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Repeat Photography of Lake Michigan Coastal Dunes: Expansion of Vegetation Since 1900 and Possible Drivers

Kevin G. McKeehan[a]* and Alan F. Arbogast[a]

[a] Department of Geography, Environment, and Spatial Sciences, Michigan State University, Geography Building, 673 Auditorium Rd, East Lansing, MI 48824, United States.

*Corresponding author: mckeeha2@msu.edu

Abstract

Coastal dunes are prominent features along the Lake Michigan shoreline, especially along Michigan's Lower Peninsula. Numerous studies in recent years have reconstructed the geomorphic history of these dune systems, from their initial formation in the mid-Holocene to about 300 years ago. These studies have suggested linkages between past dune behavior and climatic variability and fluctuating lake levels. Less is known, however, about how these dune systems change on shorter-temporal scales in the modern era and the potential drivers of that change. Using repeat photography, this paper attempts to demonstrate how the coastal dunes of Lake Michigan's eastern shore have changed since the 19th century. We collected hundreds of photographs of these dunes, taken between the years 1885 and 2018, from archives and citizen scientists. In the spring and summer of 2019, we took ~70 new photographs replicating the original images. The changes between coastal dune conditions in the original photographs and in the 2019 photographs show a general expansion of vegetation across formerly barren and active surfaces along the entire shoreline. Although human development has also played a role in reshaping the coastal dune systems, the most pronounced difference between historical and current dune conditions where repeat photography was conducted is the expansion of vegetation – grasses, shrubs, and even trees. Here, we present the 20 photograph pairs most representative of these trends, explore these changes, and discuss the likely causes, including the increase in precipitation in Michigan in the past ~80 years.

Keywords: Coastal dunes, Lake Michigan, repeat photography, bare sand, vegetation, climate trends, Holocene

Introduction

The coastal dunes along the eastern shoreline of Lake Michigan comprise a unique aeolian system. They are the largest freshwater coastal dunes in the world (Peterson and Dersch, 1981) and developed under different conditions than most coastal dune systems elsewhere, as they are not associated with tectonic or tidal activity (Hansen et al., 2010). Instead, as successive studies from the last ~25 years have shown, Lake Michigan's coastal dunes formed mostly due to reworking of sandy glacial and lacustrine deposits by forces related to climatic and lake level variability (Hansen et al., 2010; Loope and Arbogast, 2000; Lovis et al., 2012; Thompson et al., 2011). This understanding followed the dating of aeolian sands and buried soils at many dune sites (e.g., Arbogast and Loope, 1999; Kilibarda et al., 2014; Loope and Arbogast, 2000) that was paired with robust reconstructed lake level chronologies (e.g., Baedke and Thompson, 2000). Accordingly, the coastal dunes began forming during ancestral Lake Michigan's Nipissing high phase (~5.5 ka) (Lovis et al., 2012), although in some locations, especially along the southern shore, dune development may have started later (e.g., Argyilan et al., 2014; Kilibarda et al., 2014). Periods of dune stability and instability followed along much of the shoreline in the mid and late Holocene, culminating in a time of pronounced stability from ~2 ka to ~1 ka during which vegetation expanded across the previously mobile dunes (Arbogast et al., 2004; Lovis et al., 2012). This period of stability resulted in the Holland Paleosol, which is an inceptisol present in dunes along Lake Michigan's southeastern coast. Subsequently, dunes reactivated ~1ka (Lovis et al., 2012) and again ~0.5 ka (Hansen et al., 2010).

Reconstructed geomorphic histories from several sites indicated similar patterns of dune activity followed by sometimes brief periods of stability (e.g., Arbogast et al., 2002; Argyilan et al., 2014; Blumer et al., 2012; Hansen et al., 2004; Kilibarda et al., 2014; Lepczyk and Arbogast, 2005; Van Oort et al., 2001). From this, six phases of dune behavior since the Nipissing transgression were identified by Hansen et al. (2010), each characterized by distinct periods of dune stability or instability. These distinct phases were likely driven by a complex system of climate and lake-level changes, which either increased or restricted the supply of sand (Anderton and Loope, 1995; Arbogast et al., 2004; Dow, 1937; Loope and Arbogast, 2000; Lovis et al., 2012). Since then, a more complex explanation has emerged (van Dijk, 2004). Loope and Arbogast (2000) found dune building overall occurred during ~150-year cyclical lake-level fluctuations detected over the last 4,700 years on Lake Michigan through an examination of beach ridges and swale sediments (Baedke and Thompson, 2000; Thompson and Baedke, 1997).

On shorter temporal scales, additional variables were found to be critical in understanding Lake Michigan coastal dune behavior. In a series of related studies focusing on decadal changes in dune behavior at Indiana Dunes National Park, Olson (1958a, b, c) observed the relationships between wind, vegetation, lake levels, sand transport and deposition. In three related studies, Olson: 1) tested the manner in which wind, topography, and different types of vegetation built and eroded dunes primarily through the changes in surface roughness (Olson, 1958a); 2) examined the stabilizing geomorphic force of vegetation in more detail (Olson, 1958b); and 3) formulated a dune-building model tailored for Lake Michigan's coastal environments (Olson, 1958c). The model demonstrated how exposed offshore bars could be stabilized by pioneering grass assemblages during periods of low lake levels, leading to the development of a dune cap or incipient foredune (Olson, 1958c). Subsequent higher lake levels might then erode the newly formed foredunes, reworking the sandy sediment and increasing sand supply in the aeolian system, unless the incipient foredune stabilized sufficiently and became new foreshore-backshore margin. Olson's model comports somewhat to later dating research showing a time-transgressive structure exists in Lake Michigan's dune fields, with older dunes inhabiting the backshore areas and younger dunes forming lakeward (Hansen et al., 2010; Lovis et al., 2012).

Other studies identified wind energy in conjunction with human interventions as a primary factor in dune behavior (Bennett and Olyphant, 1998, 1993), while Loope and Arbogast (2000) found dune building on Lake Michigan's eastern shore is somewhat irregular and largely governed locally by differences in littoral geomorphology, available sand, wind regimes, and wave energy. In two related studies at P.J. Hoffmaster State Park south of Muskegon, indirect variables on foredune behavior, such as seasonality, proved to have more influence than variables directly impacting the landforms, such as wind velocity and direction, beach width, surface moisture, snow, ice, ground freezing, and dune vegetation (van Dijk, 2014, 2004). These two studies concluded that aeolian processes were strongest during autumn and winter months, when storms were stronger and vegetation less prevalent, and that further research regarding the relationships between important variables and aeolian landform response needed to be conducted. Similarly, Lepczyk and Arbogast (2005), in their ~4,800-year geochronology of dune behavior at Petoskey State Park, called for better understanding of modern dune conditions in an attempt to validate the accepted dune building models proposed by various workers.

Vegetation plays an important role in dune behavior and can be indicative of changes in the regimes of several variables, including precipitation. According to two classic studies from the region, vegetation affects geomorphic form, but specific species of grass and trees affect form in different ways, with some species more effective than others (Cowles, 1899; Olson, 1958b). This geomorphic variance by species has been confirmed in other, later dune vegetation studies (e.g., Lee et al., 2019; Ruggiero et al., 2018). The amount of vegetation coverage can also determine a dune's susceptibility to aeolian erosion (Hesp et al., 2021; Pelletier et al., 2009). The impetus for the establishment of coastal dune vegetation is dependent on several factors (Hesp et al., 2021), principally climate (Doing, 1985; Tsoar, 2005), favorable edaphic conditions (Baldwin and Maun, 1983; Cowles, 1899; Gardner and McLaren, 1999), and the availability of seed and rhizomes along with stochastic events (Hesp, 2002; Lichter, 2000). Seasonal variations of these and other factors play a role as well. For example, the summer establishment of grasses on bare dunes does not necessarily portend an expansion of vegetative coverage, as increased deposition of sand in autumn and winter buries the previous summer's new growth (Olson, 1958b; van Dijk, 2014). In the Lake Michigan-Huron basin, the establishment of vegetation was seen as a classic successional process involving pioneering plant species reliant on the amount of soil moisture, bare sand albedo and upper soil horizon temperatures, and topographic position of colonization, among other factors (Cowles, 1899). Alternatively, the factors governing establishment and dune succession are multifaceted and often random, reflective of the varied and harsh conditions of a complex coastal dunefield (Lichter, 2000, 1998). For example, dune succession is sometimes dependent on topographic aspect, the size of the rodent population, frequency of storms, and whether leaf litter is present, amongst other considerations. Importantly for our study, a recent paper examining dune landforms along the west African and the Canary Islands coasts linked vegetation density and dune stability closely with rainfall amounts (Hesp et al., 2021). This relationship also was suggested by White et al. (2019) with regards to changes in vegetation density on Lake Michigan's eastern shore.

As reported by White et al. (2019), vegetation appears to have expanded at many dune sites in state parks and Sleeping Bear Dunes National Lakeshore (SBDNL) along Lake Michigan's eastern shore since the 1930s. Aerial images from 1938 and 2014 of 16 dune park sites were compared to determine the change in vegetation coverage (White et al., 2019). Vegetation coverage expanded at 13 of the 16 sites, with vegetation growth by 2014 at Holland State Park and SBDNL exceeding 30% over coverage in 1938. It was speculated based upon meteorological data from Muskegon that precipitation may be driving the change in vegetation coverage in these dunefields (White et al., 2019). One site where White et al. (2019) did not detect an expansion of vegetation was P.J. Hoffmaster State Park. In an earlier study at this location, Belford et al. (2014) reported that bare sand expanded slightly at the park and an adjacent site at the expense of vegetation.

The goal of this paper is to further fill the gap in knowledge that exists within current literature about changes in general vegetation patterns in Lake Michigan coastal dunes during the modern era, defined here as the last ~200 years. We also aimed to quantify those changes as much as possible and determine potential drivers of these changes if they indeed occurred. Such findings may also shed light on past drivers of dune changes and place the Lake Michigan coastal dunes in current context of dune stabilization trends elsewhere, such as northern Europe, where bare and mobile sand dunes are declining at the expense of vegetated, immobile dunes (Provoost et al., 2011). Our paper attempts to determine if the changes reported by White et al. (2019) are occurring elsewhere on Lake Michigan's eastern shore using a different methodology, repeat photography, that is rarely employed east of the Mississippi River. After recapturing historical photographs of dune sites, we measured the amount of vegetative change between the original photos and those photos we captured in 2019 using a semi-quantified categorization.

Having evaluated the changes in dune vegetation, we then attempted to identify possible drivers of those dunefield changes by examining a wider array of meteorological data, including hourly wind reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), and by calculating three dune mobility indices – Lancaster's *M*, Chepil's C, and Drift Potential (*DP*) (Chepil et al., 1963; Fryberger and Dean, 1979; Lancaster, 1988). Each of these indices weighs meteorological data differently. Thus, relative changes or inertia over time amongst the indices could inform regarding the possible drivers of Lake Michigan dune conditions. We also applied Mann-Kendall tests to determine if any of the trends in the meteorological or dune mobility data are statistically significant. Additionally, we also examined the original land survey notes from the 19th century to understand if longer trends in vegetation coverage could be deduced, especially as those surveys were conducted in the closing years of the Little Ice Age.

Methodologies

Repeat Photography

Repeat photography has been a tool in the physical sciences for over 100 years (Rogers et al., 1984). The first documented series of photographs taken from the same location in a temporal sequence (i.e., repeat photography) was in 1888 in Switzerland, when Sebastian Finsterwalder first began surveying and photographing alpine glaciers in the eastern Alps (Hattersley-Smith, 1966; Rogers et al., 1984). A review of repeat photography studies since Finsterwalder reveals fewer studies have been set in the eastern United States than in the more arid, less tree-covered western United States. However, a few notable Michigan dune studies did accentuate photography (e.g., Cowles, 1899; Olson, 1958a, 1958b, 1958c), including Gates' study of the "disappearing" Sleeping Bear Dune (Gates, 1950). For our purposes, the results of White et al. (2019), coupled with other research regarding recent dune behavior (e.g., Abhar et al., 2015; Belford et al., 2014; Kilibarda and Shillinglaw, 2015; Millington et al., 2009), suggest that employing the practice of repeat photography, both ground-level and aerial, is a useful approach to determining trends in coastal dune systems, even in areas where more dense vegetation can be a photographic limitation. Most of these studies, including the White el al. (2019) paper in Michigan, employed the use of repeat aerial photography. We used ground-level repeat photography by obtaining historical photographs, evaluating each photograph's usefulness, recapturing the photos in the field, and then analyzing the results (Figure 1). The process involved libraries, archives, citizen scientists, several field trips to perform repeat photography, and software to analyze photographs digitally.

The first step in this process was to locate caches of historical photographs. An effort was made to search several known archives, including those in counties along the Lake Michigan shoreline. The primary sources for historical photographs were the Archives of Michigan, the Bentley Historical Library at the University of Michigan, the Photographic Archive at the University of Chicago, which included images from scientist Henry Chandler Cowles' coastal Michigan field trips, and the Saugatuck-Douglas Historical Society Museum. Another fruitful repository of historical dune photographs was the Michigan Department of Environment, Great Lakes, and Energy (EGLE), where several binders of photographic slides documenting coastal conditions from approximately 1965 to 1995 were discovered. Once suitable photographs were gleaned from these repositories, they were subsequently downloaded digitally into a database if online or a picture was taken of the photo with a digital camera. Additional photographs in various media were forwarded to researchers from citizen scientists, who answered appeals for their vacation photographs by local and social media through the *Sands of Time* project coordinated through the Michigan Environmental Council (Arbogast et al., 2020).

Eventually, 207 photographs were considered as potential candidates to be recaptured as part of this study. For a candidate to be truly viable, however, its precise location had to be identifiable and the photograph of good quality. Additionally, for the purposes of temporal analyses, it was necessary to know the approximate year the photograph was taken. All 207 candidates were documented in a database with information such as the year of the photograph, the image source, photographer (if known), year, and a description of the likely location, which was determined either through archival notes associated with the photograph or through an investigation using online and topographic maps.

Of the 207 candidates for repeat photography, 193 photographs were selected for field investigation. A total of seven field trips were made to the Lake Michigan coast to visit the locations where these photographs were originally acquired. Some photograph locations proved somewhat easy to find, while others were never located, as the human-built environment or other forces had altered the site beyond recognition. In addition, the aeolian nature of the landscape made it sometimes impossible to reshoot from exactly the same elevation as the original photograph. Once the approximate location of the photograph was found, care was taken to obtain the correct focal height, or camera's distance above the ground, angle, and light. Three cameras were used to take multiple photographs, including a 1974 Bell & Howell FD35 film camera, a Nikon Coolpix S6000 digital camera, and a personal cellphone. Multiple pictures from a variety of angles and *z* heights were taken with each camera.

Measuring Vegetation Expansion

Quantifying landscape change detected in repeat photographs is a challenge (Kull, 2005) as the process encompasses many variables. For instance, the precise location of the photographer of the original image is often impossible to determine in the field, while important camera variables such as focal length, *z* distance above the ground, tilt, roll, and azimuth are unknown unless recorded by the original photographer, which was unlikely. Taken together, these variables and others are often referred to as the projection matrix (Harley et al., 2019; Kohek et al., 2017). If too many variables in the projection matrix are unknown, then it is difficult to perform the pixel-to-pixel analysis between photographs. Moreover, there are often questions of resolution with the digital camera, the processing computer, and the output format all potentially having different resolutions (Hall, 2001). To accomplish the pixel-to-pixel effect, camera stations – known locations with a fixed stand and a camera cradle – were established to provide the repetitive conditions necessary for the process. Early glacial geomorphologists were amongst those who pioneered this process (Hattersley-Smith, 1966) and other disciplines, such as coastal geomorphology (e.g., Harley et al., 2019), have followed. Absent a camera station, researchers have either developed qualitative means for measuring landscape change, created a constrained quantitative methodology that focuses on only what can be measured with certainty, or crafted a mixed-methods approach (Bayr, 2021; Kull, 2005; Manier and Laven, 2002).

For our study, we estimated the change in vegetation by measuring the amount of bare dune sand visible in both the historical photographs and the re-photographs. To do this, we used ESRI ArcGIS software to georeference both photographs to each other in a local Cartesian coordinate system using control points visible in each (Figure 2). Then, the photos were cropped to include only the overlapping areas and the bare sand portions mapped as polygon feature classes. The unitless areas of bare sand were calculated and compared, with a percentage increase or decrease in bare sand computed. The final pixel analysis effect appears similar to other studies (e.g., Bayr, 2021 $_{\text{fig. 9}}$). Rather than report the exact or even approximate percentage change between the year the original photograph was captured and 2019, the year of the re-photograph, we rolled all results into broad categorical bins. We used this more qualitative reporting approach as we had neither camera stations nor fully known projection matrix values. These categorical bins are somewhat similar to those used by Kull (2005). Further, we measured bare sand, rather than vegetation, using heuristics due to sand's reflectiveness, which we felt was less subjectively observed. A machine learning process was not employed because of the wide variability and quality of the historical photographs.

U.S. Public Lands Survey (PLS)

Our study focuses on dune behavior in the modern era, roughly since 1830 when European patterns of settlement began in the region. To help estimate the coastal dune behavior just prior to the earliest photographs taken in our database, we used the U.S. General Office Public Lands Survey (PLS) notebooks kept by the field surveyors who walked the land in the 19th century to prepare the areas for formal settlement. Surveyors were instructed to inspect the land down to the quarter-section level, which was a ½ mi. x ½ mi (0.8 km x 0.8 km) . slice of a 36 mi^2 (93.6 km^2) township area, and report on the soil quality, trees and vegetation, and topography, amongst other features (Delcourt and Delcourt, 1996). For our purposes, the focus by the surveyors on these three landscape variables should yield information about the state of dunes on Lake Michigan's eastern shore at the time of the original survey, at least along quarter-section lines. Other geomorphologists and physical scientists have used the PLS notebook descriptions or similar texts to reconstruct pre-European settlement environments. For example, the diary descriptions of early European explorers were employed to reconstruct dune conditions on the Great Plains during the early 1800s (Muhs and Holliday, 1995), while PSL surveyor notebooks were used to determine that presettlement forests in Michigan's Upper Peninsula were more heterogenous than present (Delcourt and Delcourt, 1996). While there are concerns regarding the quality of some PLS notebook descriptions, the source overall has been considered "quantitative" (Schulte and Mladenoff, 2001) and "one of the best records of the pre-European settlement" (Manies and Mladenoff, 2000). We accessed PLS notebook descriptions for the nearest survey to each of our repeat photograph locations from Michigan History Center, then examined the records for indications of bare sand or dune vegetation. We recorded the surveyor's words for each site, along with the year, and created a word cloud to gauge dune conditions at the time of the original survey in the study area prior to the era of our photographs. The notebooks are sprawling datasets; as such, we confined ourselves to reporting descriptions associated with the nearest section line boundary or meander survey.

Meteorological Data

To determine possible drivers of dune vegetation trends, we obtained meteorological data from the Midwestern Regional Climate Center (MRCC) for three sites that are geographically distributed along the Lake Michigan coast – South Bend, Ind., and Muskegon and Traverse City in Michigan. These three sites were chosen for two reasons. Firstly, they are geographically well-distributed across our study area (Figure 3). Secondly, they possess the longest, most complete meteorological records for the eastern shore of Lake Michigan. From the MRCC data, we were able to extract 79 years worth of uninterrupted precipitation and temperature data for South Bend, 91 years of data with some gaps for Muskegon, and 111 years for Traverse City. Other stations, including Benton Harbor and Grand Haven, did not possess such unbroken, complete datasets. Neither South Bend nor Traverse City are on Lake Michigan, although the latter is on the West Arm of Grand Traverse Bay. Both sites, however, are ~35km from the eastern shore of Lake Michigan. These stations are the closest stations to the lake we could find that had the most complete records.

Unfortunately, hourly observational wind data are often incomplete. Reanalysis data, which are often utilized in atmospheric and climate models, attempt to solve this problem by blending known, historic weather observations with modeled data to fill in the gaps (Hayes et al., 2021). The dune mobility indices we are utilizing in this study require complete wind data as an input without any gaps. As a result, we obtained hourly wind reanalysis data from the European Centre for Medium-Range Weather Forecasts' (ECMWF) the ERA5 dataset, which are stored in grib messages in a 0.25°x0.25° or ~1,000km^2 grid (Bell et al., 2020; Hersbach, H. et al., 2018).

The hourly wind speed represents the wind speed at the given hourly interval averaged for the entire reanalysis grid (Yan et al., 2020). To process the grib messages and extract the 10m-height *u* and *v* wind components, we used the PyGrib 2.1.3 interface module with Python 3.9.1, NumPy 1.20.0, and Pandas 1.2.3 in the Google Colaboratory environment. After translating the grib messages, we were able to determine hourly wind speed in m/s and use these data to feed into the dune mobility indices.

Dune Mobility Indices

Dune mobility indices can evaluate the capacity of sand to mobilize based upon a location's climatic conditions (Abbasi et al., 2019; Lancaster and Helm, 2000). Each index considers and emphasizes a different set of variables when determining dune mobility potential. We calculated three different indices – Lancaster's *M*, Chepil's C, and Drift Potential (*DP*) (Chepil et al., 1963; Fryberger and Dean, 1979; Lancaster, 1988) – for each year beginning in 1950 for the three abovementioned meteorological stations – South Bend, Muskegon, and Traverse City. Our goal was to determine if any trends in the indices correspond to trends in dune vegetation change. Lancaster's *M* was developed to measure mobility in desert continental dunes and has been applied as such in several studies (e.g., Cordova et al., 2005; Muhs and Maat, 1993). Lancaster's *M* has also been applied to studies of coastal dunes in northwest England (Delgado-Fernandez et al., 2019), Wales (Rodgers et al., 2019), and the Canary Islands (Smith et al., 2017), although never to our knowledge in the study of inland coastal dunes like those found along Lake Michigan. The index considers sand mobility to be a function of the annual percentage of time the wind is above the threshold for sand transport (W), which is determined to be 4.5 m/s, and the ratio between annual precipitation (P) (mm) and adjusted potential evapotranspiration (PET) (mm) as calculated using the Thornthwaite method (Lancaster, 1988; Lancaster and Helm, 2000; Thornthwaite, 1948; Thornthwaite and Mather, 1957):

$$M = W/(P/PET)$$

(1)

As mentioned earlier, annual precipitation across Lower Michigan appears to have increased since 1930 (White et al., 2019). Thus, as an index, we hypothesize that Lancaster's *M,* as it is attuned somewhat to precipitation, might reflect this increase by returning diminished mobility over time, especially since Lancaster's *M* performs well at decadal timescales (Rodgers et al., 2019). However, it is also possible temperatures have risen since the 1930s, perhaps due to anthropogenic climate change. This would drive PET higher, potentially offsetting any index changes attributed to precipitation.

Chepil's C*,* or average annual wind erosion climatic index (Chepil et al., 1963), is the second mobility index we calculated. Developed after studying wind erosion and dust storms on the Great Plains, Chepil's C attempts to measure wind erosion capacity by dividing the cube of average annual wind velocity (*v*) by the square of soil surface moisture or by Thornthwaite's effective precipitation index (P-E) (Chepil et al., 1963; Talbot, 1984). Thornthwaite's effective precipitation index is defined as precipitation divided by evaporation and is sometimes written as P-E (Thornthwaite, 1931). The formula for Chepil's C is (Chepil et al., 1963):

$$C = v^3/(P\text{-}E)^3$$

(2)

Chepil's C was used to understand potential dune mobility in the mostly vegetated Sahel of West Africa (Talbot, 1984). Its emphasis is somewhat distinct from Lancaster's *M*, in that Chepil's C uses Thornthwaite's effective precipitation index to approximate soil moisture (Skidmore, 1974; Talbot, 1984) and considers the effect of wind differently, using the average annual wind velocity instead of the annual percentage of time the wind is above the threshold for sand transport. Moreover, Chepil et al. (1963) concluded that the index values could track with annual episodes of storminess and created an iteration of C that accounted for the lag in landscape response to years with a high number of storms. This iteration, which is known as C_3, is a three-year running average of C (Chepil et al., 1963). Thus, if a decrease in storminess has occurred on the eastern shore of Lake Michigan and is driving dune stabilization, Chepil's C may be the vehicle that detects such a change, although we hypothesize that the values of C_3 will largely be unchanged since 1950. A decrease in C_3 could also be interpreted as an increase in dune soil moisture, although Thornthwaite's index has issues in this regard (Talbot, 1984). We feel these features make Chepil's C_3 unique from Lancaster's *M*, which focuses on precipitation and temperature, as C_3 attempts to gauge storminess and soil moisture indirectly. Here, we report C_3 as Chepil et al. (1963) did. Moreover, we adhere to the unnormalized, simplified formula seen above that was used by Talbot et al. (1984) and reported by Abbasi et al. (2019).

The final dune mobility index we calculated is Drift Potential (DP), which considers the potential for sand transport by focusing solely on wind power (Fryberger and Dean, 1979; Yizhaq et al., 2007). DP as constructed by Fryberger and Dean (1979) uses a higher sand mobilization threshold (6 m/s) than Lancaster's *M* and was first reported as Q. DP is expressed as the squared observed hourly wind value multiplied by the wind value minus the sand mobilization threshold (V_t), the result of which is multiplied by 1/n of the number of observations, a value originally reported as t (Fryberger and Dean, 1979). Here, we have simplified the DP formula from that reported by Fryberger and Dean (1979):

$$DP = V^2(V - V_t) \cdot 1/n$$

(3)

We did not calculate other associated DP statistics, such as resultant drift potential (RDP), as we are concerned with overall wind power only. Based upon our knowledge of regional meteorological trends, we hypothesize that there has been no significant change in wind power along the Lake Michigan shore that could explain a possible expansion of dune vegetation. However, there are indications that some locations in the Great Lakes basin are becoming windier (Desai et al., 2009). Nevertheless, windier conditions would somewhat preclude dune stabilization as erosion would increase (Pye et al., 2014), although it is unclear how much influence wind power alone has in determining dune, vegetation, or erosion conditions (Mason et al., 2008; Smalley, 1970). Taken together, we hypothesize that none of the three dune mobility indices will have changed relatively in ways which can explain a possible increase in vegetation since the 1930s, suggesting a complex forcing similar to studies elsewhere that found some changes in climate may not be enough to explain vegetation gains (e.g., Delgado-Fernandez et al., 2019). In fact, some indices may trend in ways which suggest Lake Michigan's coastal dunes should be mobilizing, rather than stabilizing. In that case, we will be left to explain the expansion of vegetation through alternative explanations.

Determining Trends and Statistical Significance

Mann-Kendall tests can be calculated to determine if trends exist with an observed variable over time by evaluating Kendall's τ and its significance (Helsel and Hirsch, 2002; Mann, 1945). If monotonic trends in the aforementioned meteorological and dune mobility metrics exist, Mann-Kendall tests could detect their strength and if they are statistically significant, helping us establish possible drivers for dune conditions. While similar to a regression analysis, the Mann-Kendall tests does not assume a normal distribution of residuals and, thus, is nonparametric (Helsel and Hirsch, 2002). Mann-Kendall tests trends by calculating the *S*-statistic (Pohlert, 2020a), which is done by evaluating the difference in earlier observed values X_k and later observed values X_j through the sign function (Meals et al., 2011)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k)$$

(4)

The properties of the *S*-statistic can be transferred into two other metrics, both of which we will report instead of *S*. The *Z*-statistic, which is occasionally reported in geoscience studies (e.g., Gocic and Trajkovic, 2013), detects the existence of trends through the *Z*-transformation of *S* (Gocic and Trajkovic, 2013; Pohlert, 2020a):

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(s)}} & if \quad S < 0 \end{cases}$$

(5)

Additionally, Kendall's τ_b, a measure of rank correlation and association (Kendall, 1938) which is often reported in studies along with or instead of other metrics (Corbella and Stretch, 2013; e.g., Mason et al., 2008; Reyes et al., 2020), is derived from its relationship to the *S*-statistic (Pohlert, 2020a) and the maximum possible value of *S* (*D*) given the number of observations (*n*) and accounting for tied results (*t*) (Brophy, 1986):

$$\tau = \frac{S}{D}$$

(6)

Where:

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{P} t_j\left(t_j - 1\right)\right]^{\frac{1}{2}} \left[\frac{1}{2}\, n\,(n-1)\right]^{\frac{1}{2}}$$

(7)

The Mann-Kendall test is relatively common in hydrological studies (Yue et al., 2002b) and even has been used to evaluate the factors behind dune mobility (e.g., Mason et al., 2008) and arid land conditions (Li et al., 2015; e.g., Wang et al., 2017). Here, we utilized the "trend" r package to produce three metrics: the *Z* statistic, Kendall's τ, and P-values (two-tailed) (Pohlert, 2020b).

However, one of the assumptions regarding the proper application of the Mann-Kendall test is that the data are free of serial correlation, also known as autocorrelation (Yue et al., 2002b). In other words, since Mann-Kendall evaluates a variable Y over a time series, it is possible that Y accumulates or dissipates over time naturally, resulting in a statistical influence on the reported trend (Ezekiel and Fox, 1959). This condition could induce Type I errors in Mann-Kendall tests (Bayazit and Önöz, 2007), or make the test too "liberal" in its trend analysis (Kulkarni and von Storch, 1995). One approach in reducing serial correlation is to perform a process known as "pre-whitening", which seeks to model the time series data as an autoregressive (AR1) model with a mean of 0 by subtracting the time-accumulated "memory" of the data (Kulkarni and von Storch, 1995). This procedure makes any time series more "orthogonal" (Box and Jenkins, 1976). While some studies suggest a trend analysis involving atmospheric phenomenon should contain a pre-whitening procedure (e.g., Collaud Coen et al., 2020), others have suggested the process introduces significant Type 2 error by not detecting trends when they exist (Bayazit and Önöz, 2007; Razavi and Vogel, 2018). In fact, alternative pre-whitening techniques have been proposed to address these issues (e.g., Yue et al., 2002b). However, Bayazit and Önöz (2007) determined that pre-whitening was unnecessary in data with more than 50 observations, a threshold all our data achieves.

To determine if pre-whitening our data was necessary, we employed a different approach and calculated serial correlation within our Y variables by conducting a series of Durbin-Watson tests. Although a less common approach, other studies have employed a Durbin-Watson test of serial correlation in conjunction with a Mann-Kendall trend analysis. This includes, most relevantly, a study of precipitation trends in Brazil in which the authors performed the Mann-Kendall test after finding no serial correlation in their data from the Durbin-Watson test (Blain and Bardim-Camparotto, 2014). We employed a similar approach.

The Durbin-Watson test is an evaluation of serial correlation through the calculation of the *d*-statistic, where *z* is the residual from the regression (Durbin and Watson, 1951):

$$d = \frac{\sum(\Delta z)^2}{\sum z^2}$$

(8)

We calculated the Durbin-Watson test using the dwtest function within the "lmtest" r package (Zeileis and Hothorn, 2002). As Chepil's C_3 is a moving average and, consequently, inherently autocorrelated, we ran Durbin-Watson tests on the raw Chepil's C instead.

Results

Repeat Photography

Of the 193 candidates, a total of 72 repeat photographic pairs were created (Figure 3). Citizen scientists contributed a handful of photo candidates and only 2 of those were part of the 72 eventual pairs. Here, we report on 20 pairs (Table 1) that best represent the trends seen in dune systems along Lake Michigan's eastern shore. These 20 pairs are also relatively well-distributed geographically north to south along the coast. The remaining 52 repeat photographic pairs were set aside for a variety of reasons. For example, some photographic pairs were not used because the site had changed so much that a vegetation analysis was impossible; others were not used because the re-photograph was taken at the correct vicinity, but at the wrong tilt, roll, *z* height, or distance from the original camera location.

Of the 20 pairs we report here in this article, we visually present the 6 most representative repeat photographic pairs in Figures 4 – 9. All 20 pairs are available in the Electronic Supplementary Material Appendix S1. Additional photographs can be viewed on the Michigan Environmental Council's Learning to Live in Dynamic Dunes website (Learning to Live in Dynamic Dunes, 2020). In most of the paired photographs, two distinct trends have emerged – one extensive, the other less so. In most of the historical photographs, regardless of their year, bare sand is abundant, while in the 2019 re-photographs, vegetation has expanded considerably. This expansion of grasses and, in some cases, invasive species, trees, and other woody vegetation is a considerable trend, one which we evaluated (see below). At some of the sites, the presence of vegetation allowed the landscape to aggrade, or become slightly convex. This is likely due to the ability of grasses and trees to trap additional entrained and saltating mobile sand. The other, less ubiquitous trend involves the advent of the human-built environment, in the form of beachside homes, barriers, buildings, roads, and trash. This human intervention is not seen at all or even most sites, but it is pronounced south of Warren Dunes, around Holland, and near Muskegon. Perhaps the best example of human intervention in the dune environment can be seen in the far south at Grand Beach (Figure 4), where a dune known as Eiffel Tower Dune was flattened partially and made into homesites, not all of which contain homes.

Measuring Vegetation Expansion

We categorized the trends in dune vegetation expansion seen in Figures 4 – 9, as well as the other 14 photos in ESM Appendix S1. An example of the results of the process can be seen in Figure 10. At no site did bare dune sand expand overall at the expense of vegetation (Table 2). Most sites lost much of their bare dune sand. Moreover, there was no geographic distribution amongst the results; sites that lost the least bare sand (i.e., Big Sable Point) or the most bare sand (i.e., Laketown Beach), were found in the southern, mid, and northern sections of the coast. These semi-quantified results confirm the trends seen visually in the repeat photograph pairs.

U.S. Public Lands Survey (PLS)

PLS notebooks revealed many sites contained bare sand in the early- to mid-19th century (Table 3). While it is difficult to draw conclusions based upon historical or qualitative data, some patterns do emerge. First, bare sand is mentioned at 15 of 20 sites by the PLS surveyors and at least once by each of the 6 different surveyors. Second, "bare sand" becomes more ubiquitous and vegetation less so in the notebooks as the surveys move north and forward in time, lending the results the veneer of a spatio-temporal pattern. Specifically, north of Holland and after 1832, trees species are mentioned only once by the surveyors – at Sleeping Bear Point in 1850. This is somewhat reflected in an analysis of the words and phrases the surveyors used to describe the landscape (Figure 11). The words "sand" and "hills" or "hilly" appeared most frequently in the notebooks, as did other dune-associated descriptions. There were 78 total dune-related words or phrases out of 105 that we recorded, while the word "sand" appears 17 times in PLS notebooks for our sites. Additionally, an addendum added in the 1950s to the PLS notebooks by the U.S. Geological Survey (USGS) noted that surveying irregularities in the Sleeping Bear area were due to the difficult conditions encountered by the surveyors, especially near the Dune Climb (Figure 9).

Meteorological Data

We compared annual mean temperature, annual total precipitation, annual total PET, and average annual wind speed for our three meteorological stations (Figure 12). Results for South Bend, at the southern end of our study area, show that conditions on the southeastern Lake Michigan shore have been warmer, wetter, and less windy than the other stations since the early- to mid-20th century. Conversely, conditions at Traverse City, which is a proxy for coastal dunefields in the north of the Lower Peninsula, have been cooler, drier, and windier than the other stations. South Bend and Muskegon have seen similar tendencies in temperature, precipitation, PET, and wind. Average annual wind speed has declined since 1950 for both locations, while mean annual temperatures have risen nearly 1°C. Precipitation has increased over 100mm and PET ~50mm in the same time period (Figure 12). Traverse City's mean annual temperature, total annual precipitation, and total annual PET have changed less since the early- to mid-20th century than was experienced in South Bend and Muskegon, while the region's average yearly wind speed has largely remained unchanged (Figure 12).

Dune Mobility Indices

The spatial and temporal patterns present in the meteorological data are somewhat evident in the results from our dune mobility calculations (Figure 13). Overall, the capacity for dune mobility in coastal dunefields nearest South Bend was lower than the other sites and has declined by all metrics since 1950. Conversely, Traverse City, a proxy for dunefields on the northeastern Lake Michigan shoreline, had a higher potential dune mobility that increased over time by all metrics. Nevertheless, these results should be put into perspective; compared to inland semi-arid dunefields worldwide, these results represent a low capacity for dune activity. For example, Lancaster (1988) provided guidance on how to interpret *M* results; any dunefield *M* value below 50 should be considered "inactive" with vegetation cover >20% (Figure 14). All *M* data points for all three stations since 1950 with the exception of one – Traverse City in 2007 – were <50. The relatively high M value for Traverse City in 2007, a spike which was also captured by Chepil's C_3, appears predicated on an exceptionally dry year as the Traverse City meteorological station recorded the least amount of annual precipitation since the 1920s. This coincided with low lake levels, as by December 2007 levels on Lake Michigan-Huron were near record lows at 175.7m (Indiana DNR, 2020). Still, the dune mobility critical value for 2007 at Traverse City was $50<M<100$, which is interpreted as "crestal areas only active (vegetation cover 10-20%)" (Lancaster, 1988). These results for Lancaster's *M* reflect similar findings from the application of this dune mobility metric in the temperate coastal dunes in northwest England, where the *M* values never exceeded 50 (Delgado-Fernandez et al., 2019). The results for *DP*, which are directly immune from swings in precipitation, are largely unchanged through time since 1950 for all three stations. Moreover, as interpreted from Fryberger and Dean (1979), any site returning *DP* values in vector units (vu) <200 should be interpreted as having "low" drift potential. Results for Lancaster's *M* and Chepil's C_3 do demonstrate trends and these were evaluated for strength and significance, along with all the other variables.

Determining Trends and Statistical Significance

Based on the *d*-statistic returns from the Durbin-Watson tests, our meteorological and dune mobility data are without serial correlation, except for one variable (annual mean temperature) for Traverse City (Table 4). The *d*-statistic ranges from 0 to 4, with the value of 2 denoting the absence of serial correlation (Draper and Smith, 1998). The closer the time series data are to 2, the less first-order serial correlation exists (Draper and Smith, 1998). For the 1% significance levels with one regressor and between 70 and 111 observations, any *d*-statistic value within a bounding range of ~1.5 to ~2.5 should indicate a lack of serial correlation (Savin and White, 1977) and would suggest that pre-whitening is unnecessary, although the range gets slightly narrower as observations increase (Durbin and Watson, 1951).

All other variables possess *d*-statistic scores at 1% significance levels between the acceptable bounding range for serial correlation (Savin and White, 1977). The lower bounding limit for a dataset with $n=100$ observations with 1 regressor is 1.522, which the *d*-statistic for the temperature variable for Traverse City exceeds at 1.452. However, the violation of the Durbin-Watson test for this variable may be an artifact of the test itself, which narrows the acceptable bounding range as *n* increases (Draper and Smith, 1998). Considering this, the severity of the test violation, which amounts to ~0.07 on a 4-point scale, and the lack of violations amongst the other variables, we decided to avoid the pre-whitening process and proceed to the Mann-Kendall test stage.

Understanding the results of our Mann-Kendall tests (Table 5) requires interpreting Kendall's τ_b and the *Z*-statistic, which can both be used to determine trends. The *Z*-statistic is rather straightforward as the no trend hypothesis is rejected if $Z > \pm 1.96$ at the 5% significance level (Gocic and Trajkovic, 2013), which we use here as it seems to be standard. Interpreting Kendall's τ_b, even if it is employed more frequently, is more difficult, as it has "no direct probability interpretation" (Somers, 1962). Kendall's τ_b yields a value $-1 \leq \tau_b \leq 1$, with a higher absolute value equating to a stronger trend association (Puth et al., 2015). The determination of what Kendall's τ_b value signifies as a weak versus strong association is somewhat subjective. There are many approaches, including evaluating Kendall's τ_b in a manner similar to Spearman's ρ (Akoglu, 2018) and several informal thresholds (Botsch, 2011; e.g., van den Berg, 2021). In some cases, Kendall's τ_b is visualized spatially as a choropleth map rather than binned into groupings (e.g., Reyes et al., 2020). If Kendall's τ_b is correlated to Spearman's ρ, as is suggested (Khamis, 2008; Yue et al., 2002a), then it follows that we could utilize a Spearman's correlation coefficient table to describe our results. Thus, we use as a base the groupings reported by Corder and Foreman (2009, pg. 123) and modify it slightly based on the findings of Tabari et al.'s (2014) PET study in Iran. For this study, we consider trend strength to be trivial if $\tau_b < \pm 0.1$, weak if $\pm 0.1 \leq \tau_b < \pm 0.25$, moderate if $\pm 0.25 \leq \tau_b < \pm 0.5$, and strong thereafter (Corder and Foreman, 2009, p. 123; Tabari et al., 2014).

Based on those interpretations, the Mann-Kendall test results fail to show a clear picture of potential drivers for the changes in dune bare sand and vegetation seen in our repeat photographic analyses. Trends, as represented by the *Z*-statistic are present, especially for temperature, precipitation, PET, and Lancaster's *M* for South Bend and Muskegon; no trends exist in the data for Traverse City. Relatively stronger trends, as measured by Kendall's τ_b, were found for only two variables – mean annual wind speed at South Bend and PET at Muskegon. Yet, there was no variable that trended either positively or negatively across all three stations. Relatively weak-to-moderate positive statistically significant trends for temperature and PET at South Bend and Muskegon are interesting, but theoretically would be driving toward reactivation not stabilization through vegetation maintenance.

Discussion

The mixed results of our statistical analysis leave open speculation for possible drivers of the expansion of coastal dune vegetation on Lake Michigan's eastern shoreline. What is clear is that vegetation has expanded at the expense of bare dune sand in the modern era. It is unclear why, but there are possibilities. For example, a regional increase in annual precipitation remains a possible driver. While it may not have signaled a strong trend, a weak positive statistically significant trend in precipitation was evident for South Bend and Muskegon. Moreover, annual precipitation did increase at those two stations by ~175mm on average since the 1940s and by ~75mm since the 1900s in Traverse City. It is possible that these gains, or a shift in how precipitation is delivered, could have provided enough water to the vadose zone of these aeolian sand dunes to affect changes in vegetation. Specifically, an increase in annual precipitation may have expanded the typical wetting front patterns and raised the soil moisture percentage above a threshold at which available water increased and plant growth began.

Sand response to water is "an extremely complex phenomenon" (Dincer et al., 1974) and is characterized by the rapidity with which it conducts water through the profile (Salisbury, 1952). In fact, Dincer et al. (1974) concluded that "no universal theory" exists that predicts water behavior in sand. Yet, we can understand sand response to water broadly as a function of climate, soil texture, topography, the presence of laminae, and vegetation (Bagnold, 1941; Dincer et al., 1974). When precipitation falls on unsaturated sand and infiltrates it, a wetting front extends downward through the soil profile (Gardner and McLaren, 1999). This front moves quickly downward under the influence of gravity and the matric suction gradient, then more slowly as the edge effects of an extended wetting front begin to exert their influence and the gravitational and matric forces diminish (Gardner and McLaren, 1999). Sands with a coarser texture tend to conduct the water downward through the profile more efficiently due to larger and fewer pores between particles, amongst other factors (O'Geen, 2013). Additionally, moisture in the top ~30cm of sandy soil quickly is reduced due to the effects of evapotranspiration (Mehta et al., 1994), meaning the upper horizons of dune sand possess a rapid response to both percolation and evapotranspiration (Gardner and McLaren, 1999). This is the phenomenon Cowles (1899) identified in conjunction with the albedo and the associated higher temperature of bare dune sand in Michigan. Yet, dune response changes with the delivery of persistent episodes of precipitation. Bare sand dunes are sensitive to as little as 2-3mm of rainfall and more sensitive to larger amounts, especially lower in the profile (Gardner and McLaren, 1999). Given such sensitivity, it is not difficult to imagine that dune vegetation has expanded due to the gains in precipitation that we have presented in this study.

If a soil moisture threshold has been exceeded because of an increase in precipitation, it is possible dune vegetation will continue to expand based upon the theory of the temporal stability of soil moisture (*TS SM*) (Vachaud et al., 1985), especially under a positive trend in precipitation and after vegetation has already established itself (Wang et al., 2008). The presence of vegetation increases the amount of organic material and finer-grained particles in soil. Further, cycles of wetting and drying in coastal sand dunes are extended from mere days under bare sand to weeks in vegetated dunes (Gardner and McLaren, 1999), likely perpetuating a feedback loop that helps maintain and promote vegetation. In a study of Lake Huron dunes, field capacity of water was higher on vegetated back dunes than on younger foredunes (Baldwin and Maun, 1983). Soil moisture clearly is an important component for our study area, for even though PET increased according to our findings, the region still is an Udic soil moisture regime, where P>PET and dry conditions are rare (Schaetzl and Anderson, 2005). Additionally, it is important to note that recent research found precipitation to be a controlling factor of dune vegetation and morphology along a ~3,500km reach of the African shore (Hesp et al., 2021).

The reduction in mean annual wind speed since 1950 may also play a role in dune stabilization through vegetation expansion, although this is unlikely to be a primary driver. A moderate negative statistically significant trend in wind speed was found at South Bend, but the effect is not uniform and tapers farther north along the shore. This supports recent findings of less frequent strong winds in Minnesota (Klink, 2002) and the Great Plains (Hugenholtz and Wolfe, 2005), and contrasts with a study of Lake Superior winds (Desai et al., 2009). Wind affects dune behavior (Lancaster, 1988), foredune morphology in conjunction with other factors (Davidson-Arnott et al., 2018; Duran and Moore, 2013), and even dune vegetation dynamics, as sand and burial tolerant species are promoted at the expense of those species less tolerant of sand burial, according to a Lake Huron dune study (Dech and Maun, 2005). As Tsoar's (2005) hysteresis model of wind power and vegetation coverage demonstrated, a reduction in wind has a greater impact on vegetation expansion than an increase in wind does on dune remobilization. According to the model, once vegetation has established itself in dunes, the *DP* necessary to remobilize stabilized, vegetated dunes is significantly higher than the reduction of power necessary to foster vegetation growth (Tsoar, 2005). Yet, in a study from China, a sharp reduction in wind power and *DP* proved to be a smaller factor than land use changes in dune stabilization there (Mason et al., 2008). In our study, the reduction in annual wind speed was not uniform and only significant in one location. Thus, in our estimation, the reduction in mean annual wind speed is likely here to be a minor, local control, contributing to dune stabilization by reducing erosion and the burial of vegetation, but is not regionally uniform to affect the broad changes captured in our repeat photo pairs.

Other local controls could be influencing dune and vegetation behavior. These fall into two categories – 1) controls operating at short- and meso-term temporal scales, and 2) those controls operating at longer scales from which a lag in landscape response delayed changes in dune vegetation. In the former category are fire suppression, the importation of invasive species – especially baby's breath *(Gypsophila paniculata*) – and dune stabilization planting programs. The suppression of fire would allow the accumulation of biomass on the land (Bowman et al., 2011) and it is also tied to the behavior and control of invasive species. Studies have shown fires can exacerbate invasive species proliferation (D'Antonio and Vitousek, 1992) or help control it (Emery and Gross, 2005). *G. paniculata* has established itself in dune areas mostly northeast of Point Betsie since its introduction there (Emery et al., 2013), although it has also been found at Arcadia Dunes to the south (Leimbach-Maus et al., 2020). By their nature, dunes are disturbed landscapes and, as such, can be susceptible to invasive species colonization. *G. paniculata*, with its deep taproot and large seed disbursement, has successfully directly competed for limited resources from more sensitive native species such as Pitcher's thistle (*Cirsium pitcher*) (Leimbach-Maus et al., 2020; Yang et al., 2019). Grass planting programs, such as those around Ottawa Beach in the 1980s, have accomplished much the same effect, as one of our repeat photo pairs from that area demonstrates. One such program, which directed the planting of ~25,000 non-native Austrian pines (*Pinus nigra*) in and around Saugatuck Dunes State Park from the 1950s to the 1970s, was both a planting program and an invasive species introduction (Leege and Murphy, 2001, 2000). Planting programs, dune restoration efforts, and the advent of invasive species were shown to contribute to the stabilization of coastal dunes in northwest England (Delgado-Fernandez et al., 2019). Unfortunately, other than documenting their presence, there has not been, to our knowledge, any study systemically investigating the dune fixation properties or trends associated with these invasive species introductions or planting programs along the Lake Michigan coast.

The second category of local controls includes the effects of logging and agricultural clearing which mostly occurred in the 19th century. Our PLS investigation was an attempt to understand the prevalence of these practices. If they were widespread and present at a majority of our repeat photography sites, then it would be possible that the dune systems along Lake Michigan's eastern shore were responding in an asymmetrical and lagged manner to the removal of natural landcover ~100+ years ago in an attempt to reach its vegetated steady state. While Native American agriculture was present near Saugatuck in the 1830s, only 6 of 20 survey sites we present in this paper showed signs of vegetation or trees. Certainly, there was logging and agricultural activity in the region, but there is no evidence it played a substantial role in the expansion of vegetation. In fact, PLS survey notes indicate the prevalence of bare sand long before European agricultural practices or logging would have impacted the landscape.

Despite the questions regarding invasive species and timber activities in dunes, these factors are local controls operating at a site-specific scale, one that cannot influence the broad, longitudinal, long-term geographic trend evident in our repeat photography analysis. A uniformity must be exhibiting some control regionally to account for the trend in vegetation. Either it is precipitation, a combination of factors, or another factor operating at high levels. One such uniform factor is the increased atmospheric concentration of C0$_2$ through anthropogenic means, although much of the direct impact of this phenomenon on regional ecosystems is unclear. Atmospheric C0$_2$ has grown from ~280 ppm from the pre-industrial era, just before the PLS was conducted, to over 400 ppm at current (Baso et al., 2021). By some measures, this has caused and will continue to increase the growth of vegetation globally (Thompson et al., 2004). One early estimate using a review of greenhouse experiments predicted a 33% increase in vegetation productivity with a doubling of mid-20th century atmospheric C0$_2$ (Kimball, 1983). A more recent estimate determined that the leaf area index (LAI) or greening had grown in 25-50% of the global environment, including in the Lower Peninsula of Michigan, between 1982 and 2009 and that ~70% of that growth was due to increased C0$_2$ fertilization (Zhu et al., 2016). Certainly, these findings and others fit the pattern demonstrated in our analysis, especially given the stabilization of European coastal dunes through vegetation expansion since ~1900 (Provoost et al., 2011). Unfortunately, much is uncertain with regards to the coupling between regional vegetation productivity and increased atmospheric $C0_2$. Ultimately, if the expansion of coastal dune vegetation in our study area is being driven by higher atmospheric $C0_2$, then the future persistence of this trend will be based on the physiological tradeoffs presented by this phenomenon: Increased amounts of $C0_2$ drive photosynthesis and facilitate water efficiency in plant, while the higher temperatures associated with most climate change scenarios will cause plant stress, increased water usage, and less photosynthesis (Sperry et al., 2019). Much like the effects of increased atmospheric $C0_2$, greater atmospheric nitrogen deposition from anthropogenic means might also be uniformly driving N enrichment of dune soils across the region. Greater atmospheric N deposition would foster plant growth and influence the composition of dune grassland ecosystems (van den Berg et al., 2005), although more work needs to be done with respect to this topic in North American dunefields.

An additional, if intriguing, uniform control on dune vegetation is the possibility that the expansion of plants in coastal dunes along Lake Michigan is a lagged response to the colder and stormier conditions of the Little Ice Age (LIA), the most recent global Holocene cooling event (Jackson et al., 2019). This event, defined broadly as from 1300–1900 CE in the Northern Hemisphere with regional variations (Nordstrom, 2015), coincided with well-documented, episodic coastal dune activity in western and northern Europe (Jackson et al., 2019; Provoost et al., 2011). While conditions during the LIA were often asynchronous and varied, climate reconstructions show the core of the LIA to be particularly cool conditions from 1580-1880 CE that were fully reversed only in the last 50 years (PAGES 2k Consortium, 2013). The causes of the LIA were complex, but workers generally have focused on solar forcing and volcanic activity as the primary drivers (Jackson et al., 2019; PAGES 2k Consortium, 2013). With regards to LIA aeolian activity, coastal dunes displayed transgressive behavior at several locations from Portugal (e.g., Clarke and Rendell, 2006), to the Aquitaine Coast in the southwest of France (e.g., Clarke et al., 2002), the British Isles (e.g., Wintle et al., 1998), and into Scandinavia (Clemmensen et al., 2015), amongst other areas. There is disagreement as to whether the LIA aeolian activity in Europe was primarily the consequence of an increased supply of sand in foreshore due to storminess and sea level fluctuation or a reactivation of existing dunes in the backshore (Clarke et al., 2002; Jackson et al., 2019; Nordstrom, 2015; Szkornik et al., 2008). Regardless, there is little doubt that the LIA was a period of coastal dune activity in much of Europe.

In the Great Lakes region, there is evidence of the effects of the LIA, but not necessarily in dune environments. The LIA began a few hundred years after a pronounced ~1,000-year period of stability amongst Lake Michigan's dunes, as evidenced by the development of the Holland Paleosol (Lovis et al., 2012). Hansen et al. (2010) in their study of eastern Lake Michigan dunes suggested that the ~6,000-year record of dune behavior in the region could only be explained by something "in addition to lake level and modern land use practices." One factor they considered as a uniform control was storminess (Hansen et al., 2010), noting a study from Green Mountain Beach south of Holland where much of the annual sand transport was in response to strong storms (Hansen et al., 2009) along with similar findings at P.J. Hoffmaster State Park (van Dijk, 2004). Storminess was a suspected hallmark of LIA dune behavior in Europe, but a link to dune behavior in Michigan and the LIA was not explored in those studies.

In a non-dune study, geochemical and radiocarbon analysis on Lake Michigan sediment showed that an abrupt change in deposition occurred around ~1400 CE (Colman et al., 2000). Lake deposits had been coarse-grained and consistent with river and lake bluff erosion, but became finer-grained and consistent with soil erosion around 1400 CE (Colman et al., 2000). Pollen records from the Lower Peninsula of Michigan for the LIA found a significant decline in the wet-mesic conifer *Thuja* genus of trees, while genera typically found farther north – specifically *Pinus* and *Tsuga* – increased, in a clear response to cooler and drier conditions (Hupy and Yansa, 2009). A new study examined tree ring data from South Manitou Island in Lake Michigan just off Sleeping Bear Point for roughly the same period and determined that the LIA period contained multiple decadal severe droughts, especially in the late 1500s CE, which coincided with an event known as the Late 16th-Century Megadrought (Warner et al., 2021), a ~25-year period driven by one of the most intense occurrences of cold tropical Pacific Ocean sea surface temperatures (Cook et al., 2018). Climate reconstructions show that the drought indices may have been slightly elevated along the middle and northern sections of the Lake Michigan eastern shoreline (Cook et al., 2018, Fig. 1), aligning somewhat with our PLS findings, where surveyors noted bare sand at sites in the middle and northern sections of the coast. In this regard, the PLS notebooks could be interpreted as windows into a landscape emerging from the cooler ~500+ year LIA event and a related megadrought. Moreover, a long lag in dune soil response to increasingly mesic conditions over the last ~100 years is more plausible given Salisbury's (1952, pg. 161) observations from cold dunes in England that the mere "passage of time" eventually provides the conditions for beneficial pedogenesis, especially if dune migration slows. Thus, it is conceivable that the dune systems of Lake Michigan operate as a dynamic multiple state system that is still in nonequilibrium in response to conditions of the LIA.

The idea of landscape steady state or equilibrium is contested (Huggett, 2007; Perry, 2002; Thorn and Welford, 1994; Turner et al., 1993), but as Turner et al. (1993) argued the concept has merit if the spatial and temporal scales of landscape disturbance and recovery are understood. There is much about the Lake Michigan dune systems which is not well understood. Yet, we have presented evidence of a landscape response on a coastal scale over several decades, possibly as a system that is returning to a steady state, fluctuating between alternative states, or in non-equilibrium. In other words, based upon the evidence we presented here, Lake Michigan's coastal dunes are either returning to their natural vegetated steady state – a condition punctuated only by the storminess of the LIA – or transitioning between two natural alternative states (bare sand and vegetated) based upon current drivers or something more chaotic. A more chaotic geomorphological circumstance would involve multiple uniform and local factors interacting in dynamic ways to drive landform response, perpetuating a state of nonequilibrium (Huggett, 2011; Phillips, 2007).

Thus, the results of a study from coastal dunes in northwest England may be instructive. There, Delgado-Fernandez et al. (2019) concluded that the loss of bare sand and the increase in vegetation was the result of the "interaction of multiple drivers" that "act together with different degrees of predominance depending on the location and characteristics of the coastal dune field." Yet, perhaps climate was ultimately responsible for most of the changes, acting as a uniform "primary control on dune vegetation cover" (Delgado-Fernandez et al., 2019). Evidence presented from our study demonstrates that a type of ecogeomorphic regime shift may be underway, possibly due, as is often the case, to external controls such as climate interacting with the internal dynamics of a system (Andersen et al., 2009), such as dune sand soil. Nonlinear regime shifts owing to threshold response, as is perhaps occurring, "are typically rapid" and "difficult to foresee" (Ratajczak et al., 2014), especially in complex systems which exhibit high degrees of connectivity and homogeneity (Scheffer et al., 2012), which might describe Lake Michigan coastal dune systems.

The most likely driver of the changes presented in our study is a uniform control operating at the meso and macro spatio-temporal scales, with a combination of local controls and feedbacks providing variability and heterogeneity of dune conditions at microscales. One of the candidates of increased dune stability is a modest increase in annual precipitation. Yet, as van Dijk (2014) noted in a study of multiple possible drivers of foredune conditions, "We still have a considerable distance to go in our understanding of how events combine to produce the cumulative effects that we see at longer time scales." With that in mind, other uniform controls may be at work, such as an ecogeomorphic lag from the LIA or CO_2 fertilization. We see the need for further specific research into the soil moisture and precipitation regimes of these dunefields, along with a regional quantification of vegetative growth associated with increased concentrations of atmospheric CO_2, possibly involving remote sensing, and controlled experiments investigating the response of native and invasive plant species to CO_2 fertilization. We would also encourage more conceptual research into the multiple steady state systems comprising inland coastal dunefields.

Conclusions

In this study, we demonstrated that vegetation has expanded at 20 sites in dunes along Lake Michigan's eastern shoreline through the use of repeat photography. These findings support recent research from White et al. (2019) that demonstrated expanding vegetation in state parks along Lake Michigan since 1938. We used a semi-quantified process to describe the expansion of vegetation seen in these repeat photography pairs, then attempted to identify drivers of such a change through a statistical analysis of meteorological data and dune mobility indices for three stations – South Bend, Muskegon, and Traverse City. To learn if trends existed in these data, we first employed Durbin-Watson tests to detect serial correlation rather than use the pre-whitening process in a somewhat novel approach. Finding little evidence of serial correlation, we performed a series of Mann-Kendall tests designed to find trends in a time series, calculating the Z-statistic and Kendall's τ. Some weak-to-moderate trends were detected in our meteorological data and dune mobility indices, but the results were mixed. Still, an increase in annual total precipitation, which was represented by weak positive statistically significant trends at South Bend and Muskegon, stood out as a possible driver of dune vegetation expansion, a finding similar to White et al. (2019). Given the spatial consistency of vegetation expansion in our study, we considered the possibility that other uniform controls may be at work as drivers, including the increased concentrations of atmospheric CO_2 and a possible ecogeomorphic lag from the cooler and stormier conditions of the LIA. Regarding the effects of the LIA, the PLS notebooks from surveyors in the 1830s to 1850s that we examined showed signs of dune bare sand at most repeat photography sites, supporting the possibility that LIA conditions constrained vegetation growth on coastal dunes. Additionally, we discussed various local controls which could be contributing to dune behavior. Given the probable nonequilibrium of the coastal dune systems in our study area, we have concluded that a uniform control – possibly an increase in precipitation since the 1930s or an ecogeomorphic lag from the LIA – is primarily driving the expansion of vegetation in dunes along the eastern shore of Lake Michigan. We call for more research into how these potential drivers are interacting in a process-response manner with local internal dynamics, such as dune soil moisture thresholds and invasive species, to better understand the processes underway in Lake Michigan's coastal dunes.

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Figure 1: Repeat photography workflow process.

Figure 2: Photographic analysis workflow process. Adapted from Manier and Laven (2002, fig. 6).

Figure 3: Location of repeat photographic pairs (ESRI) listed in Table 1. Coastal dune areas from Arbogast et al. (2018).

Figure 4: Grand Beach, looking WSW along Lake Park Drive. Original photo (left) is from 1987 courtesy of EGLE. Re-photo (right) is from 2019 by K. McKeehan. Note the expansion of vegetation and the built environment between the two photographs in the 32-year interval.

Figure 5: Laketown Beach, looking SSW. Original photo (left) is from 1989 courtesy of EGLE. Re-photo (right) is from 2019 by K. McKeehan. Note the expansion of vegetation between the two photographs and the establishment of trees in the 30-year interval.

Figure 6: Meinert Park, looking SSE. Original photo (left) is from 1987 courtesy of EGLE. Re-photo (right) is from 2019 by K. McKeehan. Note the expansion of vegetation between the two photographs, the changes in the Lake Michigan shoreline, and the new channel of Little Flower Creek in the 32-year interval.

Figure 7: Silver Creek at the south end of Silver Lake State Park, looking ESE. Original photo (left) is from 1915 from the Univ. of Chicago. Re-photo (right) is from 2019 by K. McKeehan. Note the expansion of vegetation at the expense of bare sand plus the growth of the forest on the dune slip face between the two photographs in the 104-year interval.

Figure 8: Taken from The Sleeping Bear, Sleeping Bear Dunes National Lakeshore, looking NNE. Original photo (left) is from 1907, Bentley Historical Library, Univ. of Michigan. Re-photo (right) is from 2019 by K. McKeehan. Exact location of original photograph had eroded and re-photograph was taken a few meters to the east and closer to base elevation. Note the expansion of vegetation, especially in the distance, between the two photographs in the 112-year interval.

Figure 9: Taken from below the Dune Climb at Sleeping Bear Dunes National Lakeshore, looking NNW. Original photo (left) is from 1917 from the Univ. of Chicago. Re-photo (right) is from 2019 by K. McKeehan. Note the expansion of vegetation at the expense of bare sand, with the

exception of the location of the Dune Climb trail (center right), between the two photographs in the 112-year interval.

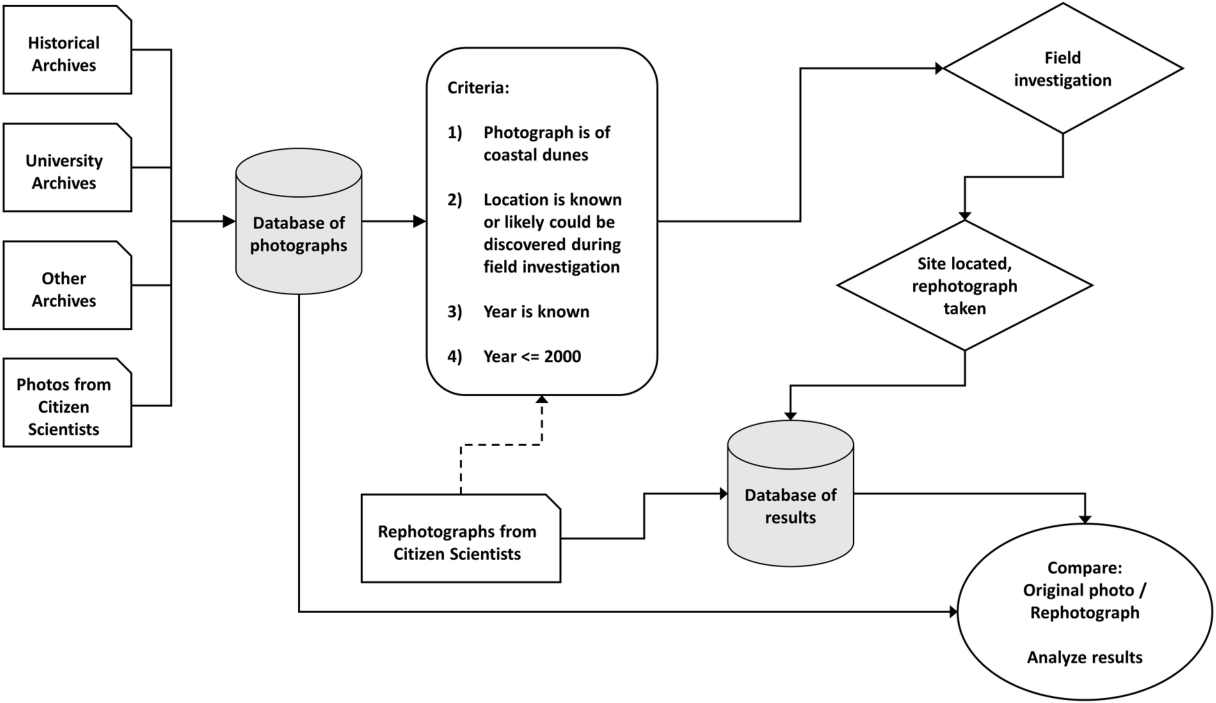
Figure 10: Quantification process example, from Silver Creek. Bare sand was mapped in hatched areas.

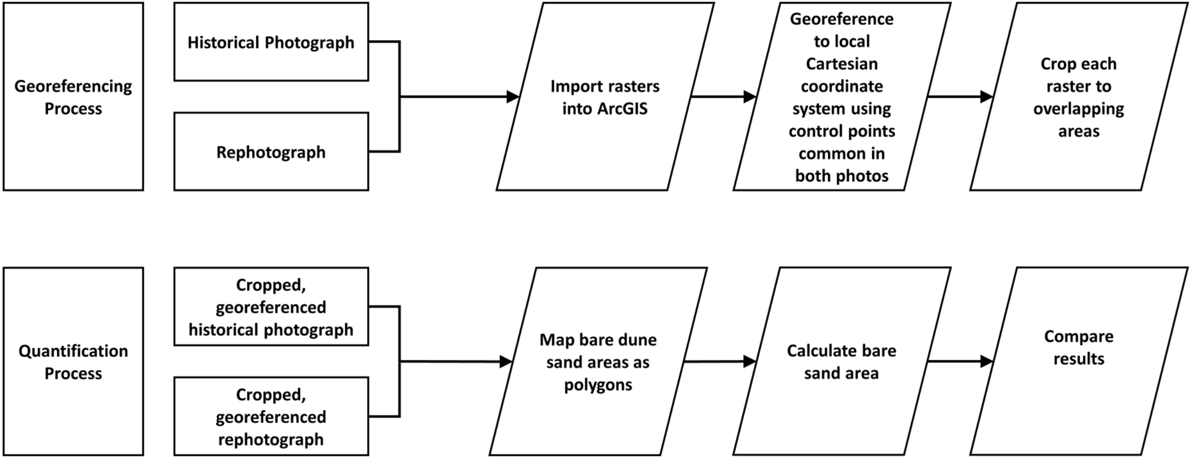
Figure 11: Word clouds for PLS notebook descriptions of repeat photography sites from 1829-1850 using Bjorn's Word Clouds software. Words evocative of bare sand dunes, such as “sand”, “hills”, “loose”, and “rolling”, are prominent, as is the term “3rd-rate”, which is indicative of poor soil. The word sand was recorded 17 times out of 105 words or phrases in the PLS notebooks.

Figure 12: Meteorological data for South Bend, Muskegon, and Traverse City. Top row is mean annual temperature (C), followed by total annual precipitation (mm), corrected potential evapotranspiration (mm) using the Thornthwaite 1948 method, and the mean annual wind speed (m/s). Linear trend model lines are shown for each chart. All wind data is from 1950-2019. South Bend data is from 1941-2019 and Traverse City from 1909-2019, with a small gap in P data in the 1990s. Muskegon T and PET data is from 1929-2019, while precipitation data is from 1938-2019.

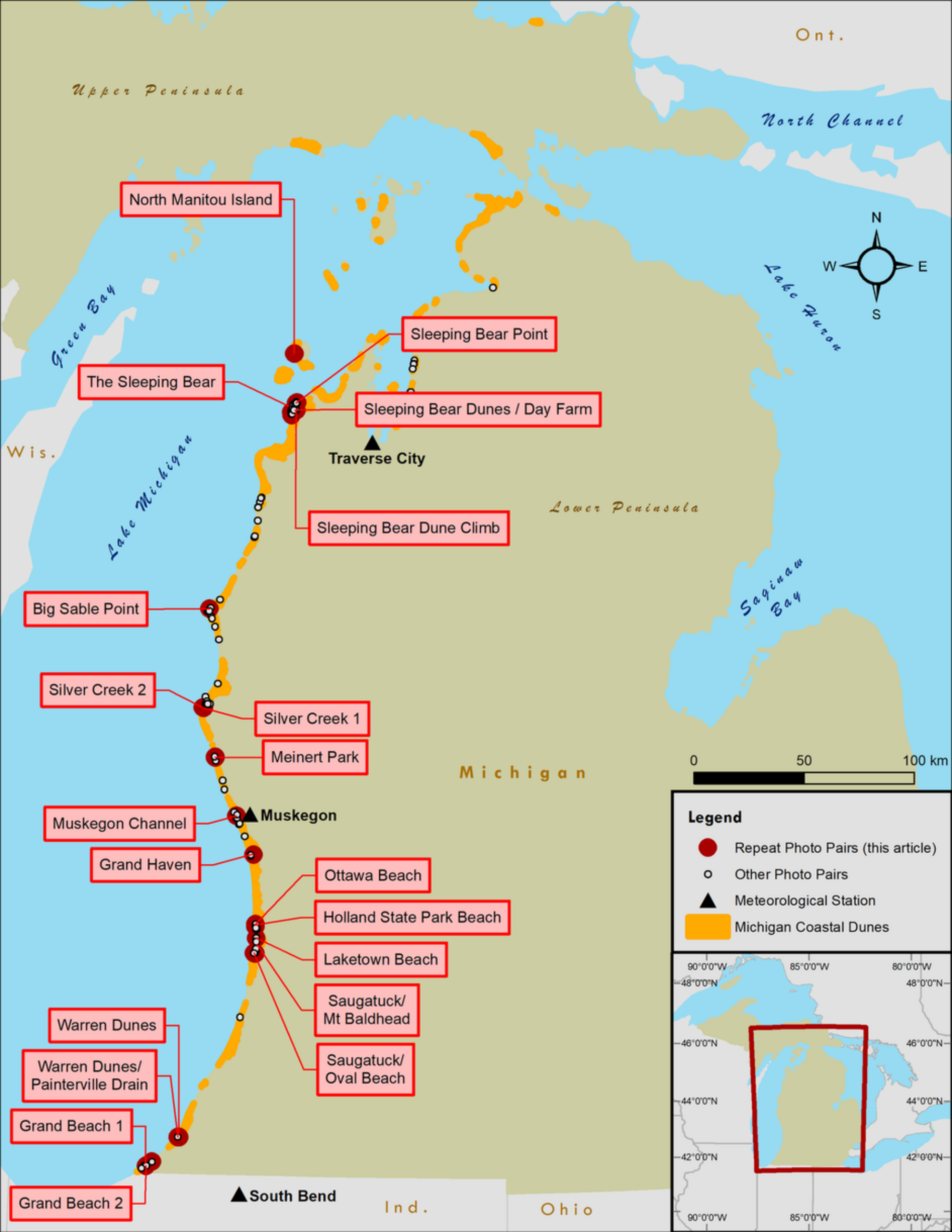
Figure 13: Dune mobility index results, 1950-2019.

Figure 14: Lancaster's M for Lake Michigan coastal dunes using data from the three closest meteorological sites and the ECMWF. This statistic is plotted as the percentage of time wind speed exceeded 4.5 m/s in a year against the ratio of precipitation to potential evapotranspiration, which is the formula for M. All results were <50, with the exception of Traverse City in 2007, which would suggest inactive dunefields. From Lancaster (1988) and Muhs and Maat (1993).


Historical Archives
University Archives
Other Archives
Photos from Citizen Scientists
Database of photographs
Criteria:
1) Photograph is of coastal dunes
2) Location is known or likely could be discovered during field investigation
3) Year is known
4) Year <= 2000
Field investigation
Site located, rephotograph taken
Rephotographs from Citizen Scientists
Database of results
Compare: Original photo / Rephotograph
Analyze results

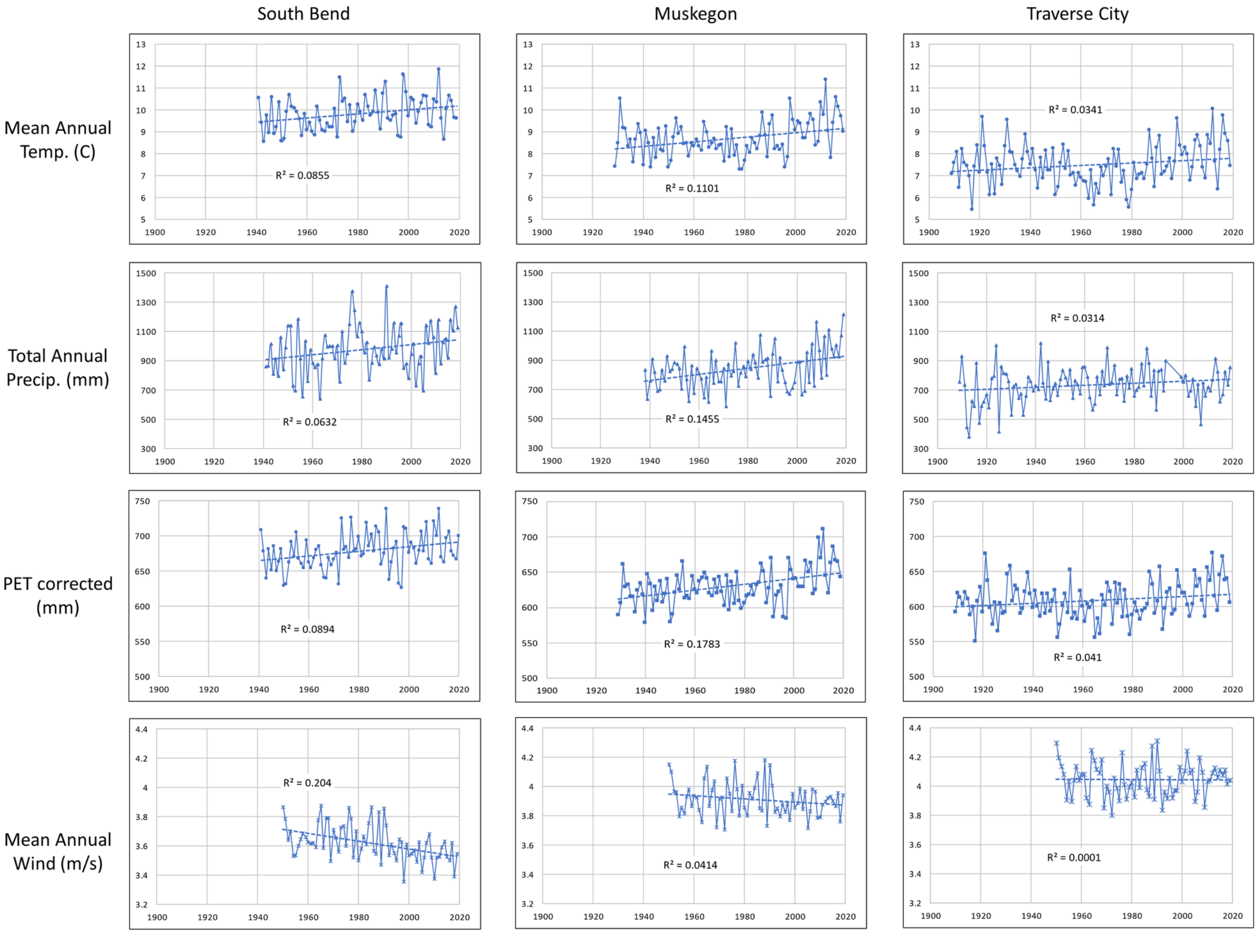

Georeferencing Process
Historical Photograph
Rephotograph
Import rasters into ArcGIS
Georeference to local Cartesian coordinate system using control points common in both photos
Crop each raster to overlapping areas
Quantification Process
Cropped, georeferenced historical photograph
Cropped, georeferenced rephotograph
Map bare dune sand areas as polygons
Calculate bare sand area
Compare results


STOP
SPEED LIMIT 25

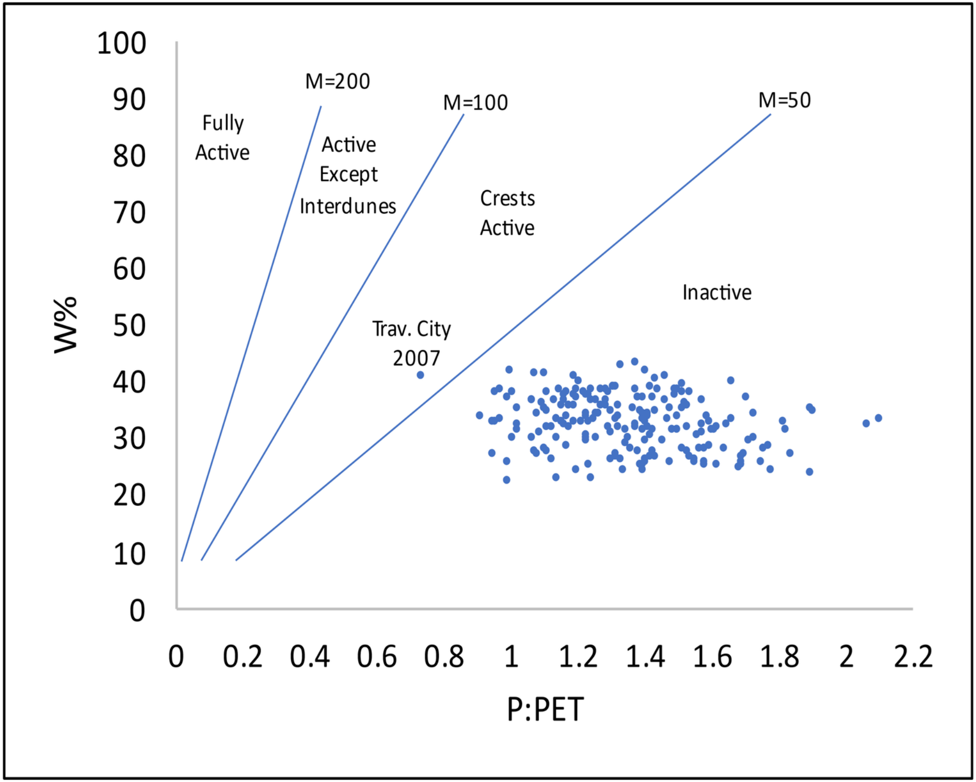

Upper Peninsula
Ont.
North Channel
North Manitou Island
Green Bay
Sleeping Bear Point
The Sleeping Bear
Sleeping Bear Dunes / Day Farm
Traverse City
Wis.
Lake Michigan
Lake Huron
N
W
E
S
Sleeping Bear Dune Climb
Lower Peninsula
Big Sable Point
Saginaw Bay
Silver Creek 2
Silver Creek 1
Meinert Park
Michigan
0
50
100 km
Muskegon Channel
Muskegon
Grand Haven
Ottawa Beach
Holland State Park Beach
Laketown Beach
Saugatuck/ Mt Baldhead
Saugatuck/ Oval Beach
Warren Dunes
Warren Dunes/ Painterville Drain
Grand Beach 1
Grand Beach 2
South Bend
Ind.
Ohio
Legend
● Repeat Photo Pairs (this article)
○ Other Photo Pairs
▲ Meteorological Station
Michigan Coastal Dunes
90°0'0"W
85°0'0"W
80°0'0"W
48°0'0"N
46°0'0"N
44°0'0"N
42°0'0"N


Sand
Beach
Hilly
No-Trees
Oak
Hills
Barren
Drifting
Hemlock
Pine
Sandy
3rd-Rate
Beech
High
Sliding
Soil
Very-Broken
Broken
Loose
Cedar
Bald
Dune
Fields
Fir
Hill
Bare
Drifts
Indian
Poor
Ridges
Rolling
Bluffs
No-Bearings
Dwarf
Dry-Swamp
No-Timber
Sugar
Thin


Poor
Indian
No-Timber
Bare
Hemlock
Very-Broken
Broken
Fields
Sugar
Rolling
Barren
Loose
Hilly
Dry-Swamp
Fir
Drifts
Pine
Sand
Hills
Sliding
High
Sandy
Cedar
Hill
3rd-Rate
No-Trees
Dune
Oak
Beach
Beech
Thin
Soil
Bluffs
Drifting
Bald
No-Bearings
Ridges
Dwarf


South Bend
Muskegon
Traverse City
Mean Annual Temp. (C)
Total Annual Precip. (mm)
PET corrected (mm)
Mean Annual Wind (m/s)
R² = 0.0855
R² = 0.1101
R² = 0.0341
R² = 0.0632
R² = 0.1455
R² = 0.0314
R² = 0.0894
R² = 0.1783
R² = 0.041
R² = 0.204
R² = 0.0414
R² = 0.0001
5
6
7
8
9
10
11
12
13
300
500
700
900
1100
1300
1500
500
550
600
650
700
750
3.2
3.4
3.6
3.8
4
4.2
4.4
1900
1920
1940
1960
1980
2000
2020


South Bend
Muskegon
Traverse City
Lancaster's *M*
Chepil's *C* (reporting C_3)
Drift Potential (vector units)
R² = 0.1107
R² = 0.0901
R² = 0.0448
R² = 0.1397
R² = 0.1696
R² = 0.1521
R² = 0.0401
R² = 0.001
R² = 0.0097
0
10
20
30
40
50
60
70
80
90
100
5
15
25
1950
1960
1970
1980
1990
2000
2010
2020


100
90
80
70
60
50
40
30
20
10
0
W%
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
P:PET
M=200
M=100
M=50
Fully Active
Active Except Interdunes
Crests Active
Inactive
Trav. City 2007

Tables

Table 1: Repeat photographic pair details. New structure column refers to any new human-built structures on the dunes since the original photograph.

Photo Pair Site	Coast Location	Lat., Lon.	Original Photo Year	Re-Photo Year	Photo Interval (y)	New Struct.
Grand Beach (1)	South	41.782578, -86.778755	1987	2019	32	Y
Grand Beach (2)	South	41.782932, -86.779561	1987	2019	32	Y
Warren Dunes/ Painterville Drain	South	41.904067, -86.610062	1900	2019	119	N
Warren Dunes	South	41.903323, -86.603600	1946	2019	73	N
Saugatuck/ Oval Beach	Mid	42.662274, -86.216413	1947	2019	72	Y
Saugatuck/ Mt. Baldhead	Mid	42.661227, -86.207821	1890	2019	129	N
Laketown Beach	Mid	42.724575, -86.20641	1989	2019	30	N
Holland State Park Beach	Mid	42.777575, -86.2117	1958	2019	61	Y
Ottawa Beach	Mid	42.78062, -86.210398	1987	2019	32	Y
Grand Haven	Mid	43.063741, -86.230219	1935	2019	84	N
Muskegon Channel	Mid	43.220897, -86.330887	1915	2019	104	Y
Meinert Park	Mid	43.458357, -86.45728	1987	2019	32	N
Silver Creek (1)	Mid	43.657587, -86.529723	1915	2019	104	N
Silver Creek (2)	Mid	43.657858, -86.533719	1915	2019	104	N
Big Sable Point	Mid	44.062615, -86.509579	1915	2019	104	N
The Sleeping Bear	North	44.874237, -86.069461	1907	2019	112	N
Sleeping Bear Dune Climb	North	44.880368, -86.042494	1917	2019	102	Y
Sleeping Bear Day Farm	North	44.881866, -86.048518	1918	2019	101	N
Sleeping Bear Pt.	North	44.911859, -86.039546	1915	2019	104	N
N. Manitou Island	North	45.111807, -86.058765	1905	2019	114	N

Table 2: Bare sand/vegetation change analysis results.

ANY BARE SAND GAIN/ VEGETATION LOSS	**SLIGHT BARE SAND LOSS/ VEGETATION GAIN**	**MORE BARE SAND LOSS/ VEGETATION GAIN**	**SIGNIFICANT BARE SAND LOSS/ VEGETATION GAIN**	**ALMOST COMPLETELY VEGETATED IN 2019**
	Painterville Drain	Meinert Park	Warren Dunes	Grand Beach 1
	Big Sable Point	Sleeping Bear Day Farm	Ottawa Beach	Grand Beach 2
	The Sleeping Bear		Grand Haven	Oval Beach
			Sleeping Bear Point	Mt. Baldhead
			Sleeping Bear Dune Climb	Laketown Beach
			North Manitou Is.	Holland State Park Beach
				Muskegon Channel
				Silver Creek 1
				Silver Creek 2

Table 3: Phrases contained in U.S. Public Lands Survey notebooks for each repeat photography site.

Photo Pair Site	Township/ Range + Sec.	Survey Year	Surveyor Name	Dunes/ Sand?	Veg.?	Surveyor Notes Selection
Grand Beach (1)	08S21W17	1829	Lucius Lyon	Y	Y	Section 8/17 boundary: No mention of sand dunes or vegetation. Section 17/18 boundary: “Land rolling and 3rd rate” “Timber dwarf oak” Meander 17/18: “Sandy beach with hills of loose sand”
Grand Beach (2)	08S21W17	1829	Lucius Lyon	Y	Y	Section 8/17 boundary: No mention of sand dunes or vegetation. Section 17/18 boundary: “Land rolling and 3rd rate” “Timber dwarf oak” Meander 17/18: “Sandy beach with hills of loose sand”
Warren Dunes/ Painterville Drain	06S20W34	1829	Lucius Lyon	N	N	Section 34/35 boundary: No mention of sand dunes or vegetation. Meander: “beach 2 chains wide”
Warren Dunes	06S20W35	1829	Lucius Lyon	N	N	Section 34/35 boundary: No mention of sand dunes or vegetation. Meander: “beach 2 chains wide”
Saugatuck/ Oval Beach	03N16W08	1831	Calvin Britain	Y	N	Section 8/17: “Land broken and soil the same”.
Saugatuck/ Mt. Baldhead	03N16W09	1831	Calvin Britain	Y	Y	Section 8/9: “Indian fields”, “hemlock”, “sugar”, “sand banks”, “pine”, “land broken”, “soil thin”.
Laketown Beach	04N16W21	1834	Calvin Britain	Y	N	Section 16/21: “Sand hills”. Surveyor reported having difficulty finding a tree to use as a post.
Holland State Park Beach	05N16W33	1832	Noah Brookfield for Calvin Britain	Y	Y	Section 28/33: "Land very broken, 3rd rate", “Timber beech, pine, oak, and hemlock". According to map, camera location was likely the mouth of the Macatawa River.

Ottawa Beach	05N16W33	1832	Noah Brookfield for Calvin Britain	Y	Y	Section 28/33: "Land very broken, 3rd rate", “Timber beech, pine, oak, and hemlock".
Grand Haven	08N16W20	1837	John Mullett	Y	N	For entire area: “Land high barren sand hills west of river”.
Muskegon Channel	10N17W28	1837	John Mullett	Y	N	Section 28/33: “Land hilly 3rd rate”, “Sand hills”.
Meinert Park	12N18W09	1838	John Mullett	Y	N	Section 9/10: “Land hilly loose sand”.
Silver Creek (1)	15N19W36	1838	John Mullett	Y	N	Section 25/36: “Land bald sand hills”, “hilly”, “poor sandy soil”.
Silver Creek (2)	15N19W36	1838	John Mullett	Y	N	Section 35/36: “Loose drifting sand”, “no trees”, “Land hilly loose drifting sand”. Corner post was driven into sand.
Big Sable Point	19N18W07	1838	Sylvester Sibley	Y	N	Section 6/7: “No trees”, “Land sand hills”.
The Sleeping Bear	29N15W36	1839	Sylvester Sibley	Y	N	Section 25/36: “No baring trees”, “rolling and drifting sand hills”, “no timber”.
Sleeping Bear Dune Climb	29N14W30	1850	Orange Risdon			Section 30/31: “Sliding sand dune”, “no bearings”.
Sleeping Bear Day Farm	29N14W30	1850	Orange Risdon	Y	N	West boundary of 29N14: “No trees or timber”, “land barren”, “rolling sand drifts and ridges”.
Sleeping Bear Pt.	29N14W18	1850	Orange Risdon	Y	Y	Section 18/19: “Cedar and fir to foot of sliding sand hill … from 100 to 150 ft high.”, “Land barren”, “rolling sand drifts”, “cedar”, “dry swamp”
N. Manitou Island	31N15W01	1847	Orange Risdon	Y	N	From survey maps parts 1 and 2: “Bare sand bluffs and hills”.

Table 4: Results for the Durbin-Watson test by variable and meteorological station. Shown is the d-statistic with the acceptable serial correlation bounding range from Savin and White (1977) in smaller font and parentheses. The d-statistic range is 0-4 and is symmetrical with a value 2 denoting the absence of serial correlation. Values within the bounding range are assumed to lack serial correlation, while those that exceed the range might possess it. The one variable that violates the Durbin-Watson test is highlighted in dark gray.

Variable	**South Bend**	**Muskegon**	**Traverse City**
Mean annual temp.	1.887 (1.47 – 2.53)	1.506 (1.5 – 2.5)	1.452 (1.52 – 2.48)
Annual total precipitation	1.833 (1.47 – 2.53)	2.037 (1.47 – 2.53)	1.993 (1.52 – 2.48)
Annual total PET	2.025 (1.47 – 2.53)	1.777 (1.5 – 2.5)	1.708 (1.52 – 2.48)
Mean annual wind speed	2.036 (1.43 – 2.57)	2.213 (1.43 – 2.57)	1.857 (1.43 – 2.57)
Lancaster's *M*	2.123 (1.43 – 2.57)	2.439 (1.43 – 2.57)	2.175 (1.43 – 2.57)
Chepil's C	2.03 (1.43 – 2.57)	2.356 (1.43 – 2.57)	2.163 (1.43 – 2.57)
Drift potential	2.064 (1.43 – 2.57)	2.028 (1.43 – 2.57)	1.561 (1.43 – 2.57)

Table 5: Results from the Mann-Kendall test. Kendall's tau, the Z-statistic, and p-values (two-tailed) are reported. Results significant at $P<0.05$ are in bold. Z-statistic values designating any significant trend are underlined and italicized, as are tau values demonstrating a moderate or strong trend over time.

Variable	**South Bend**			**Muskegon**			**Traverse City**		
	Z	τ	P-value	Z	τ	P-value	Z	τ	P-value
Mean annual temp.	***2.49***	**0.191**	**0.013**	***2.69***	**0.192**	**0.007**	1.64	0.105	0.102
Annual total precip.	***2.36***	**0.181**	**0.018**	***3.09***	**0.233**	**0.002**	1.68	0.111	0.093
Annual total PET	***2.51***	**0.191**	**0.012**	***3.81***	***0.271***	**<0.001**	1.87	0.120	0.062
Mean annual wind spd.	***-3.75***	***-0.307***	**<0.001**	-1.46	-0.120	0.144	0.07	0.006	0.943
Lancaster's *M*	***-2.65***	**-0.217**	**0.008**	***-2.34***	**-0.192**	**0.019**	1.27	0.109	0.203
Chepil's C	*-1.95*	-0.159	0.052	***-2.27***	**-0.186**	**0.023**	1.53	0.131	0.125
Drift potential	-1.39	-0.114	0.165	0.02	0.002	0.984	1.19	0.097	0.236