Spatial Data to Improve Coastal Resiliency and Better Inform Local Decision-Making

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Cover: Complex Dune Field at Fisherman’s Island State Park. J. Paskus.

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Introduction

Michigan's coastline consists of a complex array of different shoreline types. Without question, coastal dunes are one of the most iconic natural features of the Great Lakes region. A variety of dune systems can be found all along the eastern shore of Lake Michigan, the western shore of Lake Huron, the southern coast of Lake Superior, and on most of Lake Michigan's sandy islands. Sand dunes are among the most rugged and beautiful natural features of the Great Lakes shorelines. They are also among the youngest and largest geomorphic features in the state (Buckler 1978). These dunes comprise the most extensive freshwater dunes in the world, so vast that they are visible to astronauts from outer space. Many of our coastal dune systems are also incredibly rich, supporting a diversity of plants and animals (Albert 2000). According to Garmon et al (2015), Michigan's world-class coastal dunes provide significant ecologic, geologic and economic value to our state's coastal communities. As a result, they attract new residents and millions of visitors to Michigan's shorelines each year. We've been challenged with balancing our desire to build in, recreate on and even mine our sand dunes with the need to preserve their ecological integrity and dynamic nature.

When healthy, these shorelines tend to demonstrate high coastal resiliency. However, two of the biggest issues Michigan faces along the coastline are: 1) loss of property, structures, and economic value, and 2) the loss or degradation of significant natural features. Many of these negative impacts can be attributed to three contributing factors: 1) lack of access to good information, 2) lack of key geospatial datasets, and 3) lack of awareness of potential hazards, how to mitigate some of these hazards, and/or the location, characteristics, and significance of natural coastal features. Communities that don't have access to appropriate spatial data or information on how to effectively use the data, continue to struggle addressing coastal resilience in the face of climate change, invasive species, and development pressure. While some of the requisite geospatial datasets exist in one form or another, many are not available digitally, are widely scattered among different agencies, organizations, and academic institutions, and/or do not yet exist.

To address some of these challenges, the state's first dune-related law was passed in 1976. Among the numerous points made in the new law, it called for a host of new research projects to be completed to improve our understanding and management approaches (PA 222 of 1976). While not explicitly calling for new dune research, Public Act 297 of 2012 recognized the importance of science for effective dune management, specifically calling for the application of "the most comprehensive, accurate, and reliable information and scientific data available" in fulfilling the Act's purpose (Garmon et al 2015).

However, despite their ecological, economic, and cultural significance, there is quite a bit we still don't know about our coastal dune systems. To help address some of the key information gaps and advance the long-term health of coastal dunes, Coastal Zone Management Program (CZM) has supported several important research-based projects over the past five years. Importantly, each of these projects was able to build on the previous effort. In 2014, The Michigan

Environmental Council (MEC) led a project entitled, “Bringing the Latest Science to Michigan's Management of our Coastal Dunes.” The goals of the project were to develop ecological models, compile and summarize the history of dune related legislative policy, and promote better development layouts within dune systems. A key finding of that effort was the realization that despite numerous dune research projects over the decades, there were still basic but important information gaps that haven’t been adequately addressed. As a result, Networks Northwest and MNFI partnered in 2015 to develop better geo-spatial information on coastal dunes and coastal erosion within the Northwest Lower Peninsula region. That project resulted in mapping 10,400 additional acres of sand dunes, as well as a summary of which coastal communities were doing to protect sand dunes in the region. In 2016, MEC partnered with Michigan State University Department of Geography, Environment, and Spatial Sciences (GESS) to digitize the extent of all coastal dunes in Michigan, and start assessing the economic, social and cultural values associated with sand dunes.

In 2017 MNFI was funded by CZM to lead a project focused on creating spatial data to improve coastal resiliency and better inform local decision-making. The purpose of this project was to address additional spatial gaps across the state related to coastal resiliency. As part of this effort, MNFI created new geo-spatial information for coastal communities, landowners, and land managers. Specifically, MNFI researchers: 1) digitized and attributed the C. R. Humphrys shoreline classification across Michigan, 2) developed and applied a dune classification for the entire state, 3) scanned, and geo-rectified the coastal dune maps created in 1978-79 by W. R. Buckler, and 4) developed and applied a new methodology to measure the health or ecological integrity of dune sites along Lake Michigan.

By focusing on the development of key geospatial datasets, this study addresses and benefits three Department of Natural Resources (DNR), Coastal Zone Management Program (CZM) program focus areas: 1) Coastal Resilience (erosion potential mapped across the state), 2) Coastal Habitat (better understanding of coastal dune systems), and 3) Coastal Development (protecting critical areas for public enjoyment and long-term economic prosperity). This new spatial information on coastal dunes, shoreline types, and erosion potential will help support community efforts to plan and manage future growth and development on lands adjacent to the coast, while protecting critical coastal resources such as freshwater coastal dunes that provide services and benefits to everyone. Key information contained in the Humphrys shoretype database can help local communities better understand which areas have a higher potential for shoreline erosion, resulting in lower risk for new developments within the coastal zone, while also identifying potential risk to existing infrastructure. The numerous products developed as a result of this project will help coastal communities move towards making decisions that are more data driven, and even help inform scenario-based planning and zoning efforts currently being promoted by the CZM program. Lastly, dunes play a critical role in community vitality, development, and tourism. Having access to detailed information about specific dune sites will help communities and regions more appropriately develop, enhance, and promote place-based identities that incorporate the long-term health and vitality of coastal dunes.

Methods

This section describes the methods used to develop the information described in the introduction. This included: 1) digitizing existing, hard copy shoreline maps of Humphrys 1958 Shoretypes, 2) scanning and geo-rectifying Buckler's 1978-79 Coastal Dune maps, 3) developing two new coastal dune data layers (extent and classification), and 4) creating and applying prototype methodology to measure the ecological integrity or health of coastal dunes along lake Michigan. The methodology for each one of these five spatially based products is described individually below.

Digitize Humphrys' 1958 Shoretypes

MNFI obtained a copy of the original Humphrys Shoretype Classification maps (1958) as a basis to digitize the classification onto a current shoreline dataset. These maps and associated data are currently located in a single volume book housed at the MSU library. MNFI checked the publication out for the time needed to digitize the maps and attribute the associated tables. In order to digitize the different shoretypes, a clean shoreline dataset was required. Due to a number of line-based errors associated with the existing DNR CZM coastline spatial data layer, MNFI staff needed to first edit the layer. The new corrected coastline data layer was then edited with the attributes from the Humphrys shoreline classification system. The Humphry's shoretypes are line segments roughly drawn onto copies of county-based maps. The shoreline spatial data was broken into line segments representative of the classifications. Due to the large scale of the original drawings, the extent of each line segment was finalized based on additional spatial information such as soils data, USGS topographic quadrangles, and recent aerial imagery. The data table was then populated with the associated data that corresponded with each segment. Data transferred from the Humphyrs hard copy book to the ArcGIS table included information about the wet beach, dry beach, bluff, and upland zones such as soil material, width, height, slope, and erosion (degree ad type of).

Scan the W.R. Buckler's 1978-79 Coastal Dune Maps

MNFI obtained W.R. Buckler's original Mylar coastal dune maps created in 1978-79 from the Michigan Department of Environmental Quality, Oil, Gas, and Minerals Division (OGMD). These maps were temporarily stored in an MNFI cubicle in Constitution Hall until they were ready for scanning. The original mylar maps and all associated materials were then transferred over the State of Michigan Archive Unit located within the State of Michigan Library. Both the dune layer and the accompanying USGS topographic layer (both on mylar) were scanned on a large-format scanner 300-600 dpi resolution. It wasn't realized until later in the project schedule that the original mylar maps were copied at various resolutions rather than one consistent resolution. This issue was resolved by also scanning the associated USGS topographic map. This allowed MNFI CGIS staff to accurately reference and locate where each map fell along the shoreline, and to accurately geo-rectify the linework. Once scanned, each dune map was geo-rectified to the existing digital USGS topographic data layer in ArcGIS. Once scanned, all Mylar maps and associated materials and folders were housed within the State of Michigan Archives for long-term storage and access.

Delineate Coastal Dune extent and classification

Using the new coastal dune data layer produced by the MSU Department of Geography, Environment, and Spatial Sciences (GESS) (Project #17-CHab-001) in March 2018, MNFI reviewed all coastal dune boundaries for accuracy and mapped all dune types within each polygon utilizing heads up digitizing and the methodology developed as part of the CZM funded project with Networks Northwest and MNFI (Project 16-CHaz-003). MNFI utilized a series of digital aerial photographs (NAIP leaf on aerial photographs, 1998 Infrared leaf off aerials), imagery within the U.S. Army Corps of Engineers coastal oblique imagery viewer (USACE 2014), MNFI Biotics data, digital elevation maps, LiDAR, and detailed soils data (SSURGO) (See Appendix A for a full description). In addition, Hi-resolution LiDAR data was used where available. All coastal dunes were mapped as they occurred on the landscape, regardless of political or agency boundaries or regulatory designation.

In addition, surveys of eighteen sites along the eastern coastline of Lake Michigan were conducted during the 2018 growing season to determine the accuracy of both dune extent and dune types. If a dune type was observed to be inaccurate, the coastal surveyor noted the error while in the field and provide information to support the correct dune classification. Android based tablets with mapping and GPS software were used to determine boundary accuracy. In the rare case of a site being inaccurately identified as a coastal dune, information was noted in the field and the site (or a portion of the site) was removed from the GIS shapefile.

A total of six different dune types was identified as part of the desktop delineation process. Three of these types were identified in the first iteration which concentrated on the Northwest Lower Peninsula region: 1) parabolic, 2) complex dune field, and 3) dune and swale complex. Three new dune types were identified during the desktop delineation step of the project: 1) dune bluff, 2) dune ridge, and 3) low-lying aeolian sheet. The previous fields of vegetation (no, yes), and perched (high, low) remained the same as the previous classification created for the NWLP region with one exception. Dune sites with significant modifications (high density urban, agricultural row crops, quarries) were labeled as “modified” in the vegetation field. However, mining sites that eliminated the dune feature and were on the periphery of the dune formation, were not delineated.

Develop and Apply a Prototype Coastal Dune Health Index

Aside from MNFI’s element occurrence data, no methodology to evaluate the current ecological integrity is currently known to the authors of this report. As a result, the researchers needed to develop an initial or prototype health index for this project. The initial concept was to develop a health index that could be used to predict the overall health of each dune site. The first step in the process was to form an advisory committee (AC) consisting of several experts in the field of freshwater coastal dune ecology/stewardship (Appendix B). After several meetings, the committee determined that the best approach was to develop an evaluative health index that incorporated GIS spatial data layers, existing information, and new field-based data. As a result, the dune health index evolved from strictly a remotely sensed assessment to include up-to-date field data as a critical component of the index. Although the initial concept of the index started out as a tool that could be strictly assessed via existing GIS data layers, The AC has come to appreciate the nuances and diversity of coastal dune systems, and the importance of collecting specific data in the field. As a result, the index currently includes both GIS and field-based criteria to more accurately measure overall ecological health.

The AC developed an analytical spreadsheet based on a combination of NatureServe Heritage methodology (2015) and the viability assessment portion of the Open Standards for the Practice of Conservation (OS) (2015). NatureServe Heritage methodology emphasizes three primary categories for assessing the quality of a given natural community occurrence: 1) condition, 2) size, and 3) landscape context. The viability assessment of OS includes key ecological attributes, indicators and thresholds. The OS assessment also includes information on levels of confidence and sources of information. The AC also decided that two indexes should be developed; one for dune and swale complexes and one for all other dune types. Dune and swale complexes tend to extend quite far inland (as much as 5 miles), are a repetitive pattern of forested dune ridges and open swales and are driven by both hydrology (for the wetland communities in the swales) and aeolian sand at the lake interface. Hydrology is typically not an important process for the other dune formations. Indicators, thresholds and scoring were determined based on group expertise and/or literature reviews. Data for evaluating coastal dune health was also collected from secondary spatial data, aerial photography, and other existing information sources such as technical reports, site summaries, element occurrence files, and journal articles.

Approximately 10 indicators (50% of all indicators) required field-based data collection, and another four used field data for verification. To facilitate the collection of field data, a coastal dune field form was developed and filled out during each field visit (Appendix C). A spreadsheet of potential dune sites along Lake Michigan with adequate public access was developed to help determine which sites would be visited during the first field season. MNFI reviewed all dune sites along the Lake MI boundary in order to prepare for field work. Dune site boundaries were modified if needed, based on newly available high-resolution LiDAR data, different interpretation of other data layers, and/or direct knowledge of the site. Twenty sites from the eastern Lake Michigan shoreline were highlighted for potential field visits. These twenty sites were chosen based on: 1) geographic representation, 2) size (medium to small sites), and 3) travel efficiency (several dune sites located in close proximity). Based on funding and time limitations, the initial set of twenty sites was then decreased down to eighteen sites (Table 1). A notes field was included in the database to highlight changes as well as the various dune types within the site.

During the 2018 field season, ecological data was collected from each of these eighteen dune sites located along the eastern coastline of Lake Michigan. The purpose of these data was to address key information gaps and evaluate the accuracy of previously collected data. Digital images were downloaded weekly onto a laptop, and then stored as jpegs on an MSU server. Data collected in the field included information on: 1) seral stages/habitats (beach, blowouts, foredune, early successional zones, forested back dunes, great lakes barrens, and interdunal wetlands); 2) artificial structures and hardening; 3) invasive species; 4) deer browse; 5) logging; 6) vehicle traffic; 7) foot traffic; and 8) additional notes.

Table 1. Description of sites surveyed for coastal dune health index.

Site Name	Access Sites	County	Size (acres)
Oval Beach/Saugatuck Natural Area	Oval Beach; Saugatuck Natural Area	Allegan	605
Saugatuck State Park/North	Saugatuck SP; Laketown Twp Beach ; Sanctuary Woods	Allegan	5,462
Holland State Park/North	Holland State Park; Tunnel Park	Ottawa	2,524
Port Sheldon/North	Port Sheldon Park; Consumers Energy; Kirk Park	Ottawa	1,314
PJ Hoffmaster State Park/Kitchel Dunes	PJ Hoffmaster SP; North Ottawa Dunes County Park; Kitchel Dunes	Ottawa and Muskegon	3,915
Muskegon SP	Muskegon State Park	Muskegon	994
Arcadia Dunes	Arcadia Dunes: The CS Mott Nature Preserve (GTRLC Preserve)	Benzie	1,284
Green Pt. Dunes	Green Pt. Dunes Nature Preserve (GTRLC)	Benzie	433
Grace Rd. Dunes	Grace Rd. Beach access	Benzie	87
Elberta Dunes	Elberta Dunes South Natural Area (GTRLC); Elberta Beach	Benzie	293
Pt. Betsie	Pt. Betsie TNC Preserve; Pt. Betsie Lighthouse Beach; Betsie Dunes Nature Preserve (GTRLC)	Benzie	779
Leelanau State Park	Leelanau State Park	Leelanau	1,241
Fisherman's Island State Park	Fisherman's Island State Park	Charlevoix	356
Mt. McSauba	Mt. McSauba County Park	Charlevoix	128
Petoskey State Park	Petoskey State Park	Emmet	539
Woolham Preserve	Woolham LTC Preserve	Emmet	204
Cross Village	Cross Village LTC Preserve	Emmet	161
Waugaschance Pt.	Wilderness State Park	Emmet	383
Total Acres			20,702

Results

The following section provides a summary of results from each of the individual efforts described in the methods section: 1) digitize existing, hard copy shoreline maps of Humphrys 1958 Shoretypes, 2) scan and geo-rectify Buckler's 1978-79 Coastal Dune maps, 3) develop two new coastal dune data layers (extent and classification), and 4) create and apply prototype methodology to measure the ecological integrity or health of coastal dunes along lake Michigan.

Humphrys' Shoretypes

A total of 279 segments, and 107 different shoretypes totaling 2,112,582 meters were digitized across the state. The most common shoretype was Warren Dunes with 12 segments totaling 147,560 meters (91.7 miles; 7%). All segments of the Warren Dunes shoretype are located in the southwest portion of the Lower Peninsula. This was followed by the Misery Bay shoretype with ten segments totaling 111,243.8 meters (69.1 miles; 5.3%). More information about Shoretypes can be found in (Appendix E). A key piece of information embedded within the shoretype segments is erosion potential. According to Humphrys, there are four categories of erosion potential: 1) High/medium, 2) Slight, 3) None, and 4) Wind erosion. Based on Humphrys assessment, the most common type of erosion class is **None** (1,373,444.1 meters; 853.4 miles; 65%) (table 2).

Regarding erosion information, there were 58 segments with high and very high erosion levels spread across the state totaling 377,716.8 meters, or 234.7 miles of shoreline (representing 17.9% of the mapped shoretypes). The area with the highest erosion potential is located along the eastern coastline of Lake Michigan between the Indiana border and the tip of the Leelanau Peninsula. The shoreline between the Mission Peninsula and the Mackinac Bridge also contains quite a few areas categorized with high/medium erosion levels and wind erosion. None of the areas south of the Iosco/Arenac County border (east side of the state) were categorized as high/medium erosion or wind erosion. It is also important to note that the only areas in the Upper Peninsula mapped by Humphrys are located in Gogebic and Ontonagon Counties (west of the Keweenaw Peninsula). Of these two counties, no segments were categorized as high/medium erosion or wind erosion. Please refer to figure 1 for a spatial representation of erosion types in Michigan.

Table 2. Summary of Humphrys Shoretypes by erosion type.

Erosion Category	Count	Length (meters)
Mod/high	58	377,716.8
None	184	1,373,444.1
Slight	33	338,210.6
Wind Erosion	4	23,210.5
Total	279	2,112,581.9

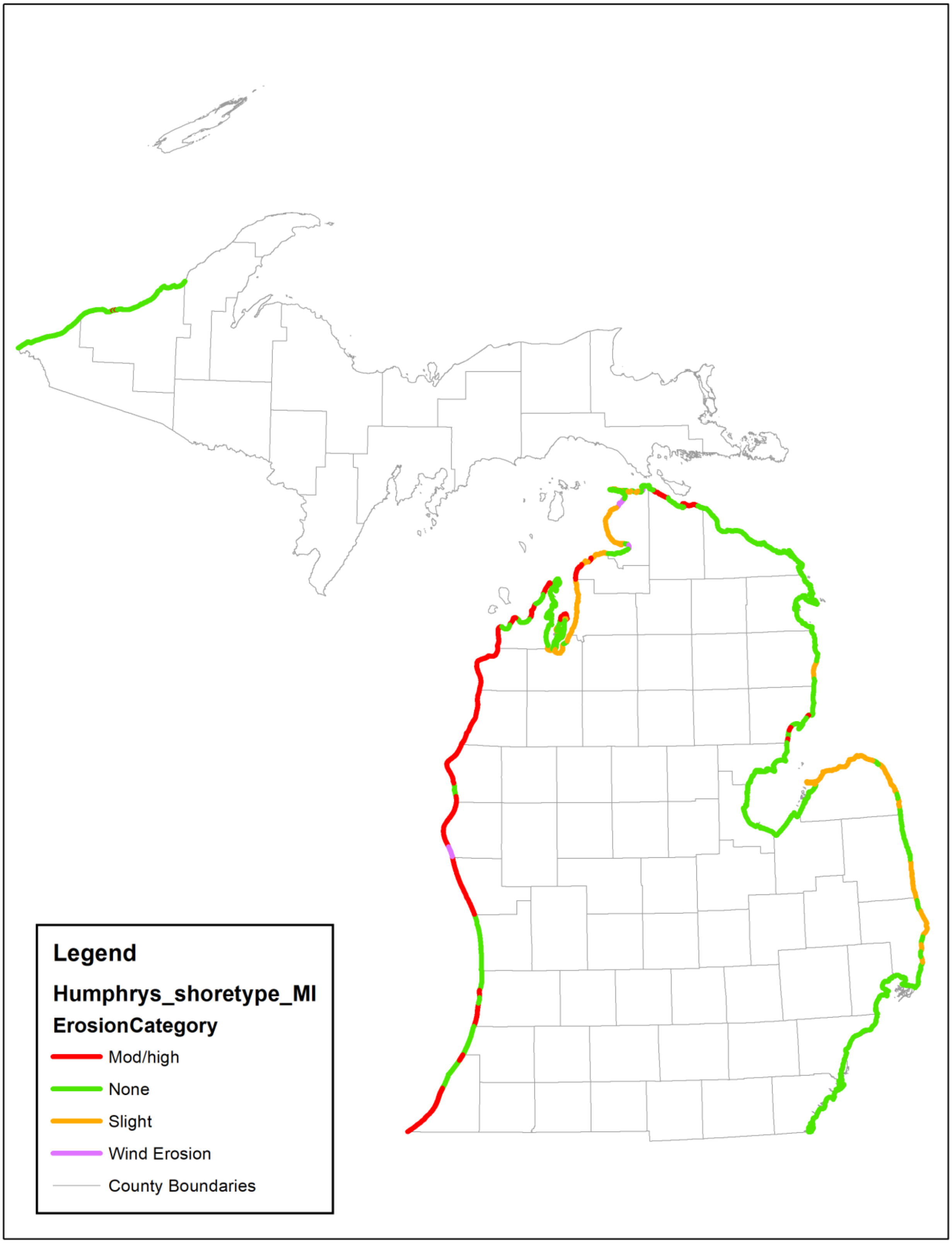

Figure 1. Humphrys Shoretypes categorized by Erosion type.

W.R. Buckler's Coastal Dune Maps

A total of 59 dune maps created by W.R. Buckler in 1978-79 on large format mylar sheets were scanned and geo-rectified to the best of our abilities. Each map depicts hand drawn polygons of and labels of different dune types based on Buckler's detailed dune classification (Buckler 1979). It wasn't realized until very late in the process that the USGS topography maps had been enlarged (to multiple unknown scales) and copied onto mylar sheets. We were also not sure as to the total number of dune maps that were originally created by Buckler, but we did recognize that several mylar sheets are unfortunately still missing. Areas that appear to be missing include: Beaver Island Archipelago, majority of Lake Huron shoreline, majority of Lake Superior shoreline, and large portions of the northern Lake Michigan shoreline in the Upper Peninsula. The resulting map is an image file that can be viewed in ArcGIS or via a pdf. Although this map image can't be analyzed like other spatial datasets, it will still be a useful tool for future coastal dune mapping and research efforts.

Dune Sites Dataset

In 2017, the Michigan State University Department of Geography, Environment, and Spatial Sciences (GESS) developed a statewide dune dataset that maps the extent of coastal sand dunes in Michigan. MNFI reviewed the boundaries of all delineated polygons and made modifications if needed. Modifications included removing or adding areas to existing boundaries and adding new dune sites. Dune site boundaries were modified based on newly available high-resolution LiDAR data, different interpretation of other data layers, and/or direct knowledge of the site. The difference in size between the two datasets is 115,957 acres, (approximately 50% increase) (table 3). Much of this discrepancy can be attributed to the addition of new sites found along Lake Huron, the northwestern portion of Lake Michigan (centered around the Garden Peninsula), the Beaver Island archipelago and several areas along the southern shoreline of Lake Superior. Excluding North and Sound Fox islands in Lake Michigan (which were omitted from the original MSU dataset), all of the additional dune sites were dune and swale complexes. These dune and swale complexes can be difficult to identify without the assistance of high-resolution LiDAR and/or direct knowledge of the site. This new dune site dataset contains 224 dune sites totaling 346,688 acres across Michigan.

Table 3. Summary of Dune Sites in Michigan (Comparison between MNFI and MSU delineation).

Source	Count	Min (acres)	Max (acres)	Mean (acres)	Total (acres)
MNFI	224	1.7	21,981.7	1,547.7	346,688.7
MSU (GESS)	235	0.0	19,921.4	981.7	230,711.0
Difference	-11	1.7	2,060.3	566.0	115,977.7

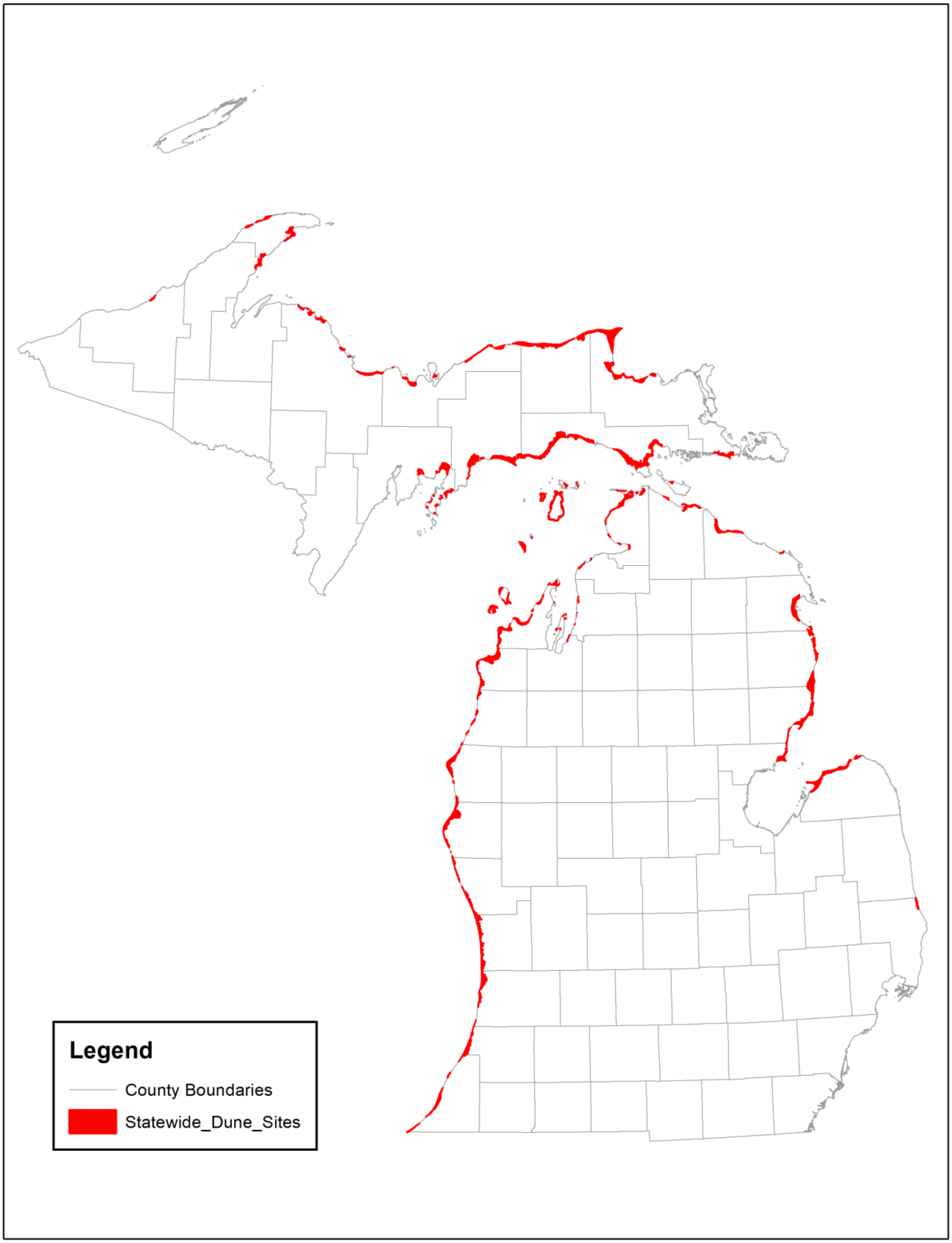

Figure 2. Map of all coastal dune sites in Michigan.

Dune Class Dataset

Using the new dune sites data layer described above as the starting point, MNFI used a variety of digital data layers, as well as the mylar Buckler dune maps to delineate specific classes of dunes. MNFI started with a relatively simple dune classification developed in a previous project focused on the Northwest Lower Peninsula region. That classification used three main categories to classify dunes: 1) dune type (dune and swale, parabolic, and complex dune field), 2) vegetation (no or yes), and 3) perch type (high or low). After reviewing additional areas of the coastline, MNFI researchers added three more dune types to the classification for a total of six dune types. The three additional types are: 1) dune bluff, 2) dune ridge, and 3) low-lying aeolian sand. In addition, MNFI researchers noted several areas of dunes that were significantly altered due to urban development, agriculture, or mining. To address this, a third type (Modified) was added to the vegetation category. As a result of these changes, MNFI researchers recognized a total of 22 different classes of dunes (see Appendix F for a more detailed description of each category). This represents an increase of 13 classes from the original analysis in 2016 which was restricted to coastal counties of the Northwest Lower Peninsula region.

A total of 900 polygons of different classes of dunes were delineated totaling 346,338 acres. Low perched, vegetated dune and swale complex (310) represents the most common class of dune in Michigan (126 units; 14%). This dune class was followed by low perched, vegetated parabolic dunes (610), low perched, open dune and swale complex (320), and low perched, vegetated complex dune field (210). Low perched vegetated dune and swale complex also covered the most acreage by a wide margin at 207,600.6 acres. This represents 60% of the total coastal dune acres delineated. Low perched, vegetated parabolic dunes (610) represent the second most acres at 35,916 acres (or 10.4% of total coastal dune acres). The least common or rarest dune classes were high perched, vegetated, dune and swale complex (1 site totaling 790.4 acres located on the northern end of Beaver Island), and vegetated dune bluff (17 sites totaling only 237.7 acres). More information about Dune classes can be found in Table 4. An example of dune classes within a dune site is shown in figure 3.

Table 4. Summary of Coastal Dune Classes in Michigan.

Dune Class	Count	Acres	Dune Type	Vegetation	Perch Type	Description
101	27	1,143.2	B	N	H	Bluff, not vegetated, high perched
111	17	237.7	B	Y	H	Bluff, vegetated, low perched
200	59	6,942.4	CDF	N	L	Complex dune field, not vegetated, low perched
201	2	3,002.3	CDF	N	H	Complex dune field, not vegetated, high perched
210	117	21,180.2	CDF	Y	L	Complex dune field, vegetated, low perched
211	7	1,551.4	CDF	Y	H	Complex dune field, vegetated, high perched
220	18	6,075.7	CDF	M	L	Complex dune field, vegetation significantly modified, low perched
300	115	4,441.2	DS	N	L	Dune and swale, not vegetated, low perched
310	126	207,600.6	DS	Y	L	Dune and swale, vegetated, low perched
311	1	790.5	DS	Y	H	Dune and swale, vegetated, high perched
320	27	26,163.6	DS	M	L	Dune and swale, vegetation significantly modified, low perched
400	54	2,315.6	R	N	L	Dune ridge, not vegetated, low perched
410	18	1,481.9	R	Y	L	Dune ridge, vegetated, low perched
420	13	1,728.1	R	M	L	Dune ridge, vegetation significantly modified, low perched
510	17	11,508.7	LLAS	Y	L	Low-lying aeolian sand, vegetated, low perched
511	4	1,542.4	LLAS	Y	H	Low-lying aeolian sand, vegetated, high perched
520	9	3,310.7	LLAS	M	L	Low-lying aeolian sand, vegetation significantly modified, low perched
600	91	2,505.6	P	N	L	Parabolic, not vegetated, low perched
601	26	1,322.3	P	N	H	Parabolic, not vegetated, high perched
610	114	35,916.4	P	Y	L	Parabolic, vegetated, low perched
611	28	3,485.3	P	Y	H	Parabolic, vegetated, high perched
620	10	2,112.3	P	M	L	Parabolic, vegetation significantly modified, low perched
Sum	900	346,358.1				

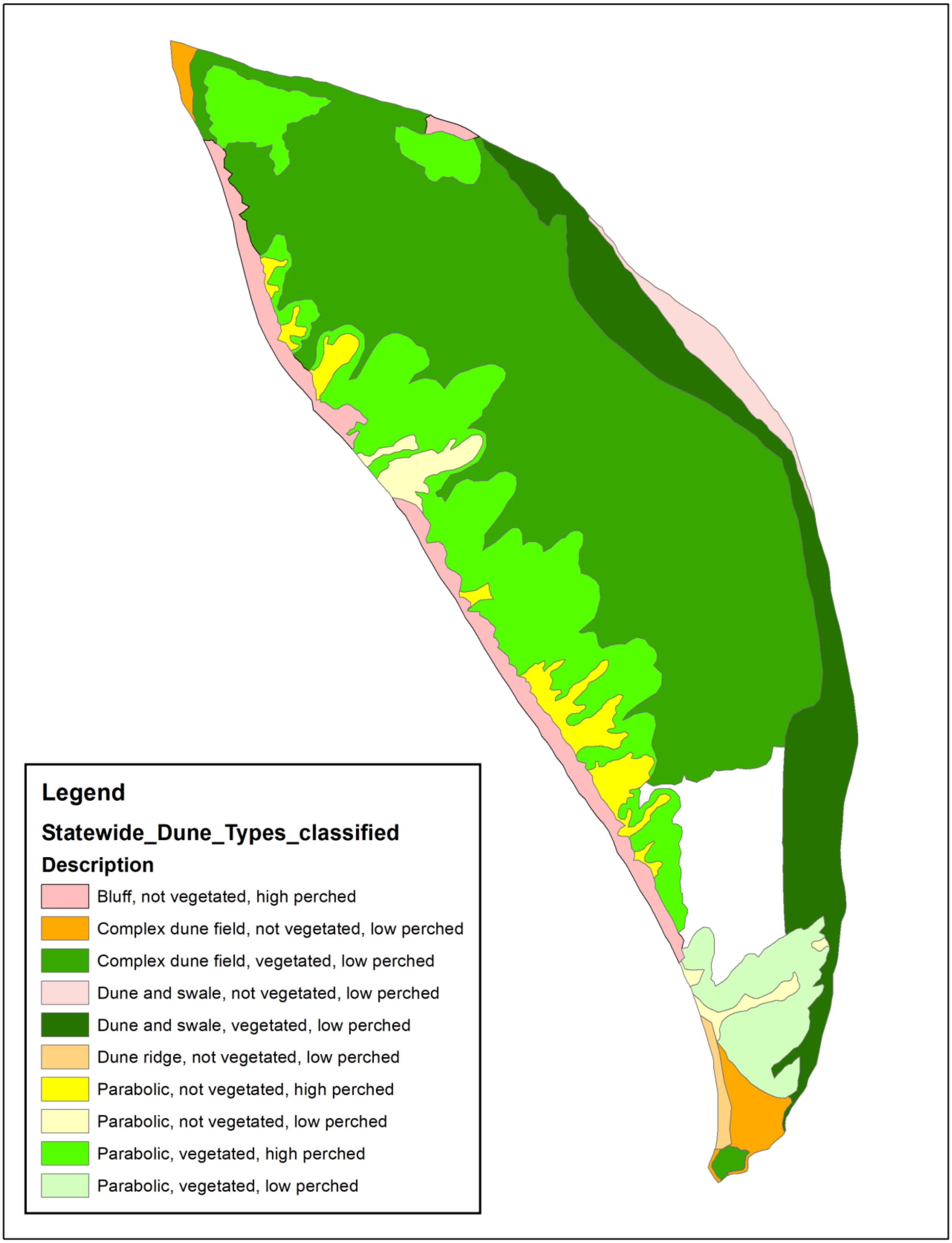

Figure 3. Example of mapped dune classes within a dune site on South Fox Island.

Coastal Dune Health Index

A key component of developing the coastal dune health index was collecting on-the-ground data at each site. MNFI identified and surveyed 18 coastal dune sites (as delineated in the spatial dune site data layer) totaling 20,702 acres. All sites surveyed were located in the Lower Peninsula along the eastern shoreline of Lake Michigan (see Figure 4). The southernmost site was located in Allegan County, while the northernmost site was located in Emmet County in Wilderness State Park. Sizes of sites ranged from a high of 5,462 acres (Saugatuck State Park/North) to a low of 87 acres (Grace Rd. Dunes). The mean size of the surveyed sites was 1,132 acres. These sites were chosen based on percentage of public access, size, and location. We attempted to identify dune sites along Lake Michigan with at least 40% public access to ensure adequate coverage for field ecologists. We also didn't include sites that were too large due to time and funding constraints. Lastly, we aimed for a relatively even distribution across the Lake Michigan shoreline. Using these three criteria, 18 sites were targeted for field surveys.

Both GIS-based and field-based data were entered into an excel spreadsheet for analysis. Each site was then given a score for each of the 20 indicators of coastal dune health. We organized the index into two major categories: 1) Condition, and 2) Landscape Context. Size was another category that was considered early on in the development of the index. However, size was eventually dropped due to the natural variation in the size of dune systems across the Great Lakes (i.e., existing size wasn't an artifact of human modification). Condition focused on the internal health of the dune site itself. Key Ecological Attributes (KEAs) of condition were: 1) Natural lands, 2) Fragmentation, 3) Invasive species, 4) Ecological processes, 5) Deer browse, 6) Logging activity, 7) Vehicle traffic, and 8) Foot traffic. Finally, there were a total of 16 indicators identified and described under the KEAs for condition (Table 5). These indicators are measurable characteristics with accompanying thresholds for determining various levels of condition.

Landscape Context on the other hand, focuses on the health of the lands immediately adjacent to each dune site. The primary assumption is that the health of the surrounding landscape has some level of impact on the health of each targeted dune site. A buffer ranging from 2 km to 1 km was used for each indicator. KEAs used for landscape context were very similar to the KEAs used for condition. Landscape context KEAs used in this analysis were: 1) Natural lands, 2) Fragmentation, and 3) Ecological processes. Other KEAs (e.g., invasive species) were also considered, however data were unavailable, and wouldn't have been feasible to collect in the field due to the high percentage of private land ownership and the total size of the buffer area. A total of four indicators were identified and described under the KEAs for landscape context (table 6).

In order to score each indicator, thresholds were determined for each of the 20 indicators. Thresholds were determined by literature review and/or expert opinion. However, due to a lack of research into many of the factors impacting dune health, in most cases thresholds were based on expert opinion and will require future research to test their efficacy. Thresholds were divided into four categories: 1) Excellent, 2) Good, 3) Fair, and 4) Poor. It is important to note that thresholds were developed using an absolute scoring method rather than a relative method. As a result, some indicators didn't have any sites that received an excellent score (a full list of references regarding indicators can be found in Appendix D).

The highest potential score for Condition was 96. Actual scores for the eighteen sites visited ranged from a low of 20 (Holland State Park/Tunnel Park site in Allegan County) to a high of 64 (Waugaschance Pt. in Wilderness State Park, Emmet County). The average score for Condition was 50.4. Using an absolute scoring system, zero sites scored in the excellent category, ten sites scored in the good category, seven sites scored in the fair category, and one site scored in the poor category.

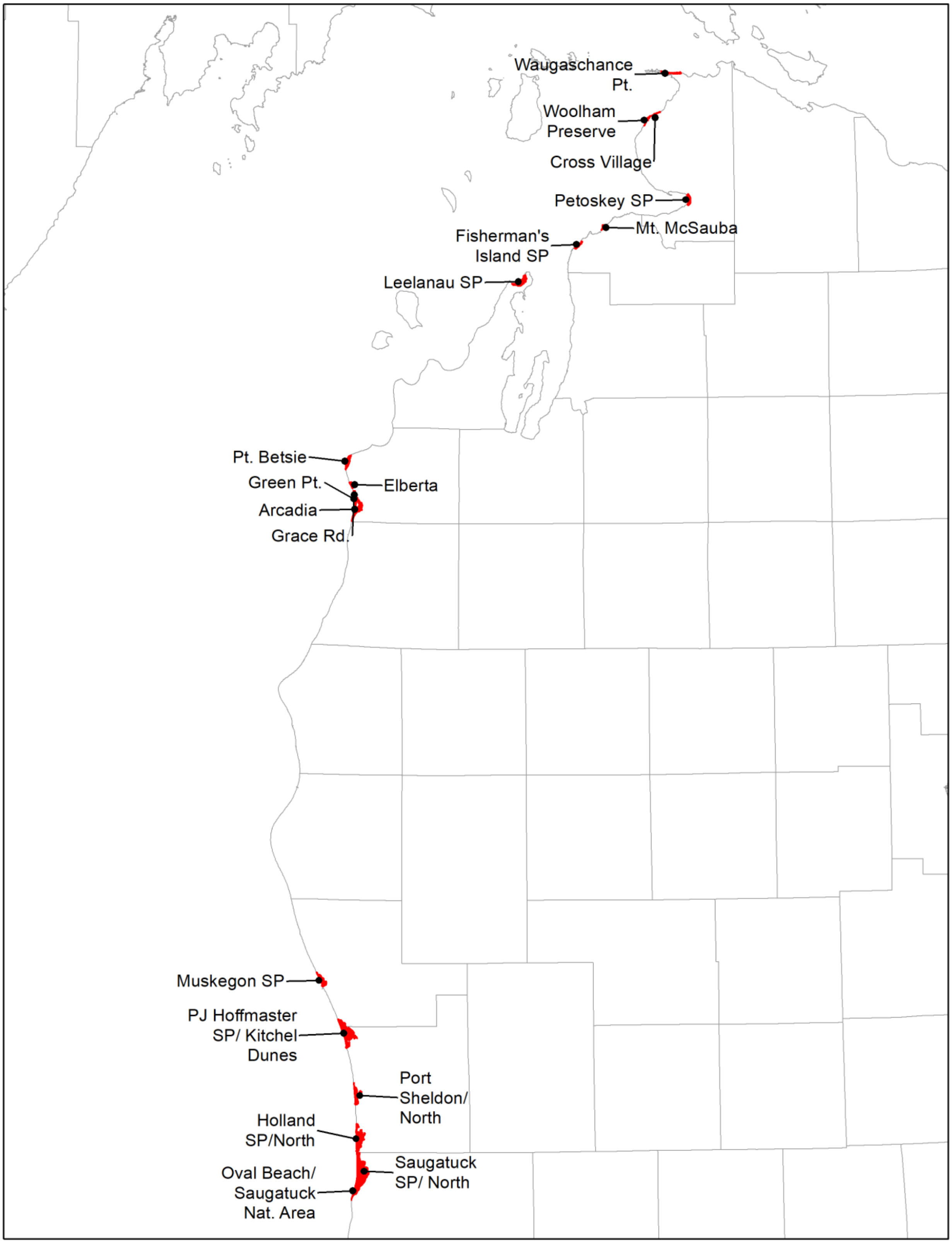

Figure 4. Dune sites selected for applying the Coastal Dune Health Index.

Table 5. Dune Health Index Spreadsheet (Condition).

Key Ecological Attributes	Indicators	Description/Assumptions	Thresholds	Scores	Relevant Spatial Data	Source of Evidence	Confidence (H, M, L)	Field data collection
Natural Lands	Average Natural community viability ranks across known element occurrences (only EOs visited within last 10 years)	MNFI ranks the quality of natural community occurrences based on a variety of field-based factors. For coastal dunes, this includes open dunes, wooded dune and swale complexes, interdunal wetlands, great lakes barrens, and northern and southern mesic and dry mesic forests.	A = Excellent; B = Good; C = Fair; D = Poor	A/AB = 8; B/BC = 4; C/CD = 2; D = 0	MNFI Biotics database	http://help.natureserve.org/biotics/#Methodology/MethodologyGuidelines.htm	H	N
	% Natural lands within dune system	Since we are evaluating the total dune system (not just the natural portion), percent natural cover is a critical measure of overall ecological integrity. The larger the area that is in a natural state, the healthier the dune system.	90 -100% = Excellent; 80-90% = Good; 60-80% = Fair; <60% = Poor	90-100% = 8; 80-90% = 4; 60-80% = 2; < 60% = 0	C-CAP 2016 (NOAA land use/land cover)	Newmark 1987; Forman 1997; Niemi et al. 2009; Dodd and Smith 2003, Findlay et al. 2001, Rubbo and Kiesecker 2005, Lougheed et al. 2001	H	Y (Verify Aerial Photos)
	Total number of seral stages/natural communities (foredune, open parabolic dune, early successional woody plant zone (shrubs/young trees), forested back dune, Great Lakes barrens, interdunal wetlands)	Dunes are highly dynamic systems that are constantly changing over short periods of time due to natural disturbances. The presence of multiple seral stages at one site is a good indicator of a healthy dune system.	>5 = Excellent; 4-5 = Good; 2-3 = Fair; 1 = Poor	>5 = 8; 4-5 = 4; 2-3 = 2; 1 = 0	field observations	Dech, J.P. 2004; Dech, J.P., M.A. Maun, and M.I. Pazner 2005; Dech, J.P. and M.A. Maun 2005; Martinez, M.L., M.A. Maun, and N.P. Psuty 2004; Albert, D. 2000; Cowles, H. C. 1899; Baldwin, K. A. and M. A. Maun 1983.	H	Y
Habitat Fragmentation	km roads/km2	Roads are the primary cause of habitat fragmentation in the US. Roads disrupt natural processes, animal movement and behavior, and provide a vector for contaminants, road salt, and invasive species.	0-1 = 8; 1-2 = 6; 2-3 = 4; 3-4 = 2; > 4 = 0	range = 8 - 0	State of Michigan roads data layer	Ritters and Wickham 2003; Eastern Ontario Model Forest 2006. Forman, R.T. and Alexander, L.E. 1998	M	N
	% of dune system that has or is currently being mined	Mining is a major disturbance that completely eliminates dune habitat. Mining also includes staging areas, processing facilities, and parking lots.	0% = Excellent; 1-5% = Good; 5-10% = Fair; >10% = Poor	0% = 4; 1-5% = 3; 5-10% = 2; >10% = 0	Hi-resolution LiDAR and best available aerial imagery.	Lake Michigan Federation 2000.		Y (Verify Aerial Photo interp)
	# of human structures/500 linear meters of shoreline	Structures are a significant contributor to fragmentation of native ecosystems. In dunes, structures alter natural processes, and tend to include activities that control erosion processes via fencing and non-native plantings. There also appears to be a high correlation between number of residences and amount of erosion from foot traffic and ORVs.	0 = Excellent; 1-5 = Good; 5-10 = Fair; >10 = Poor	0 = 8; 1-5 = 4; 5-10 = 2; > 10 = 0	Best available aerial imagery	Pearsall, D. et al. 2012	H/M	Y (verify aerial photo interp)
Ecological Processes	Presence of Ecological Processes = evidence of 1) burial (presence of standing snags); 2) active blowouts; 3) dune movement; 4) large dead and down logs/trees in forested dunes.	Coastal dunes are one of the most dynamic ecosystems in the world. They require natural disturbances in order to maintain a variety of habitat types, particularly early successional habitats. A healthy extent and distribution of diverse ecological processes is a good indicator of a healthy, dynamic dune system.	4 processes = Excellent; 2-3 processes = Good; 1 process = Fair; 0 processes = Poor	4 = 8; 2-3 = 4; 1 = 2; 0 = 0	field observations	Dobberpuhl and Gibson 1987, McEachern et al. 1989, U.S. Fish and Wildlife Service. 2002	H	Y
	presence of artificial structures (in water)	Sand supply is a critical element to the long-term viability of active dune systems. Artificial structures such as groins, jetties, and piers disrupt littoral sand drift leading to excessive sand starvation on the downdrift side of the barrier.	0 = Excellent; 1 = Fair; > 1 = Poor	0 = 4; 1 = 2; >1 = 0	Great Lakes Environmental Assessment and Mapping Project 2012 (GLEAM)	IJC 2014; Defeo et al. 2009; US Army Corp of Engineers 2017; Meadows et al. 2005	H	Y (verify aerial photos)
	% of shoreline hardening within dune boundary	Riprap, sheet metal walls, concrete walls, and gabions are commonly used along the GL shoreline to disrupt natural rates of erosion due to wave action. Shoreline hardening disrupts natural sand movement and the development of dune formations.	0% = Excellent; 1-5% = Good; 5-20% = Fair; > 20% = Poor	0% = 4; 1-5% = 2; 5-20% = 1; > 20% = 0	GLEAM (mentioned above); USACE shoreline hardening (1989)	IJC 2014; Defeo et al. 2009; US Army Corp of Engineers 2017; Meadows et al. 2005	H	Y
Invasive Species	Number of invasive plant species	Invasive species such as spotted knapweed, baby's breath, lyme grass, and lombardy poplar, disrupt natural dune processes and displace native species. Higher numbers of invasive species indicate degraded conditions and increased difficulty of control.	0 = Excellent; 1-2 = Good; 3-5 = Fair; > 5 = Poor	0 = 4; 1-2 = 2; 3-5 = 1; > 5 = 0	field observations	Emery, S.M. et al 2013; Emery, S.M. and J.A. Rudgers 2012; Maron, J.L. and M. Marler 2008; Leege, L.M. and P.G. Murphy 2001.	H	Y
	% cover of all invasive plant species	Invasive species can be sparsely populated or cover a large area of a site. High percent cover indicates that the species is well established, has already had an impact, and will be difficult to manage in the future.	0-5% = Excellent; 5-10% = Good; 10-20% = Fair; >20% = Poor	0-5% = 4; 5-10% = 2; 10-20% = 1; >20% = 0	field observations	Emery, S.M. et al 2013; Emery, S.M. and J.A. Rudgers 2012; Maron, J.L. and M. Marler 2008; Leege, L.M. and P.G. Murphy 2001.	H	Y
	Distribution of invasive plant species	Location of invasive species is also important. Invasives that are widely dispersed throughout the site are more problematic than if they are concentrated into one portion of the site, or just becoming established. Wide distribution is an indication that the species is well established, has altered native species cover and diversity, and will be difficult to eliminate.	None = Excellent; newly established = Good; concentrated in a few areas = Fair; Widely distributed = Poor	None = 4; newly established = 2; concentrated = 1; widely distributed = 0	field observations	Emery, S.M. et al 2013; Emery, S.M. and J.A. Rudgers 2012; Maron, J.L. and M. Marler 2008; Leege, L.M. and P.G. Murphy 2001.	H	Y
Deer Browse	Degree of browsed woody and herbaceous plants	White-tailed deer browsing can have a tremendous impact on native plant regeneration, particularly in forested natural communities. Coastal dune forests seem particularly susceptible due to the steep slopes, sandy soils, and conifer species which attract deer.	0 to Low = Excellent; low to moderate = Good; moderate to high = Fair; High to very high = Poor	0 -low = 8; low-mod = 4; mod-high = 2; Very high = 0	field observations	Long, T.Z., et al. 2007; Horsley, S.B., et al. 2003; Rooney T.P. 2009; White, M.A. 2012; Alverson, W.S., D.M. Waller, and S.L. Solheim 1988	H	Y
Logging	Presence/absence of logging activities in Forested Dunes	Certain logging practices have a tendency to oversimplify forests by high-grading, selecting for priority species, and managing for even-aged structure. Unlogged forests tend to have higher compositional, genetic, and structural diversity, resulting in increased resiliency.	Absence of logging = Excellent; Presence of historical logging = Fair; Presence of recent logging = Poor	Absence = 4; historical = 2; recent = 0	field observations	Moola, F.M. and L. Vassuer 2008; Hix, D.A. and B.V. Barnes 1984.	H	Y
Vehicle Traffic	Degree of ORV traffic in the dune system	Off-road vehicles can have a tremendous impact on native ecosystems. In dunes, ORVs can lead to severe erosion, habitat modification, direct plant mortality, and the spread of invasive species.	0% of site = Excellent; 1-5% of site = Good; 5-10% = Fair; > 10% = Poor	0 = 4; 1-10% = 2; > 10% = 0	field observations	Hosier, P E. and T. E. Eaton 1980; Etongue-Mayer, et al. 1999; M. C. Thompson, Luke and Schlacher, Thomas 2008.	H	Y
Foot Traffic	Degree of human foot traffic in the dune system	Human foot traffic can lead to the trampling of plants, severe soil erosion, altered animal behavior, altered soil micro-climate, and the spread of invasive species.	0-5% of site = Excellent; 5-10% of site = Good; 10-25% = Fair; >25% = Poor	0-5% = 8; 5-10% = 4; 10-25% = 2; >25% = 0	field observations	Bowles, J. M. AND M. A. Maun 1982; Hylgaard, T. and M. J. Liddle 1981; McAtee, J. W. and D. C. Drawe 1980; Slatter, R. J. 1978; Bonnano, S.E., et al. 1998.	H	Y
Highest Potential Score				96				

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Table 6. Dune Health Index spreadsheet (Landscape Context).

Key Ecological Attributes	Indicators	Description/Assumptions	Thresholds	Scores	Relevant Spatial Data	Source of Evidence	Confidence (H, M, L)	Field data collection
Landscape Context								
Habitat Fragmentation	km roads/km2 within 2 km buffer	roads are the primary cause of habitat fragmentation in the US. Roads disrupt natural processes and animal movement; and provide a vector for contaminants, road salt, and invasive spp.	0-1 = 8; 1-2 = 6; 2-3 = 4; 3-4 = 2; > 4 = 0		State of Michigan roads data layer	Ritters and Wickham (2003) and the Eastern Ontario Model Forest (EOMF 2006). Forman, R.T. and Alexander, L.E. (1998)	M	N
Natural Lands	% Natural lands within 2 km buffer	Measure the amount of natural lands within a specific buffer width. % natural lands within the surrounding landscape provides a buffer against anthropogenic disturbances, connectivity to other habitat types, and allows the dune to move inland and expand along the coast.	90 -100% = Excellent; 70-89% = Good; 50-69% = Fair; <50% = Poor	90-100% = 8; 70-89% = 4; 50-69% = 2; < 50% = 0	C-CAP 2016	Newmark 1987; Forman 1997; Niemi et al. 2009; Dodd and Smith 2003, Findlay et al. 2001, Rubbo and Kiesecker 2005, Lougheed et al. 2001	M	N
Ecological Processes	Presence of artificial structures in nearshore zone within .25 miles of edge of dune system	Sand supply is a critical element to the long-term viability of active dune systems. Artificial structures such as groins, jetties, and piers disrupt littoral sand drift leading to excessive sand starvation on the downdrift side of the barrier. Structures down current and up current of the dune site will likely alter sand supply.	0 = Excellent; 1 = Fair; > 1 = Poor	0 = 8; 1 = 4; > 1 = 0	Great Lakes Environmental Assessment and Mapping Project 2012 (GLEAM)	IJC 2014; Defeo et al. 2009; US Army Corp of Engineers 2017; Meadows et al. 2005	H	N
	% of shoreline hardening within 2 km buffer of edge of dune system	Riprap, sheet metal walls, concrete walls, and gabions are commonly used along the GL shoreline to disrupt natural rates of erosion due to wave action. Presence along adjacent shoreline areas could alter sand transport processes within the dune site.	0 % = Excellent; 1-5 % = Good; 5-20% = Fair; >20% = Poor	0 = 8; 1-5% = 4; 5-20% = 2; >20% = 0	GLEAM 2012; USACE shoreline hardening (1989)	IJC 2014; Defeo et al. 2009; US Army Corp of Engineers 2017; Meadows et al. 2005	M	N
Highest Potential Score				32				
Highest Total Score				128				

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Table 7. Summary of Dune Health Condition Scores.

Key Ecological Attributes	Indicators	Scores	Oval Beach/Saugatuck Nat. Area		Saugatuck SP/Gilligan's Lake/Laketown Twp beach /Sanctuary Woods		Holland SP/Tunnel Park		Port Sheldon/Kirk Park		PJ Hoffmaster SP/North Ottawa Dunes/Kitchel Dunes		Muskegon SP	
	Site Number		27		29		35		37		38		44	
Condition			Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score
Natural Lands	Average natural community EO ranks (only sites visited by an ecologist within last 10 years)	A/AB = 8; B = 6; BC = 4; C/CD = 2; D = 0	10033 = BC; 6702 = BC	4	10687 = C; 10033 = BC; 6702 = BC	4	None	0	10699 = CD	2	12670 = B; 8155 = BC; 8436 = CD; IW = C	2	12019=B; 7936=B; 3129=BC; 17520=BC	4
Natural Lands	% Natural lands of total dune system	90-100% = 8; 80-90% = 4; 60-80% = 2; < 60% = 0	97%	8	92%	8	56%	0	84%	4	76%	2	95%	8
Natural Lands	habitat diversity: foredune (F), open blowout (OB), re-veg blowout (RB), early successional woody plant zone (ES), forested back dune (FD), Great Lakes barrens (GB), Dune Savannah (DS); interdunal wetlands (IW), dune bluff DB), complex dune field (CDF)	>5 = 8; 4-5 = 4; 2-3 = 2; 1 = 0	(5) OB, F, ES, FD, IW	4	(7) OB, RB, F, ES, FD, IW, GB	8	(4) RB, B, F, FD	4	(4) RB, OB, FD, ES	4	(8) RB, OB, ES, FD, IW, F, DS, GB	8	(6) RB, OB, F, ES, FD, IW	8
Habitat Fragmentation	km roads/km2	0-1 = 8; 1-2 = 6; 2-3 = 4; 3-4 = 2; > 4 = 0	1.96	6	2.55	4	5.76	0	3.22	2	3.03	2	2.82	4
Habitat Fragmentation	% of dune system that has or is currently being mined	0% = 4; 1-5% = 3; 5-10% = 2; >10% = 0	0	4	0	4	0	4	0	4	5%	2	0%	4
Habitat Fragmentation	# of dwellings/500 linear meters of shoreline	0 = 8; .1-1 = 6; 1-5 = 4; 5-10 = 2; > 10 = 0	66/4,730 = 6.6/500	2	125/10,797 = 5.8/500	2	478/14,258 =16.8/500	0	171/6750 =12.7/500	0	173/9240= 9.3/500	2	6/4,988 = .6/500	4
Ecological Processes	Sedimentation (S); active blowouts (AB); erosion (E); large dead and down logsin forested dunes (DD)	4 = 8; 2-3 = 4; 1 = 2; 0 = 0	(3) AB, E, S	4	(4) AB, E, S, DD	8	(3) E, S, DD	4	(4) AB, E, S, DD	8	(4) AB, E, S, DD	8	(4) AB, E, S, DD	8
Ecological Processes	presence of artificial structures (in water)	0 = 4; 1 = 2; >1 = 0	(1) Kzoo R.	2	(2) Kzoo R. and Lake Macatawa	0	(2) Holland and Port Sheldon	0	(1) Port Sheldon	2	(1) Grand Haven	2	(1) Muskegon Lake	2
Ecological Processes	% of shoreline hardening within dune boundary	0% = 4; 1-5% = 2; 5-20% = 1; > 20% = 0	0	4	0	4	2%?	2	2%??	2	0	4	0	4
Invasive Species	Number of invasive species	0 = 4; 1-2 = 3; 3-5 = 2; 6-8 = 1; > 8 = 0	9	0	9	0	8	0	8	0	15	0	4	2
Invasive Species	% cover of all invasive species	0-5% = 4; 5-10% = 2; 10-20% = 1; >20% = 0	12%	1	9%	2	16%/32% = 24% avg	0	20%/5% = 15% avg	1	30%	0	9%	2
Invasive Species	Distribution of invasive plant species	None (N) = 4; newly established (NE) = 2; concentrated (C) = 1; widely distributed (WD) = 0	65% = WD	0	50% = WD	0	85%/50% = 70% avg WD	0	80%/40% = 60% avg = WD	0	80% = WD	0	70% = WD	0
Deer Browse	Degree of browsed woody and herbaceous plants	0-low = 8; low-mod = 4; mod-high = 2; high - very high = 0	Very high	0	mod to high	2	mod to high	2	mod to high	2	mod to high	2	mod to high	2
Logging	Presence/absence of logging activities in Forested Dunes	Absence = 4; historical = 2; recent = 0	H	2	H	2	H	2	H	2	H	2	H	2
Vehicle Traffic	Degree of ORV traffic in the dune system	0 = 4; 1-10% = 2; > 10% = 0	1-5%	2	1-10%	2	2%	2	0	4	5-10%	2	1-2%	2
Foot Traffic	Degree of human foot traffic in the dune system	0-5% = 8; 5-10% = 4; 10-25% = 2; >25% = 0	20%	2	>25%	0	>25%	0	10-25%	2	>25%	0	65%	0
Score		**96**		**45**		**50**		**20**		**39**		**38**		**56**

Key Ecological Attributes	Indicators	Arcadia		Green Pt.		Grace Rd.		Elberta		Pt. Betsie		Leelanau SP	
	Site Number	91		93		95		97		122		148	
Condition		Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score
Natural Lands	Average natural community EO ranks (only sites visited by an ecologist within last 10 years)	20456=BC;	4	20481=BC	4	None	0	10670=C D	2	10790=BC 3786=BC 1867=BC 19164=C	4	6100=BC 3342=B 4888=B 8689=B	6
Natural Lands	% Natural lands of total dune system	90%	8	97%	8	100%	8	92%	8	98%	8	99%	8
Natural Lands	habitat diversity	(5) F, OB, ES, FD, DB	4	(4) OB, F, ES, FD	4	(2) RB, F	2	(4) AB, F, RB, FD	4	(6) OB, F, RB, ES, IW, FD	8	(7) OB, RB, F, ES, FD, IS, GB	8
Habitat Fragmentation	km roads/km2	2.74	4	2.49	4	1.01	6	1.19	6	3.19	2	0.81	8
Habitat Fragmentation	% of dune system that has or is currently being mined	0	4	0	4	0	4	10%??	2	0	4	0	4
Habitat Fragmentation	# of dwellings/500 linear meters of shoreline	1/4,085 = .15/500	6	10/2,500 = 2/500	4	6/1,556 = 2/500	4	4/2,034 = .8/500	6	47/4,522 = 5.2/500	2	55/5,155 = 5.3/500	2
Ecological Processes	Sedimentation (S); active blowouts (AB); erosion (E); large dead and down logsin forested dunes (DD)	(4) AB, S, E, DD	8	(4) AB, DD, E, S,	8	(2) RB, DD	4	(4) AB, E, S, DD	8	(3) AB, E, S, DD	4	(4) AB, E, S, DD,	8
Ecological Processes	presence of artificial structures (in water)	0	4	0	4	0	4	(1) Frankfurt	2	0	4	0	4
Ecological Processes	% of shoreline hardening within dune boundary	0	4	0	4	0%	4	0%	4	0	4	0	4
Invasive Species	Number of invasive species	11	0	3	2	3	2	12	0	13	0	9	0
Invasive Species	% cover of all invasive species	18%	1	10%	1	15%	1	20%	0	20%	0	>20%	0
Invasive Species	Distribution of invasive plant species	80% = WD	0	60% = WD	0	80% = WD	0	80% = WD	0	50% = WD	0	90% =WD	0
Deer Browse	Degree of browsed woody and herbaceous plants	low to mod	4	mod to high	2	low to mod.	4	low to mod	4	high to very high	0	Mod to high	2
Logging	Presence/absence of logging activities in Forested Dunes	H	2	R (SE)	0	R (N)	0	H	2	R	0	H	2
Vehicle Traffic	Degree of ORV traffic in the dune system	0	4	0	4	0%	4	>10%	0	0	4	0	4
Foot Traffic	Degree of human foot traffic in the dune system	10-25%	2	5-10%	4	10-25%	2	>25%	0	>25%	0	>25%	0
Score			**59**		**57**		**49**		**48**		**44**		**60**

Key Ecological Attributes	Indicators	Fisherman's Island SP		Mt. McSauba		Petoskey SP		Woolham Preserve		Cross Village		Waugaschance Pt.	
	Site Number	149		151		153		179		179		180	
Condition		Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score
Natural Lands	Average natural community EO ranks (only sites visited by an ecologist within last 10 years)	4047 = C 8003 = C	2	4073=C	2	None	0	6368=C 20443=CD	2	None	0	2127=AB 5305=BC 4686=B	6
Natural Lands	% Natural lands of total dune system	96%	8	97%	8	97%	8	98%	8	97%	8	100%	8
Natural Lands	habitat diversity	(5) F, OB, ES, FD, IW	4	(6) F, OB, RB, ES, FD, IW	8	(4) F, OB, ES, FD	4	(5) F, CDF, ES, FD, GB	4	(4) F, CDF, IW, FD	3	(4) F, CDF, IW, FD	4
Habitat Fragmentation	km roads/km2	3.88	2	1.83	6	4.89	0	2.96	4	5.85	0	2.33	4
Habitat Fragmentation	% of dune system that has or is currently being mined	2-4%	3	0	4	1-5%	3	0	4	0	4	0	4
Habitat Fragmentation	# of dwellings/500 linear meters of shoreline	16/3,178 = 2.5/500	4	18/1,993 = 4.5/500	4	42/3,087 = 6.8/500	2	25/4,055 = 3/500	4	48/3,288 = 7.3/500	2	3/6,433 = .00/500	8
Ecological Processes	Sedimentation (S); active blowouts (AB); erosion (E); large dead and down logsin forested dunes (DD)	(3) E, S, DD,	4	(2) E, S	4	(4) AB, E, S, DD	8	(3) E, S, DD	4	(1) S	2	(3) S, E, DD	4
Ecological Processes	presence of artificial structures (in water)	0	4	0	4	0	4	0	4	0	4	0	4
Ecological Processes	% of shoreline hardening within dune boundary	0	4	0	4	0	4	0	4	??	4	0	4
Invasive Species	Number of invasive species	4	2	4	2	5	2	3	2	3	2	6	1
Invasive Species	% cover of all invasive species	2	4	30%	0	9%	2	8%	2	6%	2	11%	1
Invasive Species	Distribution of invasive plant species	50% = WD		100% = WD	0	60% = WD	0	70% = WD	0	65% = WD	0	55% = WD	0
Deer Browse	Degree of browsed woody and herbaceous plants	high to very high	0	Mod to high	2	High to very high	0	High to very high	0	low to mod	4	low to mod	4
Logging	Presence/absence of logging activities in Forested Dunes	H	2	H	2	H	2	H	2	H	2	N	4
Vehicle Traffic	Degree of ORV traffic in the dune system	1-3%	2	0	4	1-2%	2	0	4	1-3%	2	0	4
Foot Traffic	Degree of human foot traffic in the dune system	10-25%	2	>25%	0	>25%	0	10-25%	2	>25%	0	10-25%	2
Score			**47**		**54**		**41**		**50**		**39**		**62**

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Table 8. Summary of Landscape Context Scores for all sites surveyed.

Key Ecological Attributes	Indicators	Scores	Oval Beach/Saugatuck Nat. Area		Saugatuck SP/Gilligan's Lake/Laketown Twp beach /Sanctuary Woods		Holland SP/Tunnel Park		Port Sheldon/Kirk Park		PJ Hoffmaster SP/North Ottawa Dunes/Kitchel Dunes		Muskegon SP		Arcadia		Green Pt.		Grace Rd.		Elberta		Pt. Betsie		Leelanau SP		Fisherman's Island SP		Mt. McSauba		Petoskey SP		Woolham Preserve		Cross Village		Waugaschance Pt.	
	Site Number		27		29		35		37		38		44		91		93		95		97		122		148		149		151		153		179		179		180	
			Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score	Data	Score
Habitat Fragmentation	km roads/km2 within 2 km buffer	0-1 = 8; 1-2 = 6; 2-3 = 4; 3-4 = 2; > 4 = 0	5.63	0	3.86	2	3.46	2	2.27	4	5.02	0	2.13	4	1.32	6	1.37	6	2.8	4	4.97	0	2.2	4	2.29	4	1.38	6	6.62	0	3.92	2	1.84	6	2.01	4	0.78	8
Natural Lands	% Natural lands within 2 km buffer	90-100% = 8; 80-90% = 4; 60-80% = 2; < 60% = 0	61%	2	54%	0	68%	2	84%	4	58%	0	89%	4	83%	4	68%	2	71%	2	58%	0	92%	8	85%	4	85%	4	48%	0	64%	2	93%	8	93%	8	100%	8
Ecological Processes	Presence of artificial structures in nearshore zone within 1 km of edge of dune system	0 = 8; 1 = 4; 2 = 2; >2 = 0	2	2	5	0	3	0	2	2	2	2	7	0	0	8	0	8	0	8	5	0	12	0	3	0	7	0	6	0	1	4	1	4	3	0	0	8
Ecological Processes	% of shoreline hardening within 1 km buffer of edge of dune system	0 = 8; 1-5% = 4; 5-20% = 2; >20% = 0	22%	0	22%	0	14%	2	17%	2	31%	0	46%	0	13%	2	0	8	0	8	37%	0	22%	0	0	8	0	8	12%	2	11%	2	0	8	0	8	0	8
Score Subtotal		**32**		**4**		**2**		**6**		**12**		**2**		**8**		**20**		**24**		**22**		**0**		**12**		**16**		**18**		**2**		**10**		**26**		**20**		**32**
Total				**49**		**52**		**26**		**51**		**40**		**64**		**79**		**81**		**71**		**48**		**56**		**76**		**65**		**56**		**51**		**76**		**59**		**94**

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The highest potential score for Landscape Context was 32. Actual scores for the eighteen sites visited ranged from a low of 0 (Elberta in Benzie County) to a high of 32 (Waugaschance Pt. in Wilderness State Park, Emmet County). The average score for Landscape Context was 14.1. Using an absolute scoring system, two (2) sites scored in the excellent category, six (6) sites scored in the good category, three (3) sites scored in the fair category, and seven (7) sites scored in the poor category.

Combining Condition and Landscape Context, the highest possible score was 128. Actual scores for the eighteen sites visited ranged from a low of 26 (Holland State Park/North site in Ottawa County) to a high of 94 (Waugaschance Pt. in Wilderness State Park, Emmet County). The mean total score was 61.2. Using an absolute scoring system, one (1) site (Waugaschance Pt.) scored in the excellent category, seven (7) sites scored in the good category, nine (9) sites scored in the fair category, and one (1) site (Holland State Park/North) scored in the poor category (table 9; figure 5).

Table 9. Summary of Total Health Index Scores.

Sites Surveyed	Condition Score	Quartile	Landscape Context Score	Quartile	Total Score	Quartile
Oval Beach/Saugatuck Natural Area	45	fair	4	poor	49	fair
Saugatuck State Park/North	50	good	2	poor	52	fair
Holland State Park/North	20	poor	6	poor	26	poor
Port Sheldon/North	39	fair	12	fair	51	fair
PJ Hoffmaster State Park/Kitchel Dunes	38	fair	2	poor	40	fair
Muskegon SP	56	good	8	poor	64	good
Arcadia	59	good	20	good	79	good
Green Pt.	57	good	24	good	81	good
Grace Rd.	49	good	22	good	71	good
Elberta	48	good	0	poor	48	fair
Pt. Betsie	44	fair	12	good	56	fair
Leelanau State Park	60	good	16	fair	76	good
Fisherman's Island State Park	51	good	18	good	69	good
Mt. McSauba	54	good	2	poor	56	fair
Petoskey State Park	41	fair	10	fair	51	fair
Woolham Preserve	52	good	26	excellent	78	good
Cross Village	39	fair	20	good	59	fair
Waugaschance Pt.	62	good	32	excellent	94	excellent
Total Potential Score	96		32		128	
Avg. Score	**50.4**	**good**	**14.1**	**fair**	**61.2**	**fair**
Median Score	**49.5**	**good**	**12.0**	**fair**	**57.5**	**fair**

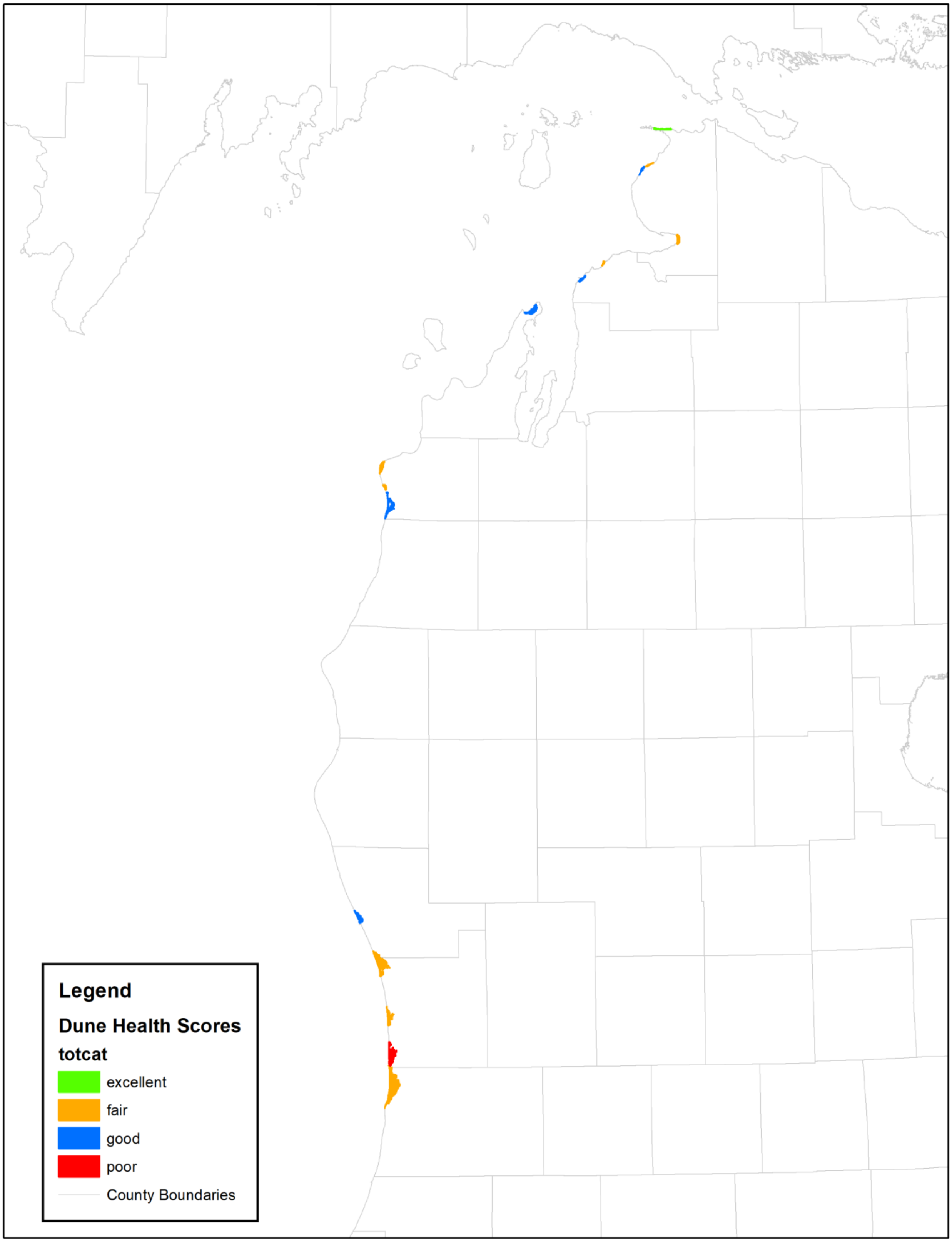

Figure 5. Overall dune health index scores (categorized) of select sites. Index scores are separated into four categories: poor, fair, good, and excellent.

Discussion/Next Steps

Overall, the work completed as part of several recent coastal resiliency projects funded by the MDNR CZM Program has significantly improved our understanding of Great Lakes coastal systems, particularly coastal dunes. Work completed by MNFI, MSU GESS, and MEC has helped improve the mapping accuracy of coastal dune systems found along Lakes Michigan, Huron, and Superior. Each of the spatial data layers completed as part of this project represent the best available information to date on both coastal erosion and coastal sand dunes in Michigan. We anticipate that the cumulative results of this work can and will be utilized by a number of coastal entities (local, regional, state, and federal) in the near future. A summary of the benefits, issues, and recommendations for each of the five spatial products resulting from this project is provided below.

1. Humphrys Shoretype Classification (1958)

The most immediate benefit of the digital version of the Humphrys shoretype classification is its application to shoreline erosion, particularly along the eastern shoreline of Lake Michigan. Existing shoreline erosion analyses are unfortunately slow and site specific. In fact, only 250 miles of shoreline (approximately 7% of the total shoreline), spread across 27 counties are designated as high-risk erosion areas along the shorelines of Lakes Michigan, Superior and Huron (Michigan Department of Environmental Quality n.d.). The Humphrys shoretype classification has the potential to help local communities and agencies flag areas for future analysis and provide initial precautions to existing and future landowners along the coast about any significant erosion issues.

One shortfall of the Humphyrs 1958 dataset is that the vast majority of the Upper Peninsula shoreline was never surveyed and classified. Additionally, the shoretype classification appears to underestimate areas of shoreline erosion on the eastern side of the state, particularly south of Port Huron. Given the age of the mapping (60 years old), vast areas of the Upper Peninsula that are unclassified, and an apparent underestimation of areas south of Port Huron along the eastside of the state, the authors recommend that the dataset be tested for accuracy. For efficiency, the authors recommend taking a random sampling approach. Considering that this information was created back in the late 1950’s, it would be useful to determine how well erosion levels assessed 60 years ago correlate with current knowledge and conditions of coastal erosion in Michigan.

2. Digital Version of Buckler’s Coastal Dune Maps (1978-79)

W.C. Buckler created a very detailed version of coastal dune types back in the late 1970’s. These maps provide an additional classification of coastal dunes that is now available digitally, as well as an initial reference point (40 years ago) of coastal dune characteristics and extent. The digital version of these detailed maps can be used by researchers to help decipher complex dune formations, and the original mylar maps provide an archival documentation of dune formations as they appeared in the 1970’s.

As MNFI studied and reviewed the hardcopy mylar maps, researchers became aware of issues such as the poor condition of maps, as well as a lack of consistent scale. Apparently the original mylar maps were enlarged at various scales in order to help create more accurate line work for dune formations. This created problems when it came time to geo-rectify the maps and create one seamless image. In addition, it was discovered that a fair number of the original maps were still missing. Authors recommend that future resources and priorities be put towards working with MDEQ Oil, Gas and Minerals Division staff to recover the missing hardcopy maps.

3. New Coastal Dune Extent and Classification Data Layers

The State of Michigan now has the best interpretation of coastal dune sites and classification along the Great Lakes shoreline. The improved accuracy and detail will assist a number of entities with a variety of coastal related activities such as landuse planning, policy, permitting, site review, conservation action and research.

As researchers delineated dune sites using heads up digitizing, several issues were identified. Fortunately, the vast majority of dune site boundaries delineated by previous efforts were confirmed by MNFI researchers. There were a few site boundaries that were revised primarily due to more accurate LiDAR imagery that became available after the prior projects ended. MNFI researchers also had the advantage of conducting site surveys at 18 dune sites, as well as viewing other dune systems while traveling between these sites. In total, MNFI added approximately 50 new sites to the latest MSU GESS dataset. With the exception of North and South Fox islands (Lake Michigan), all new dune site additions were dune and swale complexes located along the Lake Huron, northwestern Lake Michigan (Upper Peninsula), and southern Lake Superior shorelines.

It was recognized by both the MNFI and MSU GESS that there are still additional dune sites that haven’t been identified yet, and a few existing dune boundaries that require further review. The good news is that high-resolution LiDAR will be available for all coastal counties in 2019. The high-resolution LiDAR will also help better distinguish between the different dune types within a given site. When combined, high-resolution LiDAR and digital soils data provide the best information for delineating both dune sites and dune classes. It is recommended that MNFI researchers continue to work with Allan Arborgast, Department Chair for MSU GESS, to review and finalize any changes to dune boundaries based on newly obtained LiDAR data. Utilizing high-resolution LiDAR (in combination with digital soils data) will result in the best, most accurate geo-spatial information on dune boundaries and classification in the state of Michigan.

One benefit of the statewide dune classification was that several new dune classes were identified and added to the original classification focused on the Northwest Lower Peninsula. For example, “Modified” was a new category added to delineate portions of a dune site that were significantly altered. These included high density residential development, roads, commercial development, schools, large parking lots, sand mines, and quarries. Future work could include classifying these alterations into different categories. Additionally, areas that were no longer dunes and located on the periphery of a dune site (mines and quarries) were typically excluded from this process. In the future, these areas could be added to the original dune sites as a modified class.

The new statewide dune information resulting from this project provides a great opportunity to assess the distribution and conservation status of different types of coastal dunes across Michigan's Great Lakes shoreline. This should be done at multiple scales from the statewide scale down to the landscape ecoregion scale. We highly recommend taking the finalized versions of the dune site data layer and dune class data layer, and summarize it by lake, ecoregion and county. Dune sites and dune types can be summarized by total acres, number of sites, average size and size range, among other measurements. This type of assessment will help provide a better understanding of dune distribution across the state. Results from this type of analysis could also be used to identify rarity at different scales, as well as the best opportunities for conservation action. MNFI conducted this type of analysis in a previous project focused on the Northwest Lower Peninsula. Now that the same information is available statewide, it can lead to the most comprehensive understanding of dune distribution patterns in Michigan to date.

4. Prototype of Coastal Dune Health Index (Select sites along Lake Michigan)

Development of the coastal dune health index was the most ambitious and difficult tasks of this project. Based on a relatively thorough literature review, it appears that this hasn't been attempted by other researchers in either freshwater or saltwater dune systems. The concept of an index was borrowed from the conservation target viability framework used by the Open Standards for the Practice of Conservation (OS). Originally, the plan was to build a strictly GIS-based remote assessment and use field surveys to evaluate accuracy. However, as the project proceeded, MNFI and the AC determined that field data was needed to create and populate the index rather than just testing its accuracy. Researchers also realized that evaluating an entire dune site is a very difficult task. Many of the dune sites seem to have a significant portion in private ownership, and many of them were deemed too large to survey within the timeframe and budget limitations of the project. To put this in perspective, the mean size of a coastal dune site in Michigan is 1,547.7 acres, and it typically takes field scientists one day to adequately survey 200-300 acres.

The final scores for condition, landscape context, and the overall index appear to be representative of the set of sites selected for field surveys. All sites were located along the mainland of eastern Lake Michigan and were primarily selected based on accessibility and size. These two factors eliminated sites that were mostly in private ownership and/or were too large to survey (given the funding and time constraints of the project). Based on these restrictions, index scores were expected to be relatively similar rather than reflective of the distribution found in a typical bell curve. This appears to hold true for both the condition score and the overall score. Only one site was categorized as poor in regard to both condition and the overall score, and only one site was categorized as excellent (for the overall index). The landscape context scores however were more evenly distributed, ranging from seven sites categorized as poor to two sites categorized as excellent. This is probably a reflection of a north-south development trend, with more development pressure in the south, and less development pressure in the north. To ensure broader representation of overall health, the authors recommend conducting additional field surveys along Lake Huron, Lake Superior, northern Lake Michigan (Upper Peninsula), and Lake Michigan Islands.

In terms of the scoring design for the index, there were a few suggestions from the AC that should be explored. One suggestion was to evaluate the impact of a weighting system. Indicators in the prototype index have individual scores ranging from 0 to 8 or 0 to 4. Each indicator is given equal weight in regard to the condition, landscape context, and overall index scores. Weighting several indicators more than others could have a significant impact on scores for each category. Another suggestion from the AC was to try and quantify each key ecological process at a site. The current index only documents whether or not the ecological process exists at a site (e.g., sedimentation). Given the dynamic nature of freshwater coastal dune systems, quantifying ecological processes could help improve the overall robustness of the index.

Another recommendation to improve the efficacy of the index was to evaluate each individual class of dune within a dune site, and then aggregate each one into a total score for the entire site. The assumption is that this would help address both the range of habitats and human impacts within a site, as well as access issues associated with private ownership. For example, there are several sites in the Southwest Lower Peninsula that contain large areas of low-lying aeolian sand. Unfortunately, field data collection from these sites was almost impossible due to the high levels of private ownership. As a result, areas with low-lying aeolian sand were excluded from the evaluation.

Lastly, it was determined that the dune and swale complex was so different from the rest of the coastal dune systems that it required a different set of indicators to evaluate health. In order to develop a more robust coastal dune health index, the authors recommend the development of a health index specifically focused on dune and swale complexes. Dune and swale complexes have different hydrologic regimes, and typically harbor diverse wetland and upland habitats. As part of building a more robust dune health index, the authors also recommend visiting several dune sites in areas that would address significant spatial gaps (e.g., Lake Michigan islands, Lake Superior coastline, and Lake Huron coastline). The finalized coastal dune health index (for evaluating all dune sites) will be useful for determining priority activities such as protection, zoning, recreation, acquisition, management, and/or restoration efforts. Given the decreasing resources available for conservation, understanding where best to put those limited resources is becoming more and more critical.

Key Next Steps

Prioritize Dunes for Conservation Action

For decades, government agencies and conservation-based organizations have often wondered which dune sites to prioritize for future conservation actions. This was a difficult question to answer due to poor spatial data, lack of a method for measuring dune health, and inaccurate or incomplete information on ownership and conservation status. The three steps described above:

1) accurate dune boundaries and classification types, 2) summary of coastal dune patterns at multiple scales, and 3) a coastal dune health index (for all dune types) provide the key information gaps needed for dune prioritization. Additional information on other dune values will also be important for identifying priorities. To incorporate additional information, it is recommended that an advisory committee be formed, and work should build off recently completed and ongoing projects conducted by the Michigan Environmental Council (MEC). We envision the advisory committee consisting of entities already engaged in dune conservation such as (but not limited to) land conservancies, the Dune Alliance, and MEC.

Share Data and Information Online

For spatial datasets to be useful they must be in a format easily accessible to a range of users. The spatial datasets are available for viewing and download using this Link. The authors recommend the creation of a Story Map similar to the work MNFI did as part of the CZM funded project with Networks Northwest. Within AGOL these data on dune systems can be made available to any entity for permit review activities, personal decisions regarding coastal properties, management decisions, developing master plans and/or zoning ordinances, research, and broader coastal resiliency planning efforts. Users can either view interactive maps through a web browser or download the spatial data into their own spatial analysis platform. The AGOL portal is also a very dynamic system, allowing users almost instant access to any changes in the datasets. The Story Map would be a great tool for sharing key information about dune systems, including conservation priorities, with a diversity of end-users.

Conclusion

This information will help land managers make difficult decisions about dune management and stewardship, local units of government with planning, zoning, site plan reviews, and grant applications, and land conservancies and government agencies with acquisition decisions. Better spatial information on coastal dunes will help support community efforts to plan and manage future growth and development on lands adjacent to these coastal areas, while protecting critical dune systems that provide services and benefits to everyone. Information developed from this project will also help inform scenario-based land use planning and zoning efforts currently being promoted by the CZM program in coastal communities. Lastly, dunes play a critical role in community vitality, development, and tourism. Having access to detailed information of specific dune systems will help communities and regions more appropriately develop, enhance, and promote place-based identities that incorporate the long-term health and vitality of coastal dunes.

The authors recommend five key steps to fully leverage the information resulting from this project: 1) finalize coastal dune boundaries based on availability of high-resolution LiDAR data, 2) assess and summarize dune patterns at multiple scales, 3) finalize the dune health index and apply it to surveyed dune systems, 4) prioritize dune sites for conservation action, and 5) share the information with end-users via an ArcGIS Story Map and online map viewer. Together, these steps will result in the most complete understanding to date of the distribution, health, and conservation priorities of coastal dune systems in Michigan.

Acknowledgements

First, the authors would like to express their gratitude for the assistance from the Coastal Dune Advisory Committee which consisted of Shaun Howard (The Nature Conservancy), Noel Pavlovic and Ralph Grundel (US Geologic Survey), and Josh Cohen (Michigan Natural Features Inventory). Their vast knowledge and experience studying coastal dune systems in the Great Lakes region was invaluable in developing the prototype for the coastal dune health index. We would especially like to thank Shaun, Noel, and Ralph for volunteering their valuable time to advance the prototype. In addition to these four, Clay Wilton, MNFI ecologist, provided notes from field surveys at two coastal parks he visited as part of another project to help fill in data gaps.

We would also like to thank Rebecca Rogers for facilitating the scanning of the Buckler dune maps. There were several hiccups along the way, and Rebecca did a great job of keeping things on track. The State of Michigan Archives team, which included Jessica Harden, Mark Harvey and Peter Richards, did a great job of making sure all of the Buckler maps were scanned properly, and for getting them back to us in a timely fashion. We would also like to thank the State of Michigan Archives for agreeing to permanently archive all of the original mylar maps.

Nancy Toben and Ashley Adkins provided great administrative assistance throughout the duration of the project. Nancy put in extra time to ensure the budgets were accurately reflected in multiple spreadsheets and that communication between MSU and CZM went as smoothly as possible. We would also like to thank our grant officer, Karen Boase, for supporting this important work, connecting it related efforts, and showing great enthusiasm throughout the project.

Last but not least, we would like to thank Michael J. Paskus for volunteering to assist with field surveys. Mike provided great assistance in surveying the P.J. Hoffmaster/North Ottawa Dunes/Kitchel Dunes site. This site, located in Ottawa and Muskegon Counties, is the second largest site that was surveyed. It covers 3,915 acres and includes 5.75 miles of shoreline. Given the limited amount of time we had to survey the site, Mike’s keen observations, note-taking and enthusiasm helped ensure we completed the site in a timely fashion.

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Appendix A:

Secondary Data for

Mapping Coastal Dunes

DNR shoreline boundary:

This spatial dataset was prepared by the DNR CZM program. The shoreline was digitized from aerial photographs available in 1998. No metadata is available for this dataset.

Copies of this dataset were edited and attributed with attributes from the Humphreys Classification and the FEMA Greta Lakes Shoreline Classification. Quality control procedures as outlined in section 3.2.5 will apply to the editing process.

SSURGO soils:

MNFI will make use of USDA NRCS SSURGO soils data available from NRCS at https://www.lib.ncsu.edu/gis/nrcs.html. These data will be used to help better define breaks in the Humphreys' shoretype classification and to classify coastal dune systems.

Following is a description of the SSURGO data: The SSURGO database contains information about soil as collected by the National Cooperative Soil Survey over the course of a century. The information can be displayed in tables or as maps and is available for most areas in the United States and the Territories, Commonwealths, and Island Nations served by the USDA-NRCS. The information was gathered by walking over the land and observing the soil. Many soil samples were analyzed in laboratories. The maps outline areas called map units. The map units describe soils and other components that have unique properties, interpretations, and productivity. The information was collected at scales ranging from 1:12,000 to 1:63,360. More details were gathered at a scale of 1:12,000 than at a scale of 1:63,360. The mapping is intended for natural resource planning and management by landowners, townships, and counties. Some knowledge of soils data and map scale is necessary to avoid misunderstandings.

High-resolution LiDAR

High-resolution LiDAR imagery (1m) will be acquired from the Office of the Great Lakes. At present, this imagery is only available for select counties (approximately 14) along the Great Lakes shoreline. High-resolution LiDAR imagery will be a primary source for reviewing dune site boundaries, and delineating dune types where it is available.

FEMA shoreline classification:

The FEMA shoreline classification is derived from the recent Federal Emergency Management Agency (FEMA) and U.S. Army Corps of Engineers (USACE) Great Lakes Coastal Flooding study (http://www.greatlakescoast.org/great-lakes-coastal-analysis-and-mapping/technical-resources/). It was originally produced by the USACE and Environment Canada in the 1980's for the International Joint Commission's Levels Reference Study; the data were used to assess the influence of lake levels on Great Lakes shoreline erosion. No metadata is available to ascertain the map scale of the FEMA spatial data. This data will be used to compare to the newly digitized Humphrys shoreline classification and map and assist with defining breaks in shoreline types.

MNFI Biotics database:

The MNFI natural heritage database is a compilation of rare species and high-quality natural community locations. The database is maintained to the NatureServe (www.natureserve.org) standards for natural heritage data. In this project MNFI will utilize a subset of the database consisting of dune and dune related natural communities to help review existing coastal dune boundaries spatially identify specific dune types such as wooded dune and swale complex, and to develop the coastal dune health index. MNFI Biotics Database contains data on native and non-native plant species, ecological processes, threats, past disturbances, and landscape context.

MSU/MEC Coastal Dune Boundaries

MNFI will use the coastal dune boundaries developed by the recently completed project (#17-CHab-001) managed by MEC and the MSU Department of Geology, entitled "Valuing Michigan's Coastal Dunes." We will use the spatial boundaries for determining coastal dune extent as the basis for delineating coastal dune subtypes.

Michigan Critical dunes:

MNFI will utilize the critical dune spatial data available from the State of Michigan spatial data library (https://www.mcgi.state.mi.us/mgdl/) or the GIS Michigan Open Data portal. These data are described as digital form of maps used in the "Designated and Critical Sand Dune Areas" pamphlet, and published by Geological Survey Division in 1996. These are the same areas represented in the "Atlas of Critical Dunes", which was published in February 1989 and is referenced in Part 353, Sand Dune Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (NREPA). We will use this data as a reference for digitizing coastal dunes in the study area.

National Elevation Data:

MNFI will utilize USGS elevation data (http://nationalmap.gov/elevation.html) to digitize the Humphrys' shoretype classification and to classify and delineate dune systems. MNFI will use the 1/3 arc-second elevation data which are raster data having ten meter pixel resolution.

Aerial imagery:

MNFI will use a variety of aerial imagery as backdrops to digitize dune systems and to attribute the shoreline line work with the shoreline classifications. Source include (but not limited to):

National Agriculture Inventory Program (NAIP) imagery published by the USDA Farm Service Agency. NAIP imagery is acquired at a one-meter ground sample distance (GSD) with a horizontal accuracy that matches within six meters of photo-identifiable ground control points, which are used during image inspection. The most recent NAIP imagery available is from 2014. Prior year imagery may also be utilized.

Great Lakes Oblique Imagery, published by the US Army Corps of Engineers in 2012 (http://greatlakesresilience.org/maps-tools-data/data/great-lakes-oblique-imagery) and published by the DNR CZM program in 2015.

Appendix B:

Advisory Committee Members

Advisory Committee Members

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Appendix C:

Coastal Dune Field Form

Dune Polygon #________ **Shore Length (meters)________** **Area (ac)____________**

Site Name	**Date**	**Surveyor**

Dune Type (P, WDS, CDF, R)	**Vegetation (Y/N)**	**Perched (L/H)**

% Natural Lands: 90-100% 80-90% 60-80% <60%

Notes: (include GPS pts of recent human disturbances)

Seral Stages Present (Description/dominant plants/rare species/disturbances):

Beach (avg width)

Blowouts (number; evidence of erosion, sedimentation; % veg cover)

Foredune (average height and width; % veg cover)

Early successional zones (number, avg. size)

Forested back dune (natural disturbances)

Great Lakes barrens (number, avg size)

Interdunal wetlands (number, avg size)

Artificial structures in Water (# and length)

Groin ____

Jetty ____

Pier ____

Artificial hardening along shoreline (type and length) (sheet metal, rip rap, gabion, concrete)

Invasive Species (include forest diseases and inverts as well)

Name	% Cover	Distribution	Notes (habitat type)

Deer Browse (qualitative judgement based on meander surveys)

None to Low
Low to moderate
Moderate to high
High to very high
Notes:

Logging

Absence of logging in forested back dunes
Presence of historical logging in forested back dunes
Presence of recent logging activity
Notes:

Vehicle Traffic (% of site impacted)

0%   1-5%   5-10%   > 10%

Notes:

Foot Trafffic (% of site impacted)

0-5%   5-10%   10-25%   > 25%

Notes:

Additional Notes:

Appendix D:
List of References for the
Coastal Dune Health Index

References to Support the Indicators of the Coastal Dune Health Index

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Appendix E:
Summary of Humphrys Shoretypes

Shoretype	Count	Length (Meters)
Anchorville	2	12,129.18
Antrim Low	6	68,246.29
Arbutus	1	3,948.25
Au Gres	4	85,646.79
Bay Shore Bluff	2	16,242.83
Beach	6	11,670.10
Bell Isle River Rouge Dock Area	2	3,465.14
Betsie Point Dunes	2	23,961.28
Big Sable Dunes	4	38,147.65
Black River	1	17,623.77
Cecil Bay	3	12,477.47
Crystal Bluff	2	5,547.33
Detroit Ecorse Trenton Park	3	4,168.69
Detroit Metropolitan	2	13,027.36
Duncan Bay	1	2,719.89
Ecorse Cultural	2	3,531.55
Estral Beach	1	2,427.50
Fairview Bluff	1	9,568.66
Forester Low Bluff	1	4,975.37
Fourteen Mile Point	5	10,770.92
Ganges Bluff	3	24,347.44
Gaukler Point	2	4,667.73
Gibraltar	2	3,573.22
Glen Arbor	5	38,643.22
Good Hart Bluff	1	41,557.73
Grant Hill Bluff	12	44,697.68
Grass Bay	2	29,524.30
Grosse Point Parkway	1	11,954.96
Hammond Bay	1	23,644.42
Harbert Bluff	1	4,499.88
Harrisville	1	13,235.38
Huron City Bluff	2	8,693.06
Iosco	6	56,112.16
Iron River	5	11,016.93
Lake View	1	2,214.33
LakePort Beach	1	4,622.35
LakePort Bluff	1	3,351.35
Leelanau Point	1	5,219.85
Lexington Bluff	2	30,477.37
Lincoln Bay	2	11,029.26
Little Girls Point	1	1,848.66

Lone Rock	2	13,446.78
Lubaway	2	5,027.76
Shoretype	**Count**	**Length (Meters)**
Marysville Low	3	27,902.04
Maumee Marsh	4	29,951.72
Michiana Bluff	1	16,985.69
Milleview	1	1,290.55
Mineral River	2	1,968.73
Misery Bay	10	111,243.82
Monaghan Point	4	35,370.38
Montague	2	12,325.12
Montana Creek	1	13,638.44
Montreal River	1	6,308.48
Mount Clemens Marsh	2	3,201.88
New Mission	3	39,636.32
Nine Mile Point	2	15,426.47
Nipissing Bluff	6	51,414.88
North Bay	1	1,014.08
Northport	3	32,504.30
Old Mission Beach	1	7,071.36
Plaisance	6	7,139.03
Plum Creek	2	851.62
Point Aux Peaux	1	3,918.06
Point Mouille	3	33,603.87
Point Mouille Marsh	1	7,240.20
Porcupine Mountains	2	12,881.56
Port Hope Beach	3	44,513.03
Port Huron Beach	1	9,594.60
Port Oneida	4	24,816.07
Port Sanilac Bluff	1	10,859.21
Portage Lowland	9	29,909.80
Presque Isle	3	70,221.39
Pt. Aux Barques	1	15,471.96
Richmondville Bluff	1	3,919.32
River Rouge Riverview Wyandotte Trenton Industrial	3	18,298.90
Sand Point	1	25,058.38
Sleeper Beach	1	22,875.72
Sleeping Bear	1	8,392.51
South Haven Bluff	3	29,564.16
South Point Cobble	2	20,368.00
St. Clair	4	33,129.76
St. Clair Flats	1	23,488.09

St. Clair Metropolitan Beach	1	2,215.81
St. Clair River	2	9,352.21
St. Clair River Bluff	1	10,793.59
St. Joseph Bluff	1	23,517.52
Shoretype	**Count**	**Length (Meters)**
Sterling State Park	1	2,890.28
Sturgeon Bar	2	5,952.64
Sturgeon Bay	10	38,539.69
Sunshine Point	1	1,478.04
Tawas Point	1	3,337.71
Thunder Bay	1	10,795.88
Tiebel Creek	1	4,237.49
Tobico	3	68,950.40
Tobico v1	1	9,414.22
Tobico v2	1	4,029.64
Tobico v3	1	14,798.78
Traverse City Beach	5	23,122.51
Union Bay	2	5,910.88
Warren Dunes	12	147,559.97
Waugoshance	5	15,232.85
White Rock Bluff	2	20,234.26
White Stone Point	3	21,845.32
Wilderness Park	9	46,903.10
Wildfowl Bay	1	8,443.49
Willow Point Bluff	2	5,104.15

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Glen Arbor	5	38,643.22
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Harbert Bluff	1	4,499.88
Harrisville	1	13,235.38
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Northport	3	32,504.30

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Plaisance	6	7,139.03
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Point Aux Peaux	1	3,918.06
Point Mouille	3	33,603.87
Point Mouille Marsh	1	7,240.20
Porcupine Mountains	2	12,881.56
Port Hope Beach	3	44,513.03
Port Huron Beach	1	9,594.60
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Port Sanilac Bluff	1	10,859.21
Portage Lowland	9	29,909.80
Presque Isle	3	70,221.39
Pt. Aux Barques	1	15,471.96
Richmondville Bluff	1	3,919.32
River Rouge Riverview Wyandotte Trenton Industrial	3	18,298.90
Sand Point	1	25,058.38
Sleeper Beach	1	22,875.72
Sleeping Bear	1	8,392.51
South Haven Bluff	3	29,564.16
South Point Cobble	2	20,368.00
St. Clair	4	33,129.76
St. Clair Flats	1	23,488.09
St. Clair Metropolitan Beach	1	2,215.81
St. Clair River	2	9,352.21
St. Clair River Bluff	1	10,793.59
St. Joseph Bluff	1	23,517.52
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Sturgeon Bay	10	38,539.69
Sunshine Point	1	1,478.04
Tawas Point	1	3,337.71
Thunder Bay	1	10,795.88
Tiebel Creek	1	4,237.49
Tobico	3	68,950.40
Tobico v1	1	9,414.22
Tobico v2	1	4,029.64
Tobico v3	1	14,798.78
Traverse City Beach	5	23,122.51
Union Bay	2	5,910.88
Warren Dunes	12	147,559.97
Waugoshance	5	15,232.85
White Rock Bluff	2	20,234.26

White Stone Point	3	21,845.32
Wilderness Park	9	46,903.10
Wildfowl Bay	1	8,443.49
Willow Point Bluff	2	5,104.15
Woodland	1	850.13
Total	279	2,112,581.93

Appendix F:
Dune Classification Description

Dune Formations

Six major types of dune formations were identified during the mapping process: 1) parabolic dune, 2) dune ridge,3) low-lying aeolian sand, 4) complex dune field, 5) dune bluff, and 6) dune and swale complex. In general, each type was described previously by Buckler (1978).

Parabolic dune: Name is derived from their parabolic shape. They were formed by strong winds and storms that created a repeated series of blowouts in large dune ridges (Carter et al 1990). The arms tend to extend to the sand source, while the concave center is pushed inland. They can be bow, “u” or hairpin shaped. The lakeward facing side of the dune tends to have open, gentle slopes, while the inland facing side tends to have very steep, vegetated slopes (Buckler 1978).

Dune ridge: A relatively narrow, linear ridge built in close proximity and parallel to the shoreline (Buckler 1978). For the purposes of this project, dune terraces and platforms (as described by Buckler) were included in the dune ridge category.

Low-lying aeolian sand: Broad, sandy flat sheets formed by the wind, with scattered low rounded ridges and small deflation hollows or excavation pits in some areas. Buckler describes a similar formation he refers to as a sand apron. This formation is generally difficult to delineate due to the similar looking sandy glacial lakeplain and outwash landforms commonly associated with the Great Lakes coastal zone; likewise, the exact thickness of dune sand is very difficult to determine without data from the field (Buckler 1978).

Complex dune field: An area of non-oriented dunes, generally of a hummocky, chaotic nature. Slopes are highly irregular, while the overall form tends to have an undulating appearance. It is hypothesized that complex dune fields may represent an evolutionary transition from one dune form to another (Bucker 1978).

Dune bluff: Aeolian sand which has encroached upon steep sloping non-dune formations (moraines), beginning at present lake levels and then rising distinctly above it. The windblown sands are deposited on the sloping side of the formation, with the sand deposits varying in thickness from several inches to several feet within the same site. Buckler (1978) refers to these formations as overriding dunes.

Dune and swale complex: Large areas of parallel and alternating wetland swales and upland beach ridges (dunes) found in coastal embayments and on large sand spits along the shorelines of the Great Lakes. The upland dune ridges are typically forested, while the low swales support a variety of herbaceous or forested wetland types, with open wetlands more common near the shoreline and forested wetlands more prevalent further from the lake. These unique complexes were formed by retreating water levels beginning with glacial Lake Algonquin approximately 12,000 years ago. As lake levels progressively receded, they deposited a series of low, parallel, sandy beach ridges ranging in height from 0.5 meters to 4 meters. The alternating sequence of arced sand ridges and swales often extends up to two miles inland (Kost et al. 2007).

Vegetative Cover

Three main types of vegetative cover were included in this study: 1) vegetated, 2) open, and 3) modified. A more detailed vegetation cover assessment could be conducted at each site to differentiate between specific natural community types as well as stocking density and age. MNFI has conducted this type of detailed vegetative mapping at a number of state game areas and state park and recreation areas.

Vegetated: describes moderate to large dune areas primarily covered with forest. Forest types include mesic southern forest, mesic northern forest, dry mesic southern forest, dry mesic northern forest, Great Lakes barrens and boreal forest. Dune and swale complexes include wetland communities such as rich conifer swamp, mixed hardwood-conifer swamp, poor conifer swamp, and hardwood swamp.

Open: This type captures all non-forested cover including shrubland, grassland, and bare sand. All three of these types tend to be highly dynamic in nature, changing relatively quickly to dune processes and disturbances compared to forested communities.

Modified: This was a new category that was added to capture significantly altered natural vegetation patterns coupled with a relatively intact dune formation. This included moderate to high density urban development and agricultural lands placed on top of dune formations. Some mining operations were also included if they were embedded within an existing dune site boundary (as mapped by MSU GESS). Future mapping refinements should address all sand mining operations, large parking lots, and other types of intensive developments.

Perch Position

Low Perched: Occur on a substratum base near present lake levels and which has not undergone significant uplift due to crustal rebound following deglaciation (Buckler 1978).

High Perched: Occur on the upper surface of a non-dune formation adjacent to, but elevated appreciably above, the present lake level. The underlying non-dune formation (moraine) may rise greater than three hundred feet above the current lake level (Buckler 1978).

References

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