and was gradually worked to form dunes by westerly winds.

In addition to the significance of net littoral transport during the late Holocene, secondary variables may have influenced the location of dune fields along the southwestern coast of Lower Michigan. Warren Dunes, for example, is located within the subtle Grand Marais embayment immediately south of Benton Harbor (Fig. 1), suggesting that small changes in shore angle in this part of the shore has trapped littoral sediment on a local level that contributed to dune development here (e.g., Hesp, 1999). This dune field also lies about 25 km south of the point where the St. Joseph River debouches into Lake Michigan. It is possible that alluvial sands entering Lake Michigan are a secondary source of dune sediment, as has been documented on the northwest coast of the United States (Masters, 2006; Hart and Peterson, 2007). In this context, the contribution of alluvial sediment may play an important role in the formation of other coastal dune fields in this part of Michigan because the largest streams in Lower Michigan enter Lake Michigan in this area. The northern end of the Muskegon dune field, for example, is in the general vicinity of the point where the Muskegon River enters Lake Michigan. Similarly, the Grand River flows into Lake Michigan in the central part of the Muskegon dune field at Grand Haven. South of this point, the Saugatuck dune field is located at the point where the Kalamazoo River debouches into Lake Michigan. This dune field contains about 5.5% of all coastal eolian sand in Lower Michigan, making it the seventh-highest volume on the peninsula.

CONCLUSION

Coastal sand dunes are very common along the coasts of Lower Michigan. This study assessed the volume of eolian sand on the peninsula and presented its geographic distribution. Volumetric estimates were obtained by establishing basal surface elevations of dune fields and then calculating the volume of sediment contained within overlying deposits. The approach employed in this study is carefully documented and should be replicable in other contexts. Results indicate that ~1.8 km^3 of eolian sand occurs along the coasts of Lower Michigan and that 95% of it is located on the eastern shore of Lake Michigan. The amount varies slightly when factors such as base elevation and dune field size are adjusted. These scenarios not only are useful for establishing the sensitivity of the base estimate; they also serve to provide circumstantial evidence about the quality of the input data products. Expanding the dune area polygons by 90 m had only a very minor impact on volume estimates (below the level of precision reported in Table 1). This indicates that, at least on average, no substantial elevated areas, including dunes, extended just beyond the bounds of the original critical dune area polygons. Contracting the polygons, in contrast, had a substantial effect; the two scenarios with smaller polygons were 69% as large as their comparable base polygon volume estimates. Reducing the size of the dune area polygons cut substantially into the above-base volume of the region, implying that the original dune area polygons fit closely to the base of the dunes they encompassed.

The basic dichotomy between the peninsula's eastern and western coasts reflects the influence of westerly winds on the location of dune fields. Overall, most (~80%) of the eolian sand is contained within 10 dune fields. Of these fields, six are in the northern part of the coast, where they tend to occur in association with isostatically raised embayments and prominent headlands. The largest dune field along the southeastern shore of Lake Michigan, and the second largest by volume, is also associated with an embayment. These patterns suggest that changing shore angles and the sandy composition of coastal bluffs are important variables regarding dune field location. Most of the southeastern coast of Lake Michigan is less irregular and dunes thus line the shore for greater distances. Nevertheless, they generally contain smaller concentrations of eolian sand than elsewhere. The supply of eolian sand to these fields may be derived in part from large rivers such as the Manistee, Muskegon, Grand, and Kalamazoo, debouching into Lake Michigan. Dune volume may also be less in the southwestern part of Lower Michigan because extensive beach erosion has apparently occurred in the late Holocene.

REFERENCES

Anderton, J. B. and Loope, W. L. (1995) Buried soils in a perched dunefield as indicators of Late Holocene lake-level change in the Lake Superior basin. *Quaternary Research*, Vol. 44, 190–199.

Andresen, J. A. and Winkler, J. A. (2009) Weather and climate. In R. S. Schaetzl, J. T. Darden, and D. Brandt, eds., *Michigan Geography and Geology*. Boston, MA: Pearson Custom Publishing, 288–314.

Arbogast, A. F. (2009) Sand dunes. In R. S. Schaetzl, J. T. Darden, and D. Brandt, eds., *Michigan Geography and Geology*. Boston, MA: Pearson Custom Publishing, 274–287.

Arbogast, A. F., Hansen, E. C., and Van Oort, M. D. (2002) Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. *Geomorphology*, Vol. 46, 241–255.

Arbogast, A. F. and Loope, W. L. (1999) Maximum-limiting ages of Lake Michigan coastal dunes: Their correlation with Holocene lake level history. *Journal of Great Lakes Research*, Vol. 29, 372–382.

Arbogast, A. F., Schaetzl, R. J., Hupy, J. P., and Hansen, E. C. (2004) The Holland Paleosol: An informal pedostratigraphic unit in the coastal dunes of southeastern Lake Michigan. *The Canadian Journal of Earth Sciences*, Vol. 14, 1385–1400.

Baedke, S. and Thompson, T. A. (2000) A 4,700 year record of lake level and isostasy for Lake Michigan. *Journal of Great Lakes Research*, Vol. 26, 416–426.

Blewett, W. L., Lusch, D. P., and Schaetzl, R. J. (2009) The physical landscape: A glacial legacy. In R. S. Schaetzl, J. T. Darden, and D. Brandt, eds., *Michigan Geography and Geology*. Boston, MA: Pearson Custom Publishing, 274–287.

Bonanno, S. E., Leopold, D. J., and St. Hilaire, L. R. (1998) Vegetation of a freshwater dune barrier under high and low recreational uses. *Journal of Torrey Botanical Society*, Vol. 125, 40–50.

Buckler, W. R. (1979) *Dune Type Inventory and Barrier Dune Classification Study of Michigan's Lake Michigan Shore*. Lansing, MI: Michigan Department of Natural Resources, Geological Survey Division Investigation 23.

Chrzastowski, M. J. and Thompson, T. A. (1992) Late Wisconsinan and Holocene coastal evolution of the southern shore of Lake Michigan. In C. H. Fletcher and J. F. Wehmiller, eds., *Quaternary Coasts of the United States: Marine and Lacustrine Systems*, *IGCP: Project #274*. Tulsa, OK: Society for Sedimentary Geology Special Publication No. 48, 397–413.

Cooper, W. S. (1958) *Coastal Sand Dunes of Oregon and Washington*. New York, NY: Geological Society of America, Memoir 72.

Cowles, H. C. (1899) The ecological relations of the vegetation of the sand dunes of Lake Michigan. *Botanical Gazette*, Vol. 27, 95–117.

Dech, J. P., Anwar Maun, M., and Pazner, M. I. (2005) Blowout dynamics on Lake Huron sand dunes: Analysis of digital multispectral data from colour air photos. *Catena*, Vol. 60, 165–180.

Dow, K. W. (1937) The origin of perched dunes on the Manistee moraine, Michigan. *Michigan Academy of Sciences, Arts, and Letters*, Vol. 23, 427–440.

Eichenlaub, V. L., Harman, J. R., Nurnberger, F. V., and Stolle, H. J. (1990) *The Climatic Atlas of Michigan*. Notre Dame, IN: University of Notre Dame Press.

ESRI. (2005) *Arc GIS version 9.1 (UNIX)*. Redlands, CA: Environmental Systems Research Institute.

Evenson, E. B., Farrand, W. R., Eschman, D. F., Mickelson, D. M., and Maher, L. J. (1976) Greatlakean Substage: A replacement for the Valderan Substage in the Lake Michigan basin. *Quaternary Research*, Vol. 6, 411–424.

Farrand, W. R. and Drexler, C. W. (1985) Late Wisconsinan and Holocene history of the Lake Superior Basin. In P. F. Karrow and P. E. Calkin, eds., *Quaternary Evolution of the Great Lakes, Special Paper 30*. St. John's, Newfoundland, Canada: Geological Society of Canada, 17–32.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D. (2002) The national elevation dataset. *Photogrammetric Engineering and Remote Sensing*, Vol. 68, 5–11.

Hansel, A. K., Mickelson, D. M., Schneider, A. F., and Larsen, C. E. (1985) Late Wisconsinan and Holocene history of the Lake Michigan Basin. In P. F. Karrow and P. E. Calkin, eds., *Quaternary Evolution of the Great Lakes, Special Paper 30*. St. John's, Newfoundland, Canada: Geological Society of Canada, 39–53.

Hansen, E. C., Arbogast, A. F., Packman, S. C., and Hansen, B. (2002) Post-Nipissing origin of a backdune complex along the southeastern shore of Lake Michigan. *Physical Geography*, Vol. 23, 233–244.

Hart, R. and Peterson, C. (2007) Late-Holocene buried forests on the Oregon coast. *Earth Surface Processes and Landforms*, Vol. 32, 210–229.

Hesp, P. A. (1999) The beach backshore and beyond. In D. A. Short, ed., *Handbook of Beach and Shoreface Morphodynamic*. New York, NY: Wiley, 145–169.

Hesp, P. A. and Thom, B. G. (1990) Geomorphology and evolution of active transgressive dunefields. In K. Nordstron and N. Psuty, eds., *Coastal Dunes: Form and Process*. New York, NY: Wiley, 253–288.

Hunter, R. E., Richmond, B. M., and Alpha, T. R. (1983) Storm-oblique dunes of the Oregon coast. *Geological Society of American Bulletin*, Vol. 94, 1450–1465.

Larsen, C. E. (1987) *Chronological History of Glacial Lake Algonquin and the Upper Great Lakes, Bulletin 180*. Washington, DC: U.S. Geological Survey.

Larson, G. J. and Schaetzl, R. J. (2001) Origin and evolution of the Great Lakes. *Journal of Great Lakes Research*, Vol. 27, 518–546.

Lepczyk, X. D. and Arbogast, A. F. (2005) Geomorphic history of dunes at Petoskey State Park, Petoskey, Michigan: Significance to coastal dune formation models. *Journal of Coastal Research*, Vol. 14, 231–241.

Loope, W. L. and Arbogast, A. F. (2000) Dominance of a ~150-Year cycle of sand-supply change in late Holocene dune building along the eastern shore of Lake Michigan. *Quaternary Research*, Vol. 54, 414–422.

Lusch, D. P., Hudson, W., Erickson, L. K., Krist, F., and Zweifler, M. (1996) *Evaluation of Critical Dune Areas Designated Under Part 353 (Sand Dune Protection and Management) of the Natural Resources and Environmental Protection Act 1994 PA 451: Final Report*. Lansing, MI: Michigan State Department of Environmental Quality.

Masters, P. M. (2006) Holocene sand beaches of southern California: ENSO forcing and coastal processes on millennial scales. *Paleogeography, Paleoclimatology, and Paleoecology*, Vol. 232, 73–95.

Michigan Department of Environmental Quality. (2008) *Critical Dune Area Maps*. Retrieved July 31, 2008, from http://www.michigan.gov/deq/0,1607,7-135-3311_4114_4236-70207--,00.html

Michigan Department of Natural Resources (MDNR). (1989) *Atlas of Critical Dunes*. Lansing, MI: Michigan Department of Natural Resources, Land and Water Management Division.

Michigan Department of Natural Resources (MDNR). (2001) *Critical Dune Area Metadata*. Lansing, MI: Michigan Department of Natural Resources.

Michigan State Legislature. (1976) *Sand Dune Protection and Management Act. Act No. 222*. Lansing, MI: Michigan State Legislature, Public Acts of 1976.

Michigan State Legislature. (1994) *Natural Resources and Environmental Protection Act. Parts 353 and 637, Act No. 451*. Lansing, MI: Michigan State Legislature, Public Acts of 1994.

Olson, J. S. (1958a) Lake Michigan dune development 1: Wind velocity profiles. *Journal of Geology*, Vol. 66, 254–263.

Olson, J. S. (1958b) Lake Michigan dune development 2: Plants as agents and tools in geomorphology. *Journal of Geology*, Vol. 66, 343–351.

Olson, J. S. (1958c) Lake Michigan dune development 3. Lake-level, beach and dune oscillations. *Journal of Geology*, Vol. 66, 473–483.

Orme, A. R. (1992) Late Quaternary deposits near Point Sal, south-central California: A time frame for coastal dune development. In C. H. Fletcher and J. F. Wehmiller, eds., *Quaternary Coasts of the United States: Marine and Lacustrine Systems, IGCP: Project #274*. Tulsa, OK: Society for Sedimentary Geology, Special Publication No. 48, 310–315.

Orme, A. R. (2002) Ocean coasts and continental margins. In A. R. Orme, ed., *The Physical Geography of North America*. New York, NY: Oxford, 425–455.

Peterson, J. M. and Dersch, E. (1981) *A Guide to Sand Dune and Coastal Ecosystem Functional Relationships*. Extension Bulletin E-1529, MICHU-SG-81-501. East Lansing, MI: Michigan State University.

QGIS. (2008) *Quantum GIS version 0.91*. Retrieved December 7, 2008, from http://www.qgis.org/

R Development Core Team. (2008) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved December 7, 2008, from http://www.R-project.org/

Santer, R. A. (1993) *Geography of Michigan and the Great Lakes Basin*. Dubuque, IA: Kendall/Hunt.

Scott, I. D. (1942) The dunes of Lake Michigan and correlated problems. *Michigan Academy of Science Arts and Letters*, Vol. 44, 53–61.

Snyder, F. S. (1985) A Spatial and Temporal Analysis of the Sleeping Bear Dunes Complex, Michigan: A Contribution to the Geomorphology of Perched Dunes in Humid Continental Regions. Unpublished Ph.D. dissertation, University of Pittsburgh, Pittsburgh, Pennsylvania.

Timmons, E. A., Fisher, T. G., Hansen, E. C., Eisaman, E., Daly, T., and Kashgarian, M. (2007) Elucidating aeolian dune history from lacustrine sand records in the Lake Michigan Coastal Zone, USA. *Holocene*, Vol. 17, 789–801.

U.S. Geological Survey. (2008) *The National Map Seamless Data Server*. Retrieved July 31, 2008, from http://seamless.usgs.gov/

Van Oort, M. D., Arbogast, A. F., Hansen, E. C., and Hansen, B. (2001) Geomorphological history of massive parabolic dunes, Van Buren State Park, Van Buren County, Michigan. *Michigan Academician*, Vol. 33, 175–188.

Woxell, L. K. (1998) Prehistoric Beach Accretion Rates and Long-Term Response to Sediment Depletion in the Columbia River Littoral Cell. Unpublished M.S. Thesis, Portland State University, Portland, Oregon.