Delineation of Michigan's Critical Dune Areas

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Table of Contents

Appendices

Acronyms and Abbreviations

1989 CDA	Critical Dune Area Designated in the 1989 Atlas
2026 CDA	Critical Dune Area Recommended in 2025-2026 Evaluation
CDA	Critical Dune Area
CZM	Coastal Zone Management
DEM	Digital Elevation Model
DQF	Diversity, Quality, and Function
DNR	Michigan Department of Natural Resources
EGLE	Michigan Department of Environment, Great Lakes, and Energy
EO	Element Occurrence
EPC	Exemplary Plant Community
GEI	GEI Consultants of Michigan, P.C.
GIS	Geographic Information Systems
NHD	Natural Heritage Database
IGLD	International Great Lakes Datum
LWD	Low Water Datum
MEC	Michigan Environmental Council
MDC	Mapped Dune Complex
MEC 2018	Dunes mapped by Arbogast, et al (Arbogast, 2018) for the *Valuing Michigan's Coastal Dunes* report
MISIN	Midwest Invasive Species Information Network
MNFI	Michigan Natural Features Inventory
MNFI 2019	Dunes mapped by Paskas, et al (Paskas, 2019) for the *Spatial Data to Improve Coastal Resiliency and Better Inform Local Decision* Making report
MSU	Michigan State University
MTU	Michigan Technological University
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NREPA	Natural Resources and Environmental Protection Act
NHD	Natural Heritage Database
UAS	Uncrewed Aerial System
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

Executive Summary

The State of Michigan has long recognized the importance of protecting its freshwater coastal sand dunes. In response to development pressures and the recognition of the need to protect especially important dunes, The Michigan Department of Natural Resources (DNR) designated 123 Critical Dune Areas (CDAs) comprising approximately 74,000 acres throughout the state in the 1989 Atlas of Critical Dunes. These CDAs are regulated under Part 353, Sand Dunes Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 PA 541, as amended (NREPA Part 353). This act regulates actions that can be taken in areas designated as CDAs that were mapped in the 1989 Atlas published by DNR.

The Michigan Department of Environment, Great Lakes, and Energy (EGLE) has contracted with GEI Consultants of Michigan, P.C. (GEI), who subcontracted with the Michigan Natural Features Inventory (MNFI), Michigan Technological University (MTU), and Michigan State University (MSU) to delineate CDAs and recommend a proposed new atlas. The project used a combination of geospatial analysis and field-based assessments to evaluate and designate new CDAs, de-designate existing CDAs that may no longer meet designation criteria, or correct CDA boundaries as appropriate based on physical and ecological conditions, using updated geospatial data. The project included the development or refinement of criteria for the designation of CDAs, using scientifically defensible methodology that can serve as a model for future updates to the atlas.

The 1989 CDAs represent approximately 74,000 acres along 265 miles of Michigan's shorelines on Lakes Michigan, Huron and Superior, spanning 19 Michigan counties. Advancements in geographic information systems (GIS), remote sensing, and digital mapping have led to more abundant and higher resolution data, and hence more precise delineations. At the same time, our understanding of dune systems and their ecology has increased while development pressures continue to threaten these important ecosystems. This effort proposes a revised CDA atlas, using a combination of geospatial and on the ground field analysis, currently available data and advanced technology to support the potential designation, de-designation, and/or amendment of CDAs as appropriate. The intent of this combined approach is to map and characterize both the physical and ecological features of each dune system, using both existing data and new data that has been either derived or gathered in the field. This data layer consists of 212 individually Mapped Dune Complexes (MDCs), which total 357,830 acres throughout Michigan. Additionally, the new CDA delineation includes a refined consideration of factors such as development or rare and quality plant communities that may affect how the dunes are legally protected and regulated.

Purpose and Objectives

The statewide review and update of Michigan's dune systems was designed to achieve four primary outcomes:

1. **Evaluate all 1989 CDAs**, determining where boundaries should be retained, corrected, expanded, or de-designated based on changes over the past 37 years and modern conditions.
2. **Identify previously unmapped dune systems** that meet the intent and criteria of Part 353 and warrant designation as new CDAs.
3. **Develop and apply a consistent methodology** for evaluating dune systems statewide using a combination of geomorphology, ecological integrity, development impacts, and natural community rarity.
4. **Produce an updated CDA atlas** grounded in high-resolution data, field verification, and statewide expert consensus.

To accomplish these objectives, the project analyzed 212 MDCs that represent the most comprehensive and accurate statewide dune mapping effort to date. These MDCs were created by merging datasets developed by Michigan State University (Arbogast, 2018) and the Michigan Natural Features Inventory (Paskus, 2019) and served as the foundational units of analysis.

CDA Delineation Methodology

1. High Resolution Geospatial Analysis
The project used USGS one-meter digital elevation models (DEMs), United States Army Corps of Engineers (USACE)/National Oceanic and Atmospheric Administration (NOAA) topographic-bathymetric ("topobathy") LiDAR, and lake-level data referenced to federally established low water datum (LWD). Elevation surfaces were depicted in 20-foot intervals to evaluate dune height, slope, morphology, and spatial extent.

Building on the most consistently applied component of the 1989 methodology, dune systems reaching 80 feet or greater above LWD were prioritized for designation. When a dune feature met this threshold, the entire geomorphologically connected dune system was delineated to ensure consistent representation of the full landform.

2. Dune Health Assessment
Dune Health scoring was adapted from the MNFI Coastal Dune Health Index to evaluate statewide, structural development impacts. Three key indicators were used:

- **Percent natural land cover** (using impervious surface as a proxy)
- **Road density**, representing habitat fragmentation
- **Shoreline hardening**, indicating loss of sediment connectivity

This scoring is not a stand-alone determinant for CDA designation, but it provides essential context for understanding where dune systems remain intact or where ecological and morphological integrity have been substantially compromised.

3. Beach Functionality
Healthy beaches are essential to healthy dunes because they are the source of wind-blown sand. The Beach Functionality Score evaluates:

- Presence and form of a sand beach
- Number of offshore sand bars
- Wave exposure and sheltering
- Barriers to sediment supply
- Presence of dunes adjacent to the beach
- Vegetation on the foredune or back-beach

These metrics identify where beach–dune sediment exchange remains active and where human modifications have disrupted natural coastal dynamics and are used as a line of evidence in assessing overall dune integrity.

4. Ecological Field Assessments
During the 2025 field season, MNFI and GEI ecologists conducted extensive surveys to evaluate natural community diversity, quality, and function (DQF). This included:

- Verification of existing natural community Element Occurrences (EOs)
- Identification of previously undocumented high-quality natural communities
- Assessment of vegetation structure, species composition, hydrology, regeneration, invasive species, and ecosystem processes
- Documentation incidental observations of rare plant and animal species

S1/S2-ranked natural communities and A/B-ranked EOs were given strong weight in CDA designation decisions.

5. Expert Consensus Review
A rigorous expert review process that required 100% agreement was used to finalize CDA recommendations. The consensus panel included specialists in coastal geomorphology, GIS, ecology, and dune systems from EGLE, GEI, MNFI, MSU, and MTU.

If evidence was incomplete or uncertainty remained, the default position was to retain the existing 1989 designation until additional data became available.

Key Findings

The analysis provides a detailed and accurate understanding of Michigan's dune systems that builds upon previous efforts. Major findings include:

- **Improved accuracy of dune height and extent** due to modern elevation data, resulting in the correction of many 1989 boundaries.
- **Identification of dune systems not mapped in 1989** that meet the criteria for new CDA designation.

- **Documentation of exemplary natural communities**, including wooded dune and swale complexes, interdunal wetlands, Great Lakes barrens, and high-quality forested dune systems.
- **Recognition of areas where development has significantly compromised dune integrity**, suggesting de-designation or boundary reduction in those locations.
- **Validation of the 80-foot dune height threshold** as a scientifically defensible criterion for identifying Michigan's most critical dune systems.

Outcomes and Recommendations

This mapping effort recommends the Critical Dune Areas shown in Appendix F. Summarized metrics for the 1989 CDA and Recommended 2026 CDA are provided in the table below.

CDA Summary	1989 CDA	Recommended 2026 CDA
Number of CDAs	123	83*
Private Ownership (ac)	28,351	49,930
Federal Ownership (ac)	20,909	39,688
State Ownership (ac)	22,432	53,359
County Ownership (ac)	493	1,400
Local Unit of Government Ownership (ac)	1,024	2,019
Non-Governmental Organization Ownership (ac)	1,099	3,248
Total (ac)	**74,308**	**149,644**

*Fewer CDAs are recommended because, when appropriate, 1989 CDAs were merged if they were connected as part of the same dune system.

The updated analysis recommends a refined statewide CDA atlas that:

- Corrects and modernizes existing CDA boundaries using high-resolution geospatial data
- Proposes new designated areas where dune height, ecological integrity, or natural communities warrant protection under Part 353
- Recommends removal of CDA designation from areas where dune morphology or ecological function has been irreversibly compromised
- Ensures that CDA designation reflects both physical dune characteristics and ecological significance
- Provides a transparent, repeatable framework for future updates to the CDA atlas and implementation of Part 353

This updated approach provides Michigan with the most scientifically rigorous and comprehensive assessment of its dune systems to date. It offers a strong foundation for regulatory decision-making, conservation planning, and long-term stewardship of the state's globally unique freshwater coastal dunes.

1. Introduction and Background

Coastal sand dunes line much of the Michigan's Great Lakes shorelines. These distinctive features are critical resources for the state's economics, ecology, and overall quality of life. In the 1980s, the State of Michigan recognized the need to protect coastal dunes that could be permanently impacted or lost through mining or development. In response to these pressures, the State established Critical Dune Areas (CDAs) under Part 353, Sand Dunes Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. The CDAs currently represent approximately 74,000 acres along 265 miles of Michigan's shorelines on Lakes Michigan and Superior, spanning 19 Michigan counties. The CDAs were published in the 1989 Atlas of Critical Dunes.

The CDAs were delineated using the technology and data that were available at the time, largely using topographic maps by the United States Geological Survey (USGS) and to a lesser extent, aerial photography. However, advancements in geographic information systems (GIS), remote sensing, and high-resolution digital mapping have led to more accurate and abundant data, which can improve the precision of delineations. At the same time, our understanding of dune systems and their ecology has increased while development pressures continue to threaten these important ecosystems. This effort proposes a revised CDA atlas, using currently available data and technology to designate, modify or de-designate CDAs as appropriate. Additionally, the new CDA delineation includes a refined consideration of factors such as development or unique plant communities that may affect how the dunes are legally protected and regulated.

2. Project Partners and Roles

The team assembled for this project has expertise in a diversity of disciplines, integrating backgrounds in technology, engineering, geography, geology, hydrology, ecology, geographic information systems (GIS), remote sensing, and policy from a variety of organizations. The project team, consisting of the Michigan Department of Environment, Great Lakes, and Energy (EGLE), GEI Consultants of Michigan, P.C. (GEI), Michigan Technological University (MTU), the Michigan Natural Features Inventory (MNFI), Michigan State University (MSU), and Orbis Environmental brings combined governmental, academic, and professional experience to cover the multi-faceted needs of the designation and de-designation of CDAs in the state of Michigan. Core team members and their respective roles and organizations are listed in Table 1.

Table 1. Project Partners

Partner	Organization	Role
Zach Chamberlin	EGLE	EGLE Project Manager
Amy Lounds	EGLE	EGLE Assistant Director, Water Resources Division
Brian Majka	GEI	GEI Project Manager
Jamie Matus, PG	GEI	Geologist
Erin White	GEI	GIS Specialist
Asia Rasch	GEI	Ecologist
Blake Short	GEI	Ecologist
Jerald Brown	GEI	Ecologist
Colin Brooks, PhD	MTU	Remote Sensing and GIS Analyst
Jeremy Graham	MTU	Remote Sensing and Geospatial Scientist
Ryan Williams	MTU	Geospatial Research Scientist
Guy Meadows, PhD	MTU	Coastal Dynamics and Engineering
Ryan Navarre	MTU	GIS Analyst
Samuel Berger	MTU	GIS Analyst
Abby Jenkins	MTU	Research Scientist
Tyler Bassett, PhD	MNFI	Botanist
Rachel Hackett, PhD	MNFI	Botanist
Danielle Smith	MNFI	Botanist
Abraham Stone	MNFI	Botanist
Alan Arbogast, PhD	MSU	Geographer and Dune Specialist
Ethan Theuerkauf, PhD	MSU	Coastal Geomorphologist
Bradford Slaughter	Orbis Environmental	Botanist

3. Quality Assurance/Quality Control

To ensure the accuracy, reliability, and consistency of geospatial and field data, a comprehensive *Quality Assurance and Quality Control* plan was developed and reviewed throughout the project. This plan provides a means to ensure that data is collected and analyzed consistently and accurately while providing multiple levels of review at each stage of the project.

Geospatial data quality control was led by MTU researchers, with oversight from senior project team members. The deliverable process followed five phases: data gathering, tool selection, problem trend analysis, workflow development, and initial and final product review.

During data gathering, each dataset was evaluated for positional accuracy, completeness, temporal relevance, thematic accuracy, logical consistency, and overall usability. All findings were documented in ESRI-compatible metadata. Data validation included visual inspection, attribute review, and topological checks, as appropriate. Selected processing tools were vetted to ensure compatibility with the datasets and suitability for the required analyses. Trend analysis was conducted to identify recurring issues, enabling the team to proactively address potential errors in the current effort and future updates.

For shoreline and CDA boundary extraction and digitization, a geospatial analyst created the boundary polygons and polylines for each data zone, and a second analyst independently reviewed the work. Interim products were submitted to an MTU and GEI senior review group according to established deadlines, allowing for timely feedback and revisions. Final geospatial layers, including shoreline delineations and CDA boundaries, were then submitted to EGLE for approval.

Ryan Williams and Colin Brooks approved the master data layers used throughout the project, which were uploaded to the MTU CDA Enterprise ArcGIS Online site. This process resulted in a finalized and updated CDA boundary GIS dataset.

4. Relevant Literature and Data Review

The project is intended to build upon previous statewide efforts to identify and map dunes and Critical Dune Areas throughout the State of Michigan. Key documents that informed the development of the proposed CDAs are summarized below.

4.1 Dune Type Inventory and Barrier Dune Classification Study of Michigan's Lake Michigan Shore

William Buckler's 1979 investigation (Buckler, 1979) establishes the first comprehensive, morphology-based classification system for Michigan's Great Lakes coastal dunes. Using aerial imagery and topographic interpretation, the study identifies nine major dune forms—including parabolic dunes, linear dune ridges, dune terraces, dune platforms, domal dunes, complex dune fields, dune flats, marginal sand aprons, and interdune lowlands—and classifies them according to form, orientation, arrangement, and their relationship to underlying geologic formations. As the report notes, "dune assemblages were identified and mapped according to this classification in seven priority sand dune areas along Lake Michigan." This system was designed to support regulatory decisions under Michigan's Sand Dune Protection and Management Act of 1976.

A major focus of the report is the challenge of defining "barrier dunes," a term used in the Act but not easily applied to the diverse geomorphic conditions along Lake Michigan. Buckler emphasizes that barrier dunes cannot be identified by a single dune type; instead, they must be understood as the first substantial, relatively permanent dune assemblage inland from the shoreline. Because dune morphology varies widely, the study concludes that the barrier dune is best defined as "that first dune assemblage whose forms display the greatest relative relief within the officially designated sand dune areas". This approach ensures that the designated barrier dune represents the most significant topographic buffer between the lake and inland environments.
To support this definition, the report establishes relative relief categories that apply to all dune assemblages, including barrier dunes.

These height classes are:

- **Low relief:** less than 20 feet
- **Moderate relief:** 20-80 feet
- **High relief:** greater than 80 feet

These categories provide an objective basis for identifying which dune assemblage has the "greatest relative relief" and therefore qualifies as the barrier dune. As the report states, “a dune assemblage may display low, moderate or high relative relief,” and these values reflect the local elevational difference within each MDC.

Ultimately, Buckler’s work provided the Michigan DNR with a standardized framework for mapping dune types and identifying barrier dunes, which became the basis for regulatory guidelines adopted in 1978. The study remains foundational for understanding Michigan’s coastal dune landscapes and for managing sand mining, conservation, and land-use planning along the Lake Michigan shoreline.

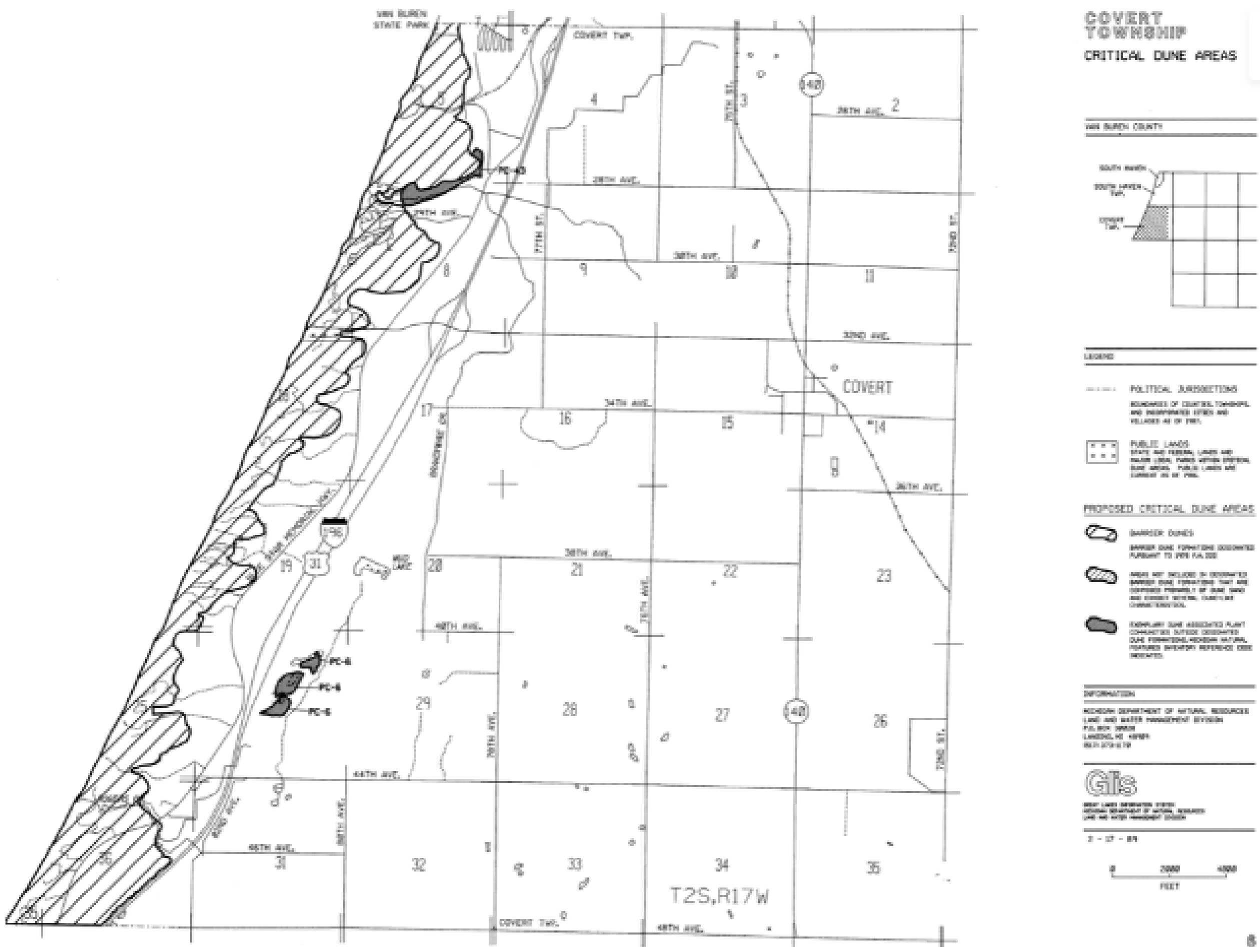
4.2 1989 Atlas of Critical Dunes

In 1989, the Michigan Department of Natural Resources (MDNR) published the *Atlas of Critical Dunes* (MDNR 1989). The atlas (1989 Atlas) is a series of maps of barrier dunes and exemplary dune associated plant communities that have been designated as *critical* throughout the State of Michigan (Figure 1). Originally issued in hard copy format, the atlas has been digitized into a GIS layer and is available through the State of Michigan website at:
https://gis-michigan.opendata.arcgis.com/datasets/egle::critical-dune-areas/about.

The 1989 Atlas used both physical and biological characteristics to designate dune areas in Michigan as critical. These primarily included:

- Dunes classified as barrier dunes that are at least 80 feet in height
- Dune-related plant communities that are considered “exemplary”
- Dunes not classified as barrier dunes or exemplary plant communities but that meet the following criteria:
    - Features composed primarily of dune sand
    - Features within 1.5 miles of shoreline
    - Dunes that are at least 20 feet in height for a significant shore length

Using these criteria, the atlas designated approximately 74,000 acres as critical within the state. For a more detailed review of this resource, see Section 5 for additional information.



PC-43 - Mesic Southern Forest, Michigan Natural Features Inventory
PC-6 - Coastal Plain Marsh, Michigan Natural Features Inventory

Figure 1: Sample area of the 1989 Atlas of Critical Dunes.

4.3 Final Report on a Natural Features Inventory of Michigan's Designated Sand Dunes

In support of the Sand Dune Protection and Management Act, the Michigan Natural Features Inventory (MNFI) was commissioned to collect data on the natural communities of Michigan's sand dunes in the early 1980s (Reese, 1986, Appendix A). The effort was intended to identify high quality dune-associated plant communities along Lake Michigan, using element occurrence (EO) ranking system of A-D, with A being the highest quality and D being the lowest. An EO is a mapped location where a rare species or natural community is present (NatureServe, 2002). To evaluate the sites, MNFI created a "Duneland Natural Heritage Scorecard."

The mapping began with interpretation of maps and aerial photographs and was followed with field investigations. The initial mapping identified 119 sites for field checking—these included open dunes, interdunal wetland, boreal forest, mesic northern forest, Great Lakes barrens, and sand and gravel beach amongst others. Field investigations of mapped sites began with a preliminary rapid assessment of the sites to determine EO ranking and the need for further investigation. Of the sites investigated, 48 were ranked excellent or good (A or B), and 48 were ranked as fair (BC and C). Follow-up visits were completed to sites ranked C or better, in an effort to assess the vegetation, soil, wildlife, and disturbances at each site in more detail.

4.4 Valuing Michigan's Coastal Dunes

The most detailed and comprehensive mapping of Michigan's Holocene-aged (< 10,000 years old) coastal sand dunes developed in a digital GIS environment was assembled through the work of Dr. Alan Arbogast (et. al.), former Chair of the Department of Geography, Environment and Spatial Sciences at Michigan State University. The following summary was assembled from *Valuing Michigan's Coastal Dune: GIS information and Economic Data to Support Management Partnerships* (Arbogast, 2018, Appendix B).

Mapping for this project was conducted by visual identification of physical dune forms on digital elevation models (DEMs) obtained from the MDNR and USGS. Across the state, spatial resolution of DEMs was variable. Some counties have high-resolution (one-meter pixel size) Light Detection and Ranging (LiDAR) derived DEMs while the rest of the state is covered by the USGS National Elevation Dataset's (NED) 3-D Elevation Project (3DEP) seamless product, with a range of spatial scales available. The product used in the creation of the map had a spatial resolution of approximately ten-meter resolution imagery (1/3 arc second).

Dunes were delineated using a process of heads-up digitization to set boundaries at the junction between dunes and adjacent landforms utilizing two categories of base data: higher spatial resolution (LiDAR products) and lower spatial resolution (NED 3DEP products). Both high- and low-resolution data utilize a solid line and a dashed line to express the spatial uncertainty of the boundary location.

In addition to the analysis of LiDAR imagery, ancillary data, such as USDA SSURGO soils data, aerial photography and satellite imagery, topographic maps, and previously mapped dune sites (the 1989 *Atlas of Critical Dunes*) were used to inform mapping decisions. Field verification was used to test the accuracy of the interpreted coastal dune boundaries and assess the accuracy of spatial-age relationship between Holocene and Pleistocene (> 10,000 years old) coastal dune systems. Representative sites were selected during the mapping process and field verification was conducted to clarify the location of boundaries and map accuracy. This effort led to the mapping of 230,714 acres of dunes in the state of Michigan.

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

After decades of effort spanning several research projects to map and manage Michigan's coastal dunes, basic, but important, information gaps remained to be addressed. The MNFI and the MDNR (now EGLE) Coastal Zone Management (CZM) Program (now Michigan Coastal Management Program) recognized that much of the current data was fragmented across several agencies and an all-encompassing geospatial dataset and methodology to evaluate the ecological integrity of dune ecosystems would be needed to provide a resource to make data driven decisions for coastal dune protection, planning, and zoning efforts. In 2017-18, the MNFI, funded by the CZM, led a project focused on the development of key geospatial datasets to address three CZM program focus areas: coastal resilience, coastal habitat, and coastal development. The following summary was assembled from *Spatial Data to Improve Coastal Resiliency and Better Inform Local Decision-Making* (Paskus, Enander, 2019, Appendix C).

The MNFI compiled and digitized three existing research projects, which represented the best available information to date on both coastal erosion and coastal dunes in Michigan, into spatial data layers to create a format that would be easily accessible to a range of users. *Humphry's Shoretype Classification (1958)* and additional spatial info (USDA SSURGO soils data, USGS topographical quadrangles, and recent aerial imagery) were used to analyze and designate high-risk erosion areas along Great Lakes shorelines. The MNFI then digitized W.C. Buckler's coastal dune maps (1978-79) through a process of scanning and geo-rectifying each map to the existing USGS topographic layer in ArcGIS. Using the coastal dune layer produced by MSU GEO (Arbogast, 2018) and ancillary datasets (aerial imagery, DEMs, LiDAR, and SSURGO soils data), the MNFI reviewed all coastal dune boundaries for accuracy and mapped all dune types using heads-up digitizing.

The culmination of research into a geospatial dataset provided a tool to identify and classify coastal dunes throughout the state, but no methodology existed to evaluate the ecological integrity of coastal dune habitats. An Advisory Committee (AC) of freshwater coastal dune experts was assembled and the AC adopted protocols from NatureServe Heritage and Open Standards for the Practice of Conservation to develop and apply a prototype Coastal Dune Health Index that could be used to assess the overall quality of specific dune sites. The result was an index that includes both GIS and field-based criteria to measure overall ecological health.

The prototype Coastal Dune Health Index was organized into two major categories: 1) Condition, which focused on the internal health of the dune site itself through 16 indicators identified and described under the Key Ecological Attributes (KEAs), and 2) Landscape Context, which focused on the health of lands immediately adjacent to the dune site through four indicators under the KEAs. Thresholds for each indicator were developed using an absolute scoring method to create a maximum potential score for each category and a combined maximum potential index score. Using this protocol, the MNFI evaluated 18 sites located along the mainland of eastern Lake Michigan and found the observed scores to be representative of the sites selected for field surveys when compared to the maximum potential index score. This effort led to the mapping of 346,688 acres of dunes and dune-associated plant communities in the State of Michigan. The increase in acreage over the MEC 2018 mapping is primarily due to the addition of dune-related plant communities that were not mapped during the 2018 effort.

4.6 USGS One-Meter Digital Elevation Models

One-meter digital elevation models (DEMs) are a tiled collection of the 3D Elevation Program (3DEP) and are one meter resolution for their raster pixels. The 3DEP data holdings serve as the elevation layer of The National Map. USGS standard one-meter DEM surfaces are produced exclusively from high-resolution terrestrial, near-infrared LiDAR source data of one-meter or higher and represent the topographic bare-earth surface. The spatial reference used for tiles of the one-meter DEM within the conterminous United States (CONUS) is Universal Transverse Mercator (UTM) in units of meters, and in conformance with the North American Datum of 1983 (NAD83). All bare earth elevation values are in meters and are referenced to the North American Vertical Datum of 1988 (NAVD88). For the Great Lakes area, the elevation values are provided in the International Great Lakes Datum of 1985. Each tile is distributed in the UTM Zone in which it lies. The one-meter DEM is the highest resolution standard DEM offered in the 3DEP product suite and has a vertical accuracy of approximately 50 cm. All 3DEP products are public domain. Data from 2022 and 2024 were downloaded in November and December 2024 from: https://apps.nationalmap.gov/downloader/.

4.7 USACE / NOAA Coastal Topobathy Lidar

Topographic-bathymetric (“topobathy”) DEM data were required for this project because the shoreline at the federal low water datum (LWD) extends beyond the coverage of the USGS one-meter DEM. The USGS DEM is derived from near-infrared LiDAR, which does not penetrate water and therefore does not capture bathymetric elevations.

To address this limitation, the project incorporated the Coastal Topobathy LiDAR dataset developed by the United States Army Corps of Engineers (USACE) and the

National Oceanic and Atmospheric Administration (NOAA). These data were collected using the Coastal Zone Mapping and Imaging LiDAR (CZMIL) system, which integrates dual-band LiDAR, a digital camera, and a hyperspectral imager. The green wavelength of the dual-band LiDAR penetrates clear water, enabling collection of bathymetric elevations to depths of approximately 20 meters under suitable conditions.

The dataset is referenced horizontally to NAD83 (2011) UTM Zone 16 North and vertically to the International Great Lakes Datum of 1985 (IGLD85). It has a spatial resolution of one meter and a vertical accuracy of approximately ±20 centimeters. Coverage typically extends about one kilometer offshore and one kilometer inland. Data were collected in 2019 for Lake Superior and in 2020 for Lakes Michigan–Huron. The files were downloaded in November and December 2024 from NOAA’s Digital Coast portal. These topobathy data were merged with the USGS one-meter DEM to create a continuous elevation surface spanning both terrestrial and submerged areas. This merged DEM enabled shoreline delineation at the federal LWD elevations of 577.5 feet for Lakes Michigan–Huron and 601.1 feet for Lake Superior (https://www.glerl.noaa.gov/data/wlevels/).

Figure 2: Merged DEM combining the USGS one-meter DEM with the USACE/NOAA coastal topobathy DEM for an area of Muskegon State Park, with example elevations based on a zero-foot contour at the LWD of 577.5 feet.

5. Review of 1989 Critical Dune Atlas

The development of criteria for designation and de-designation of CDAs is a primary goal of the proposed project. Based on the available information, it is understood that the CDA atlas developed in 1989 utilized several primary criteria to establish the CDAs—these included the following criteria:

- Dunes classified as barrier dunes that are at least 80 feet in height
- Dune-related plant communities that are considered “exemplary”
- Dunes not classified as barrier dunes or exemplary plant communities but that meet the following criteria:
  - Features composed primarily of dune sand
  - Features within 1.5 miles of shoreline
  - Dunes that are at least 20 feet in height for a significant shorelength

The assumed criteria created 123 Critical Dune Areas that totaled 74,308 acres. Because thorough documentation of the above criteria was sometimes spotty, we completed a review of the criteria to assess how it was applied throughout the 1989 CDAs. The intent of the review is to assess the criteria that was actually used in a thorough, consistent, and complete manner for the 1989 designations. Once determined, the 1989 criteria would then become the foundation for the 2026 delineation, with the intent to apply the 1989 criteria to dunes throughout Michigan in a consistent manner using high resolution data and field assessments.

There are two primary characteristics that were used to designate CDAs in the 1989 atlas—dune morphology and plant communities. Although all components that went into the original delineation are not fully documented, an understanding of the original methodology is provided below.

5.1 Dune Morphology

The creation of the 1989 dune atlas began by using barrier dunes mapped by William Buckler in 1979 (Buckler, 1979). The study was the most comprehensive and detailed mapping of Michigan’s dunes to date. The atlas then used primarily USGS topographic maps to determine where the barrier dunes met the minimum height and location criteria to be classified as *critical* (Figure 3). Although it is unclear which exact maps were used, they likely included the 1:24,000 scale 7.5-minute map series along with the USGS used computer-aided mapping developed in the mid-1970s and 1980s (Usery, 2010). While the USGS topographic maps are generally considered accurate, they often used relatively coarse scale data that may have limited the precision needed in characterizing site-specific conditions.

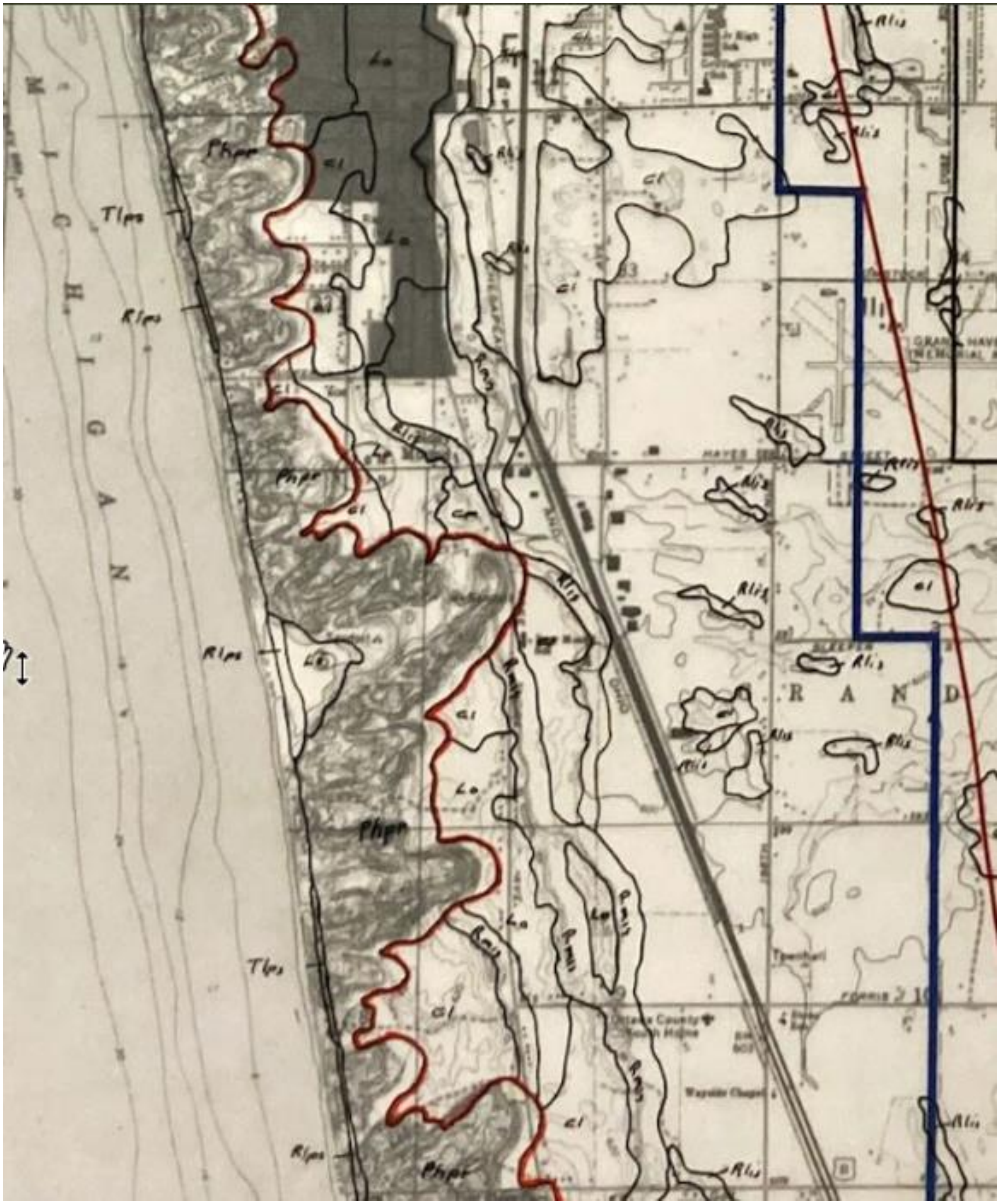


Figure 3. Delineation of dunes for 1989 Atlas using USGS Topographic Maps

5.2 Exemplary Dune Associated Plant Communities

In addition to dunes designated based on morphology, the 1989 atlas also designated exemplary dune associated plant communities that did not meet height or other criteria for CDA designation. Although the term exemplary is not specifically defined in the statute, the 1989 atlas includes approximately 15 locations where dune-associated Exemplary Plant Communities (EPCs) led to CDA designation (Figure 4, Appendix D). Each EPC location was given a unique identification, labeled as PC-1, PC-2, etc. and was assigned an MNFI natural community. Specific plant communities included open dunes, coastal plain marsh, mesic northern forest, mesic southern forest, wooded dune and swale complex, and dry-mesic southern forest (Figure 5).

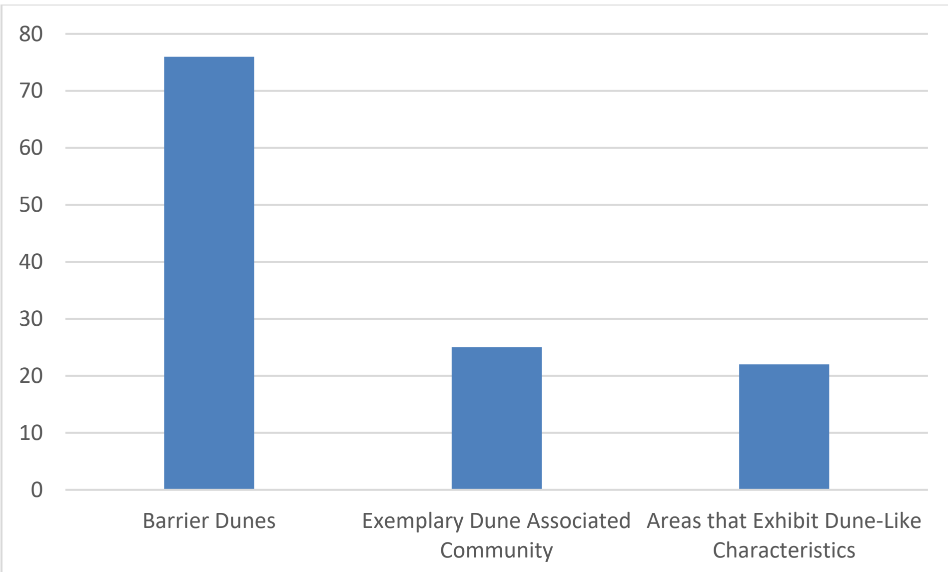


Figure 4: Breakdown of Barrier Dunes vs Other CDA-Designations in 1989 Atlas

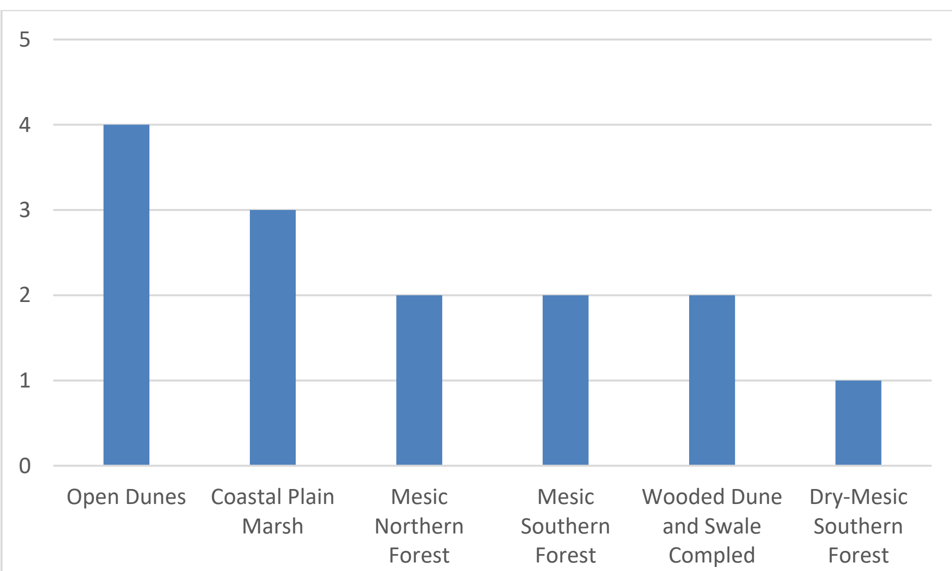


Figure 5: CDA Exemplary Plant Communities in 1989 Atlas

The exact criteria used to identify EPCs in the 1989 Atlas are unclear, but it is believed that these 15 locations represent a subset of the 96 locations ranked by MNFI as A, B, or C in the early 1980s (Reese, 1986). Mapped CDAs that used this classification range across a wide geography within the state and in a variety of settings. The CDA EPCs were cross-referenced with the Michigan Natural Heritage Database (NHD) to determine if element occurrences (EO) and rankings were available for the mapped EPC (Table 2).

Table 2. CDA Exemplary Plant Communities and Element Occurrence Rankings

County	Community Code	Community	EOID	EO Rank	Last Observed Date
Manistee	PC-1	Mesic northern forest	8649	C	1985
Mason	PC-2	Open dunes	126	AB	2010
Benzie	PC-3	Mesic northern forest	3786	BC	2015
Van Buren	PC-6	Coastal plain marsh	8108	B	2010
Muskegon	PC-10	Intermittent wetland	11484/2519	B/C	2010
Leelanau	PC-17	Mesic northern forest		BC	2010
Ottawa	PC-23	Mesic southern forest	N/A	N/A	2012
Allegan	PC-24	Dry-mesic southern forest	941	C	2010
Mackinac	PC-25	Wooded dune and swale complex	8136	CD	1986
Berrien	PC-28	Dry-mesic southern forest	1238	C	1985
Mackinac	PC-30	Wooded dune and swale complex	N/A		NA
Van Buren	PC-43	Interdunal wetland	10111	BC	1985
Emmet	PC-43	Interdunal wetland	multiple	B	2010
Emmet	PC-44	Open dunes	multiple	B	2010
Van Buren	PC-45	Mesic southern forest	7219	C	2010

While some of the EPCs, such as PC-2, PC-6, PC-43, and PC-44 align with the NHD rankings for high quality plant communities, not all do. It is therefore difficult, through desktop analysis alone, to determine the methodology used to designate the EPCs and CDA.

5.3 1989 CDA Analysis Data Summary

The results of the geospatial analysis of the 1989 CDA atlas are provided in Table 3.

Table 3. 1989 CDA Summary Statistics

1989 CDA Summary Statistics	Result
Total number of 1989 CDAs	123
Total area of 1989 CDAs (acres)	74,308
Number of 1989 CDAs designated due to Dune Morphology	103
Number of 1989 CDAs designated as Exemplary Plant Communities*	15
Total area designated 1989 CDA due to Dune Morphology (acres)	71,624
Total area designated 1989 CDA as EPC (acres)	2,684
Number of 1989 CDAs designated due to morphology that exceed 1.5 miles in shorelength	47 (47.4%)
Dune Height Summary	
Number of 1989 CDAs designated due to morphology that exceed 80' in height	86 (86.9%)
% of all 1989 CDA acreage 0-20'	22%
% of all 1989 CDA acreage 20-40'	25%
% of all 1989 CDA acreage 40-60'	19%
% of all 1989 CDA acreage 60-80'	10%
% of all 1989 CDA acreage 80'+	25%
Dune Health Summary	
% Hardened shoreline across all 1989 CDAs	14.1%
Road density across all 1989 CDAs	1.3 km/km^2
% Impervious surface across all 1989 CDAs	1.7%
Beach Functionality Summary	
Beach functionality score across all 1989 CDAs	79.9%

*Some of the EPCs were considered one CDA although they contain more than one individually mapped area, resulting in the difference in total CDA count.

6. Methodology for Analysis of Critical Dune Area Designation

The analysis of MDCs and CDAs for potential designation, de-designation, and/or amendment used a combination of both geospatial and field analysis. The intent of this combined approach is to map and characterize both the physical and ecological features of each dune system, using both existing data and new data that has been either derived from geospatial data or gathered in the field.

As described in Section 4, there were two previous efforts to map dunes and dune-associated systems in Michigan—the MEC 2018 and MNFI 2019 mappings. The MNFI 2019 effort built upon the MEC 2018 mapping, adding to and amending the dune maps along Michigan's coasts while also classifying dunes according to their physical features (morphology).

Upon reviewing both mapping efforts, the project team determined that the maps should be combined to create a comprehensive boundary for use in evaluating potential CDAs. Because the MNFI 2019 mapping both added to and amended the MEC 2018 maps, merging both sets of mapped dunes created a more holistic boundary for analysis and reduced the chances that a potential CDA could be unintentionally excluded from evaluation.

The resulting merged map of the MEC 2018 and MNFI 2019 data, with low-lying aeolian sands removed, was named the **Mapped Dune Complex (MDC)** GIS layer. This data layer consists of 212 individual MDCs throughout Michigan and was used as the fundamental boundary for both geospatial and field-based analysis. Each MDC was labeled sequentially from 1-212, beginning in southwest Michigan and following the shoreline to Lake Huron, concluding with dunes mapped along Lake Superior (Figure 6). To provide a consistent lakeward extent for each MDC, the low water datum of the adjacent Great Lake was used. This equates to 577.5 feet (IGLD 85) for Lakes Michigan and Huron and 601.1 feet (IGLD 85) for Lake Superior, as established by the United States Army Corps of Engineers (USACE). The low water datum was chosen because it provides an accepted elevation throughout the shoreline of the respective Great Lake that can be used as the lakeward extent of the shoreline regardless of the water level at any given time.

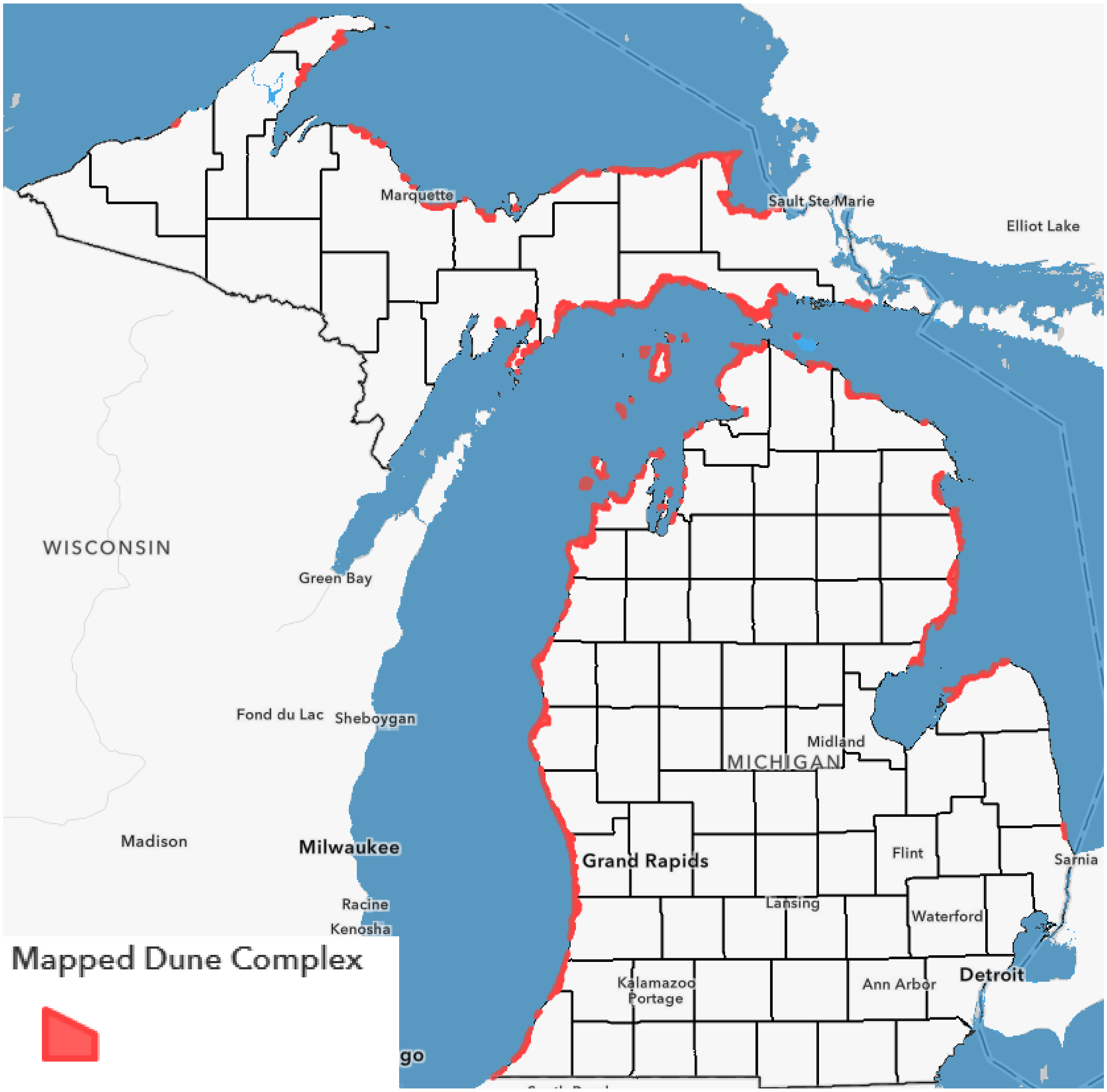


Figure 6. Mapped Dune Complexes

6.1 Amended and Refined Metrics for Designation/De-Designation of CDAs

There is no single criterion that can be used to define what makes a dune critical, according to Part 353. Dunes are complex systems that are composed of both physical and ecological characteristics, and they often coexist with human use and development. This complexity makes pure quantitative analysis impossible and unreliable, because no single metric or series of metrics can be used to define critical dune criteria.

With this understanding, we developed critical dune designation criteria that used a scientific approach that incorporated quantitative analysis with human interpretation in two ways:

- **Multiple lines of evidence** were used to evaluate every MDC and 1989 CDA. Dune morphology, beach functionality, dune health, and natural communities were evaluated either geospatially or with field assessments for each dune system to characterize the physical and ecological properties of each complex.

- **Data-driven expert consensus** is a decision-making approach that uses subjective expert judgement with objective data analysis. This approach was used for both criteria development and CDA designation decisions, using human interpretation that is supported by quantified objective analysis. Using this approach, all proposed criteria and CDA determinations have been made with agreement from the core project team listed in Section 2 using data derived from both field and geospatial analysis.

These approaches were combined with the analysis of the original 1989 criteria to develop new metrics that could be reasonably applied statewide to all dune systems within the time and resource constraints of the project effort. A detailed description of each primary characteristic is described below and is followed by the protocols used for both geospatial and field analysis. A flow chart that summarizes the process used for CDA designation is provided in Figure 7.

In the Spring of 2025, EGLE conducted a public notice period, stakeholder engagement, and tribal coordination for review and comment on the initial proposed work plan and methodology. The comments received were used to inform and refine the final methodology.

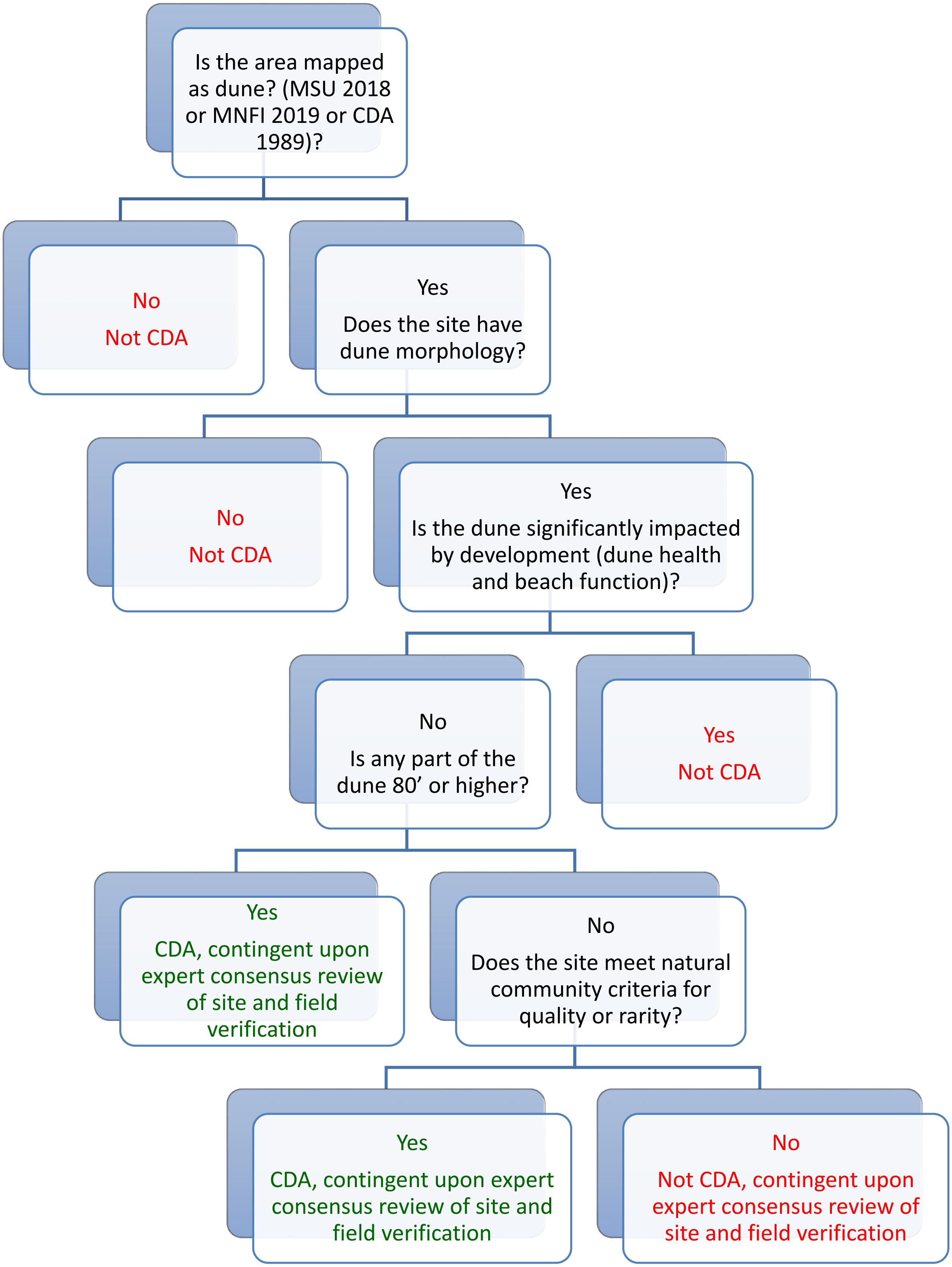


Figure 7: CDA Designation Flow Chart

6.1.1 Dune Morphology

Sand dunes are typically, but not always, distinctive physical features on the landscape. The windblown sand forms dunes in patterns that can be mapped, as was done with the MEC 2018 and MNFI 2019 mapping efforts. The MNFI 2019 dune mapping classified dunes into six categories. These include:

1) Wooded dune and swale complex
2) Parabolic
3) Complex dune field
4) Dune bluff
5) Dune ridge
6) Low-lying aeolian sands

Four of the most common dune formations are parabolic, dune ridges, complex dune fields, and wooded dune and swale (Figures 8, 9, 10, and 11), as shown below. It is important to note, however, that there are often multiple dune types that make up a dune complex, and parabolic dunes, complex dune fields, dune ridges, and wooded dune and swale complexes may intermix within a given dune complex.

Figure 8. Parabolic dunes at Warren Dunes State Park

Figure 9. Complex dune field at Sleeping Bear Dunes National Lakeshore

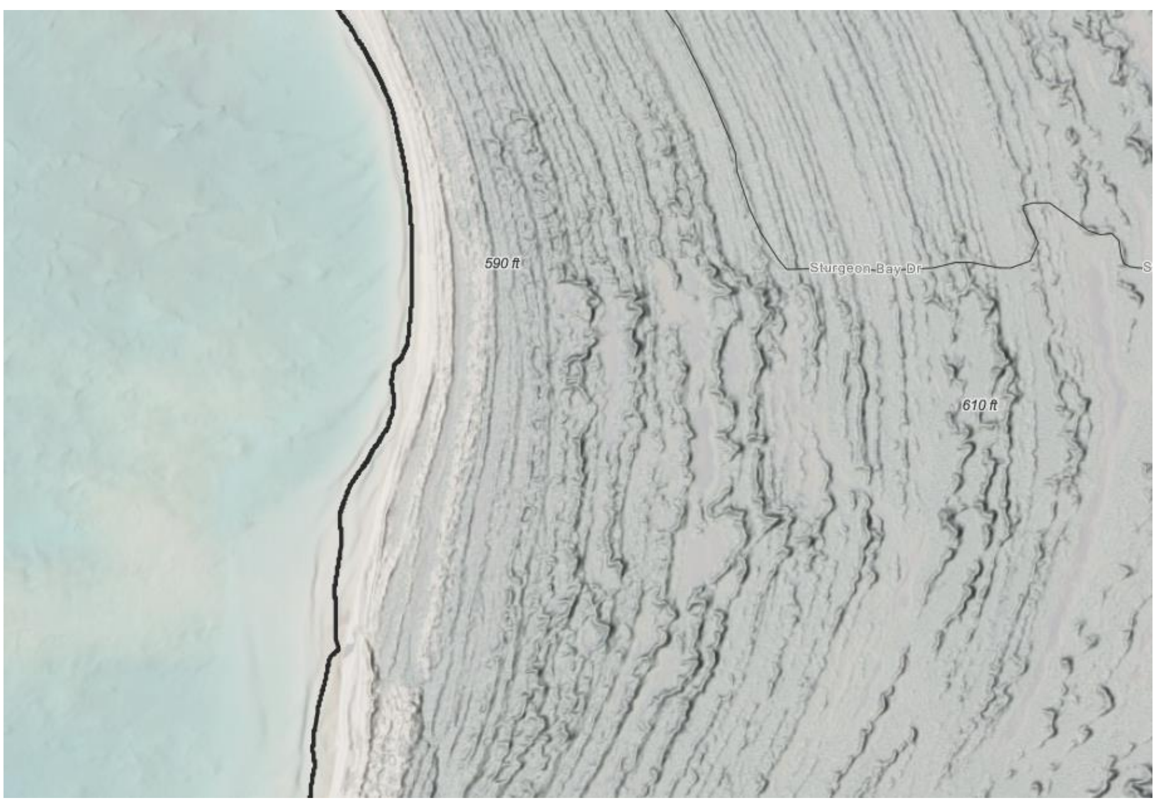


Figure 10. Wooded Dune and Swale Complex at Wilderness State Park

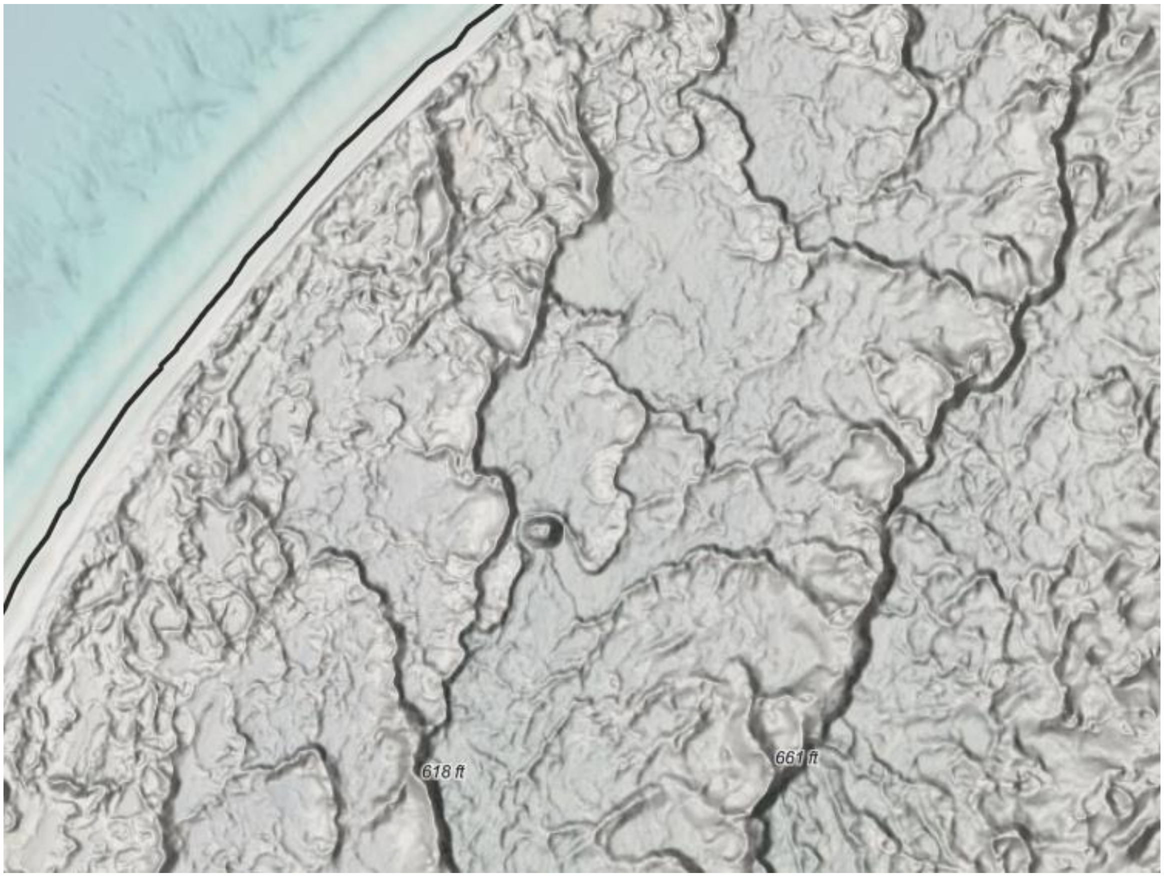


Figure 11. Dune Ridges in a Complex Dune Field at Ludington State Park

Dunes form at different heights, and the fact that Michigan has the most extensive freshwater dunes in the world is part of the reason that Part 353 was enacted into law. The analysis of the 1989 atlas in Section 5 showed that 80 feet in height was one of the most consistent criteria used in determining Critical Dune Areas, which aligns with Buckler's definition of a "high profile" dune (Buckler 1979). Shoreline length and 20 feet high dunes were less consistently applied to the designation of CDAs. It is therefore recommended that dunes that meet the morphological definition of a sand dune, lie within or adjacent to an MDC, and reach at least 80 feet in height be designated as CDA. When it was determined that a given dune system should be mapped as CDA, it was mapped using hillshaded DEMs that provided a visualization of the dune formation that make elevation easier to interpret, with a highlight on areas greater than 80 feet high (Figure 12). The dunes were mapped as an entire system, capturing both the 80 foot feature as well as the adjacent dunes that were determined to be part of a connected dunefield.

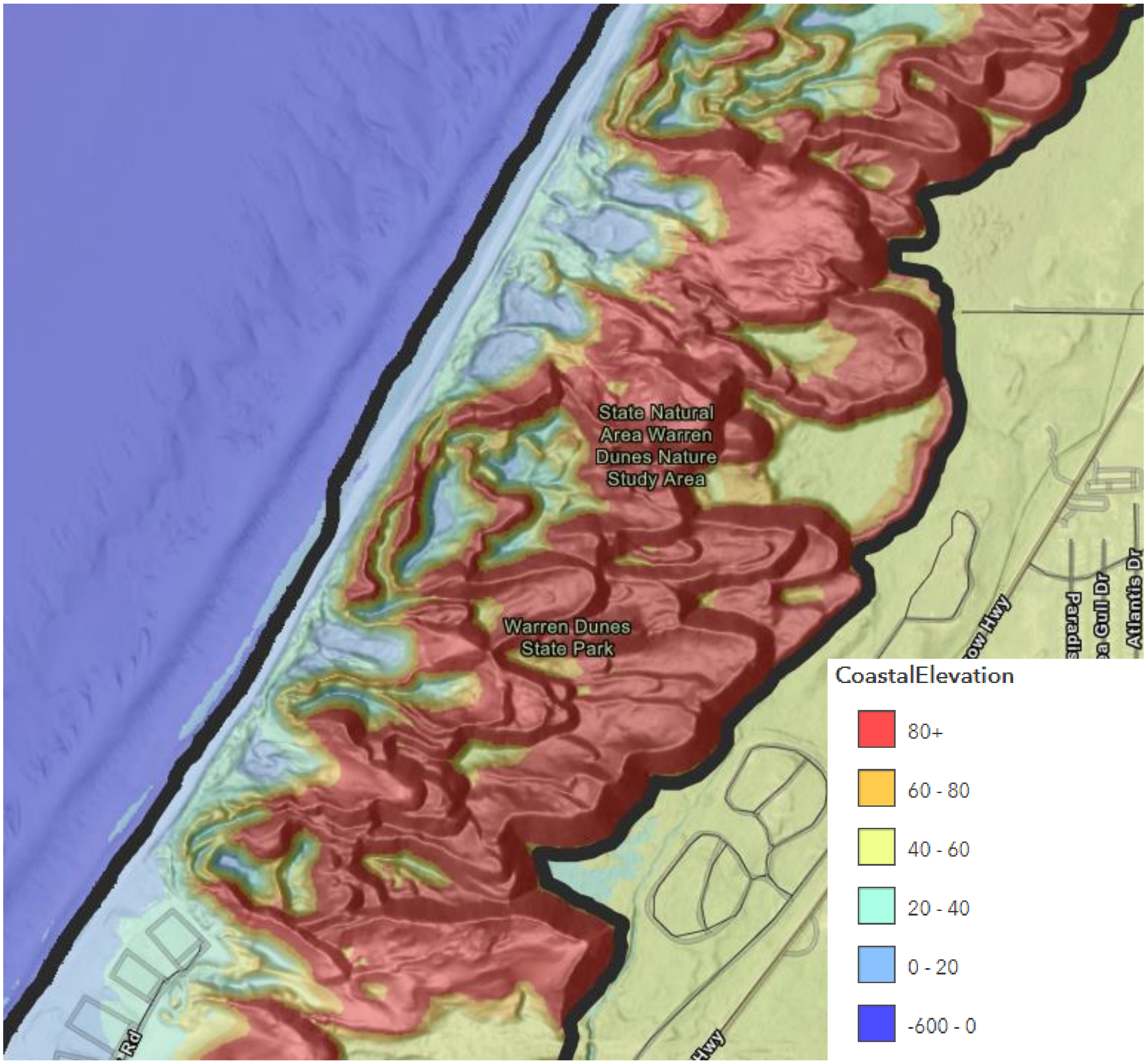


Figure 12. Coastal Elevation hillshaded DEMs, including showing areas greater than 80 feet high in red, were used to map CDAs.

CDA Designation Based on Dune Morphology

- The sand dune must lie within or adjacent to a Mapped Dune Complex AND meet the morphological definition of a dune.
- Dune complexes with a height of at least 80 feet above low water datum (LWD) will be designated as CDA. When the complex reaches 80 feet, the dune feature will be delineated as a whole, using interpretation and review by expert consensus when features are indistinct.
- Dune complexes that are large in area or are previously designated CDAs but do not reach 80 feet may be designated as CDA upon consensus by the project team.

*CDA designation may be considered in locations not specifically located within MDCs because the data resolution and technology available for this mapping effort is greater than what was available for previous mapping efforts.

6.1.2 Dune Health and Beach Functionality

The same things that make Michigan's freshwater dunes special also make them popular places for homes, businesses, and recreation. This has led to impacts to dunes through physical modification and the construction of infrastructure that has diminished diversity, quality, and function of the dunes. While some development is compatible with dunes and with Part 353, there are cases where development in CDAs is so extensive that dunes have either lost their primary morphology or they no longer warrant designation as CDA.

There are two primary ways that development impacts dune systems. The first is direct impacts through construction, paving, grading, excavation, or the removal of vegetation. The second is the impact to coastal processes that comes primarily from the hardening of the shoreline. A primary function of dunes and beaches is the natural movement of sand between the two. When shorelines are hardened, the ability of sand to migrate between the lake, beach, and dune is reduced and can cause long term impacts to the functionality of the system.

For the purposes of quantified evaluation, two scoring systems were developed by the project team to rate development impacts in coastal areas: Dune Health and Beach Functionality. These scoring systems alone are not used to designate or de-designate CDAs. However, they provide lines of evidence that support the expert consensus determination of CDA designation, de-designation, or amendment of CDAs. Each is described below.

6.1.2.1 Dune Health Scoring

In *Spatial Data to Improve Coastal Resiliency and Better Inform Local Decision Making* (MNFI 2019), a Coastal Dune Health Index system was developed to score Michigan coastal dune systems in an objective, scientific manner. The scoring system uses attributes that include natural lands, habitat fragmentation, ecological processes, and invasive species to assess the overall ecological health of a dune site.

This system was reviewed and adapted for the purposes of CDA evaluation. The attributes selected for the CDA Dune Health evaluation needed to meet several criteria. These included:

- Recent and accurate geospatial data must be available at a statewide scale or can be generated within the time constraints of the project
- Attributes should be selected that reflect permanent or semi-permanent impacts to dune morphology and/or ecology
- Attributes should be selected that impact dune diversity, quality, and function

The project team evaluated each of the attributes in the MNFI 2019 scoring, and selected the following attributes for dune health evaluation:

- **Road Density**: Calculated in road linear kilometers per square kilometer, road density is indicative of habitat fragmentation in an ecosystem. Road density was mapped using the 2024 version of the State of Michigan Roads and Highways from the Michigan Geographic Framework.
- **% Natural Lands**: As land is developed, natural lands are lost. Inversely, impervious surface is the amount of land that has been paved or covered with built structures and is representative of the permanent loss of natural lands. % Impervious surface was used as a proxy for the inverse of natural lands and was calculated using the National Oceanic and Atmospheric Administration (NOAA) C-CAP High Resolution Land Cover data for Michigan. The data provides a 1-m resolution surface of impervious surface and was released in 2024.
- **% Shoreline Hardening:** Shoreline hardening is the installation of permanent or semi-permanent structures such as seawalls, revetments, groins, or riprap that disconnect the water from the land and interrupt natural coastal processes. Shoreline hardening was calculated by digitizing features from high-resolution aerial photography.

Each of the 1989 CDAs was evaluated using the available data and total scoring was adjusted and weighted based on the averaged calculations across the sites, providing an accurate and relevant description of Michigan's coastal dune complexes. The scoring system was adjusted so that Percent Natural Lands was weighted 2X the score of Road Density and Percent Hardened Shoreline, because the permanent loss of natural lands was deemed the single largest impact to dune ecosystems. The scoring used to evaluate dune health is provided in Table 4. The highest score possible is 16, which would reflect an MDC that has no or little impact from human development.

Table 4. Dune Health Scoring

Attribute	Score
% Natural Lands	
95-100%	8
90-95%	4
85-90%	2
>85%	0
Road Density (km/km^2)	
0-2	4
2-4	3
4-6	2
6-8	1
>8	0
% Hardened Shoreline	
0-5	4
5-20	3
20-40	2
40-80	1
>80	0

Dune health scoring has been calculated for each MDC as well as each 1989 CDA and is reported in Appendix E.

6.1.2.2 Beach Functionality

With few exceptions, healthy dunes are dependent on healthy, functioning beaches. Sand is moved by wind and water between the beaches and dunes in a dynamic way that changes as Great Lakes water levels fluctuate and humans develop and alter the coast. Natural beach function is composed of several factors that work both independently and in an interconnected way, which collectively have direct bearing on dune health (Bascom 1954). A Beach Functionality scoring system was developed based on key characteristics to quantify the health of a given beach in MDCs.

The primary attributes evaluated in the Beach Functionality scoring include:

- **Geomorphology:** The physical form and material of the coast determine how it responds to waves and lake level changes. A resilient natural beach may have a mix of coarse and fine sediment, while an artificial beach is often composed of uniform, human-introduced material.
- **Offshore Sand Bars:** When sand moves from a dune or a beach to the nearshore area, it is often stored in 1-3 sand bars. The sand bars act to break the incoming waves, and can store sand until lower water levels and waves facilitate onshore transfer that helps rebuild beaches and dunes. A healthy beach in a dune system will typically have three offshore sand bars present.
- **Wave energy:** Natural beaches adjust their shape in a dynamic equilibrium with the prevailing wave conditions. The most resilient beaches are highly mobile and shift between intermediate states in response to variable wave conditions.
- **Sediment supply:** A healthy natural beach has a positive sediment budget, where the supply of sand from sources like rivers and offshore areas and/or updrift dune/bluff erosion is sufficient to offset erosion. Artificial beaches require regular, expensive "nourishment" to maintain their sand levels.
- **Presence of a dune system**: A functional natural beach often includes a healthy dune system, which provides a natural barrier against storms. The stability of dunes depends on vegetation that anchors the sand.
- **Biological diversity:** A quality ecosystem is a hallmark of a healthy natural beach.

The scoring used to evaluate beach functionality is provided in Table 5. The highest score possible is 8, which would reflect a beach that is fully functioning and healthy.

Table 5. Beach Functionality Scoring

Attribute	Score
Geomorphology	
Is a sand beach present?	Yes=1, No=0
Offshore Sand Bars	
How many sand bars are present?	0,1,2,3
Wave Energy	
Is the site free from sheltering in all directions?	Yes=1, No=0
Sediment Supply	
Is the site free from barriers to sand supply in all directions?	Yes=1, No=0
Presence of a Dune System	
Do dunes of any size exist adjacent to the beach?	Yes=1, No=0
Biological Diversity	
Is the foredune or back beach vegetated?	Yes=1, No=0

Beach functionality has been calculated for each MDC as well as each 1989 CDA and is reported in Appendix E.

CDA Designation Based on Dune Health and Beach Functionality

- Dune Health and Beach Functionality scores are not used as stand-alone or primary metrics to make CDA designation, de-designation, or amendment decisions, but were used to supplement other criteria and observations.
- The Dune Health and Beach Functionality scores will be evaluated alongside the ecological assessments and qualitative evaluation of each 1989 CDA and MDC. The scores will be lines of evidence used in support of changes to 1989 CDAs, including the potential de-designation of whole CDAs or select portions of CDAs. Dune Health and Beach Functionality scores will also be considered in the evaluation of dune systems not currently designated as CDA.

6.1.3 Dune Ecology and Natural Communities

Healthy ecosystems are a fundamental component of healthy dunes. The ecological condition of dunes is defined not only by geomorphology, but also by the diversity, quality, and functional integrity of the natural communities they support. Additionally, natural community rarity, both locally and globally, varies. In consideration of CDA designation based on natural communities, the community type, diversity, quality, function, and rarity were all considered, as described below.

6.1.3.1 Natural Community Types

Several ecosystems, or natural communities, are associated with Michigan dune systems. These communities are described in the Michigan Natural Features Inventory (MNFI) natural community classification (Cohen et al. 2015; Cohen et al. 2020). For the purposes of this assessment, dune-associated communities are organized into primary, secondary, and tertiary groups.

Primary Dune Communities
Primary communities occur exclusively within dune systems and are characteristic of coastal dune landscapes. These include:

- Open dunes
- Great Lakes barrens
- Interdunal wetland
- Wooded dune and swale complex

Secondary Dune Communities
Secondary communities frequently occur within dune complexes but are not restricted to them and may also be found inland. These include:

- Dry northern forest
- Dry southern forest
- Dry-mesic northern forest
- Mesic northern forest
- Mesic southern forest
- Dry-mesic southern forest
- Boreal forest

Tertiary Communities
Tertiary communities may occur adjacent to dune systems but are not themselves dune-dependent. These include:

- Bog
- Clay bluff
- Coastal fen
- Coastal plain marsh
- Emergent marsh
- Great Lakes marsh

- Hardwood-conifer swamp
- Intermittent wetland
- Limestone bedrock lakeshore
- Limestone cobble shore
- Muskeg
- Northern fen
- Northern hardwood swamp
- Northern shrub thicket
- Northern wet meadow
- Patterned fen
- Poor conifer swamp
- Poor fen
- Sand and gravel beach
- Sandstone bedrock lakeshore
- Sandstone cobble shore
- Southern hardwood swamp
- Southern shrub-carr
- Southern wet meadow
- Submergent marsh
- Rich conifer swamp

6.1.3.2 Natural Community Rarity

Existing MNFI natural community element occurrences (EOs) located within or adjacent to MDCs were given preference for inclusion as Critical Dune Areas (CDAs), in part based on their Sub-national Conservation Rank (S-rank) (NatureServe 2002).

S-ranks range from:

- **S1** – Critically imperiled
- **S2** – Imperiled
- **S3** – Vulnerable
- **S4** – Apparently secure
- **S5** – Secure

S1 and S2 natural communities were weighed heavily for inclusion regardless of ecological integrity (i.e., EO rank). EOs of S3 natural communities were also given significant weight when they had an EO rank of A or B.

In addition to documented EOs, intact natural communities observed during field surveys that are not documented as EOs were also considered for inclusion if they met the following criteria:

- S1 and S2 natural communities, and
- S3 natural communities with attributes supporting an A or B EO rank

that were documented during field surveys were considered for inclusion as CDAs

6.1.3.3 Diversity, Quality, and Function

Ecological integrity is defined as: “An assessment of the structure, composition, function, and connectivity of an ecosystem as compared to reference ecosystems operating within the bounds of natural or historical disturbance regimes” (Faber-Langendoen et al. 2016). The diversity, quality, and function (DQF) of dune-associated natural communities were evaluated by characterizing ecological integrity using a modified Natural Heritage Methodology (NatureServe 2002; Faber-Langendoen et al. 2016, 2024). This approach maintains consistency with field surveys conducted for the 1989 Atlas, which used an earlier version of Natural Heritage Methodology to delineate and describe original CDAs and EPCs (Reese et al. 1986). It was not feasible to fully characterize each MDC using traditional Natural Heritage Methodology. The methodology was not specifically designed for assessments framed explicitly around diversity, quality, and function as used in the Act, and time and budget constraints further limited its full application. However, Natural Heritage Methodology captures many site characteristics relevant to DQF. Therefore, we adapted the framework to evaluate dune-associated natural communities within project constraints while explicitly addressing diversity, quality, and function. Below, we first describe Natural Heritage Methodology and then how we modified it to the fit scope of the CDA and Act.

In Natural Heritage Methodology, the evaluation of the natural community results in an Element Occurrence (EO) rank based on three primary factors: 1) Condition, 2) Size, and 3) Landscape context.

Condition reflects site-level ecosystem integrity and includes an evaluation of plant community structure and composition, plant and animal indicator species, ecological processes, and hydrology. Anthropogenetic alterations to these conditions such as ditching or presence of invasive species can lower the condition ranking.

Size is evaluated relative to the historical and ecological expectations of each natural community type. Matrix communities historically dominated large portions of Michigan's landscape (typically 2,000–10,000 hectares). These include most upland forests such as dry, dry-mesic, and mesic northern and southern forests and boreal forest. Large patch communities typically occupied 50–2,000 hectares and include open dunes, Great Lakes barrens, and wooded dune and swale complexes. Small patch communities occupy discrete landscape positions (1–50 hectares) and include interdunal wetlands and coastal plain marshes.

Landscape context evaluates the degree to which surrounding land cover supports ecological integrity. Natural communities embedded within largely intact natural landscapes are buffered from biological and anthropogenic stressors and benefit from connectivity. Communities occurring within heavily managed, agricultural, or developed landscapes generally exhibit reduced integrity.

Individual natural communities are ranked for each factor above and given an overall EO Rank ranging from:

A – Excellent estimated viability/ecological integrity
B – Good estimated viability/ecological integrity
C – Fair estimated viability/ecological integrity
D – Poor estimated viability/ecological integrity

Field surveys were designed to support evaluation of DQF characteristics while aligning with overall ecological integrity goals and Natural Heritage Methodology. The methodology was refined to characterize both DQF within individual natural communities, and the overall ecological integrity of the dune complex. Although core parameters were consistently evaluated, the specific data collected were adapted to each MDC.

Diversity was evaluated using the following attributes:

- Number of characteristic species within each natural community
    - Higher ecological integrity supports greater numbers of characteristic species.
- Zonation, topographic variation, and vertical structure
    - Structural diversity reflects communities structured by natural processes.
- Habitat diversity within ecosystem complexes
    - Greater habitat diversity indicates natural process-driven systems.
- Number of rare plant and animal EOs

    - Communities with higher ecological integrity are capable of supporting more rare species.

Quality was assessed using the following attributes:

- Ecological integrity of existing natural community EOs
    - EO rank as assigned during the most recent MNFI survey and confirmed by CDA surveyors.
- Indicators of forest integrity
    - Coarse woody debris, canopy regeneration, and related features indicating mature or maturing forests structured by natural processes.
- Richness and extent of invasive species
    - Higher integrity communities exhibit lower invasive species richness and cover.
- Degree of direct anthropogenic disturbance
    - Activities such as logging, grading, or recreational overuse reduce integrity.
- Indirect impacts from residential, commercial, and agricultural development
    - Landscape-level disturbances diminish ecological quality.

Functional attributes included:

- Connectivity of natural land cover with surrounding landscape
    - Greater connectivity supports ecosystem resilience and buffering capacity.
- Process-based attributes specific to ecosystem type
    - Intact hydrology in wetlands.
    - Documented fire history in fire-dependent communities.
    - Indicators that communities are structured by natural processes.
- Degree of dynamism in open sand communities (e.g., open dunes, Great Lakes barrens, sand and gravel beach)
    - Active sand movement and disturbance regimes indicate functional systems.
- Wildlife habitat
    - Each natural community supports specific fauna, often including species of conservation concern
- Recreational value

- Public access to natural areas enhances quality of life and contributes to societal value.

CDA Designation Based on Dune Ecology

- The ecological characteristics dune system must have exemplary diversity, quality, and function using the assessment that was adapted from the Natural Heritage Database methodology.
- All EOs of S1 and S2 dune associated natural communities were weighed heavily for inclusion regardless of ecological integrity (i.e., EO rank). EOs of S3 dune associated natural communities were also given significant weight when they had an EO rank of A or B.

6.2 Protocols for Data Collection and Analysis

6.2.1 Dune Morphology

The combined USGS one-meter DEMs plus USACE/NOAA topobathymetric DEMs described in Section 4.6 were primarily used for evaluating dune morphology (Figure 13).

The combined DEM was set with the appropriate LWD, reclassed into 20 foot intervals, and intersected with each CDA polygon (both the 1989 CDAs and the Mapped Dune Complex (MDC) layers) using the Tabulate Areas function in ArcGIS Pro. The Zonal Statistics command was used to create polygon elevation statistics. This provided the area of each dune polygon that fell within each 20 feet elevation band, along with statistics such as minimum, maximum, mean, median, and standard deviation for the polygons' elevation data.

The 1989 CDAs, MDCs and the dune height statistical data were overlaid on hillshaded DEMs for interpretation and analysis. Geospatial analysts worked closely with the geographers and ecologists on the project team to map the dune features using this data. CDAs were mapped as entire dune systems when any portion of the dune reached 80' above LWD (Figures 13 and 14).

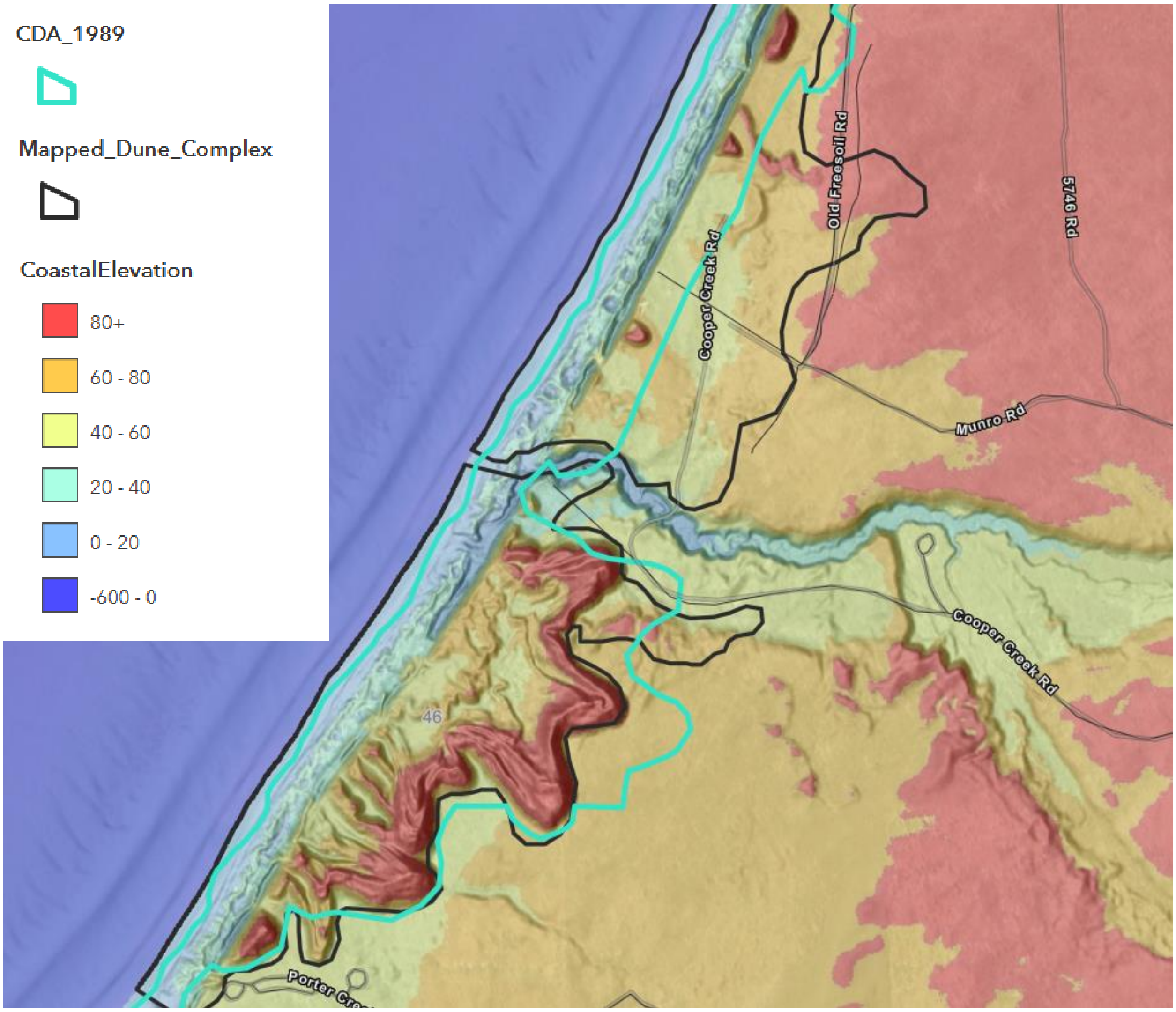


Figure 13. 1989 CDA, MDC, and Elevation Data Overlaid on Hillshaded DEM

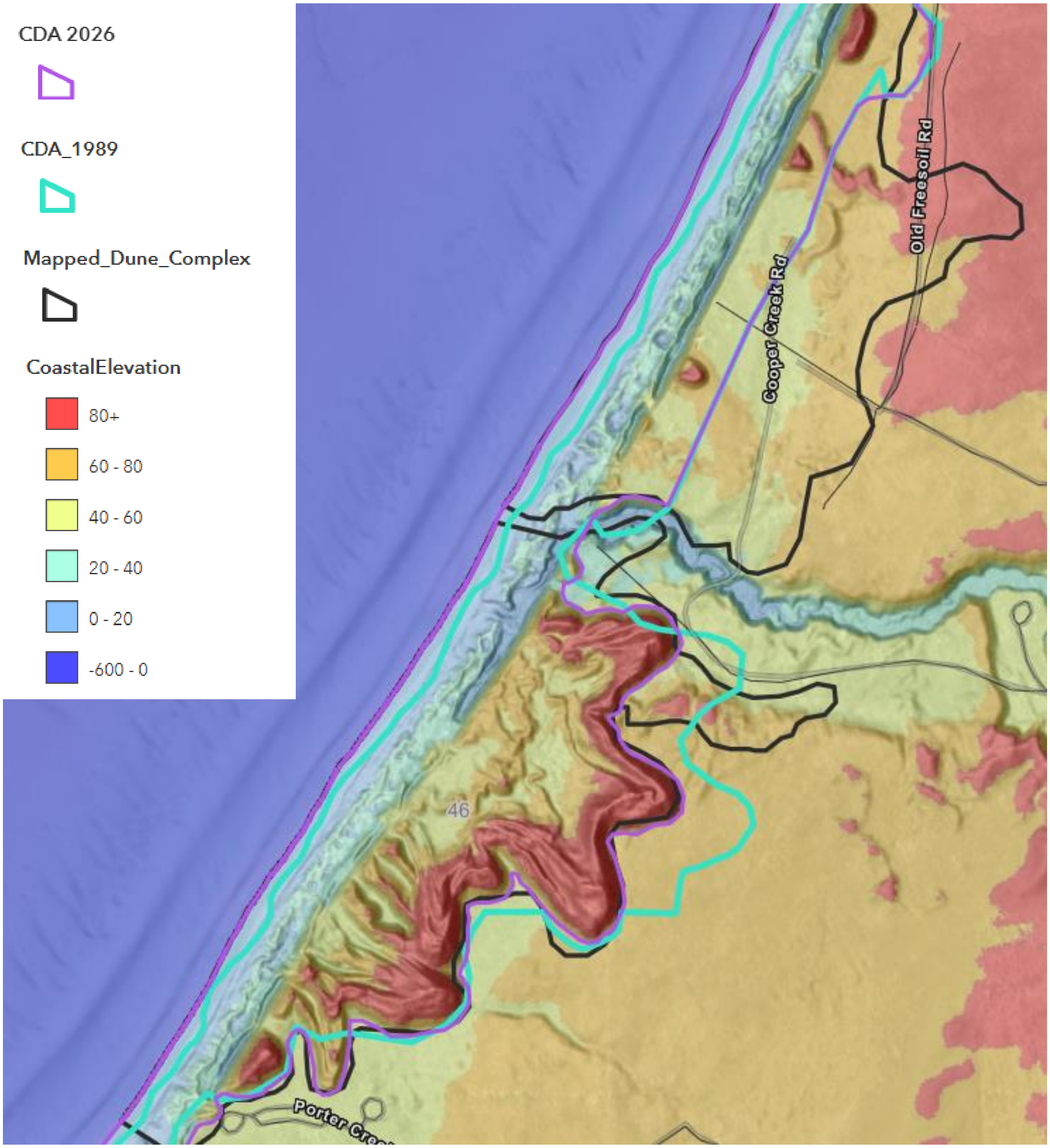


Figure 14. 1989 CDA, Proposed 2026 CDA, MDC, and Elevation Data Overlaid on Hillshaded DEM

6.2.2 Dune Health

Dune health was evaluated using remotely sensed attributes for the areas within each mapped dune complex. These attributes included percentage of shoreline hardened, density of roads, and percent coverage by impervious surface. A scoring criteria (Table 4) for each of these attributes was adapted from previous work by the Michigan Natural Features Inventory (Paskus and Enander 2019). The scores from all attributes are added together to form a cumulative Dune Health Score. A higher score indicates a healthier dune complex.

Because these attributes can vary widely across an entire dune complex, each mapped dune complex was broken into 100-meter-wide grid cells and attributes were calculated for the areas within each cell. This produced a net-like surface across each mapped dune complex, showing how dune health varied across the entire complex (Figure 15).

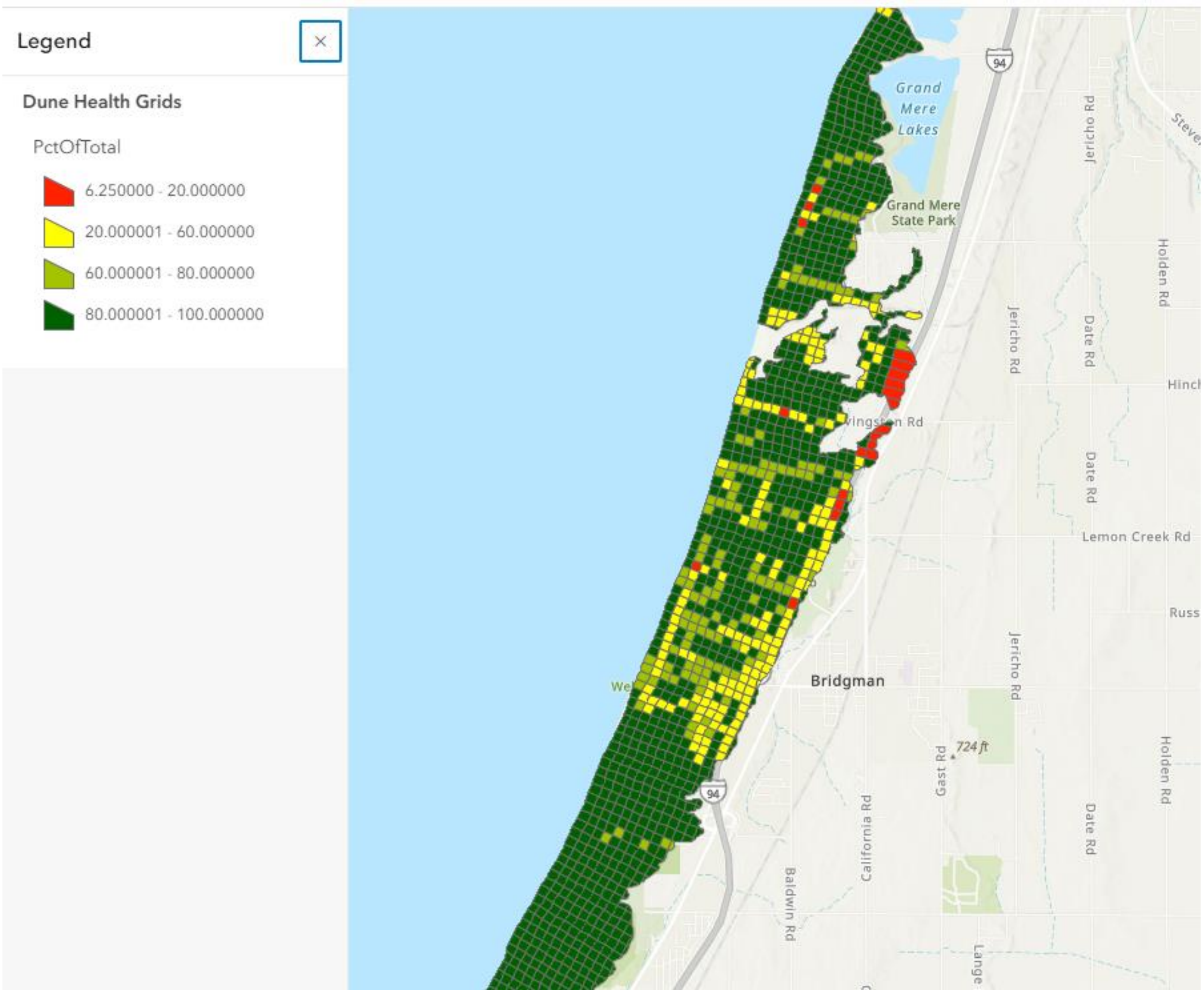


Figure 15. Dune Health Scores across a gridded mapped dune complex.

Shoreline hardening was mapped using high resolution aerial imagery captured in 2020 by NASA as part of the National Coastal Management Program. Individual structures and modifications were mapped at a resolution of 1:1,000 or higher, and categorized as rock, breakwall, jetty, wood piling, steel sheeting, sandbags, wood fencing, and debris. Wood fencing and sandbags were not considered permanent hardening.

These high-resolution maps of hardening were then summarized into a simplified shore-parallel shoreline attributed with a shore condition of Hardened or Natural. Shoreline hardening scores were calculated by dividing the meters of hardened shoreline by the meters of total shoreline for each cell in the grid that intersected the shoreline. That score was then carried landward to all other cells in the same row.

Figure 16. Shoreline hardening visible in 2020 aerial imagery (left) and mapped (right)

Road density was mapped using the 2024 version of the State of Michigan Roads and Highways from the Michigan Geographic Framework. Road density was calculated by dividing the length in kilometers of all roads within each cell by the area of each cell in square kilometers.

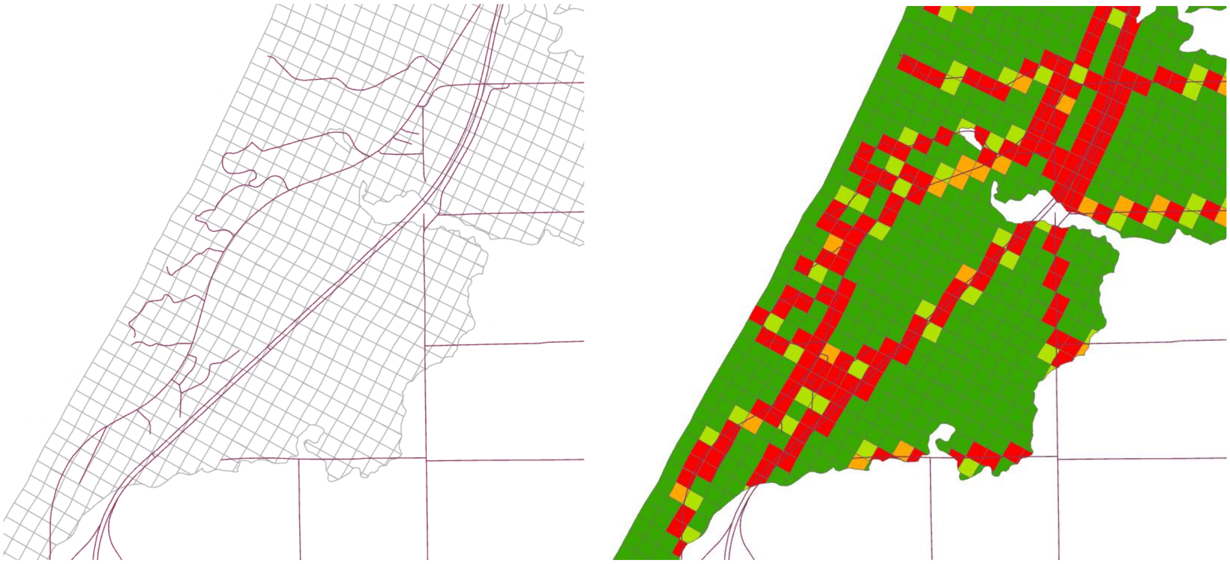


Figure 17. Road Density calculated as km of roadway per square km of land.

Impervious surface was calculated using landscape change analysis data from NOAA Coastal Change Analysis Program (C-CAP) High-Resolution Land Cover database. This raster dataset categorized impervious pixels as 1 and all others as 0. This data was summarized for each grid cell, and the percent impervious area was calculated by dividing the area of impervious pixels by the total area of all pixels within each cell (Figure 18).

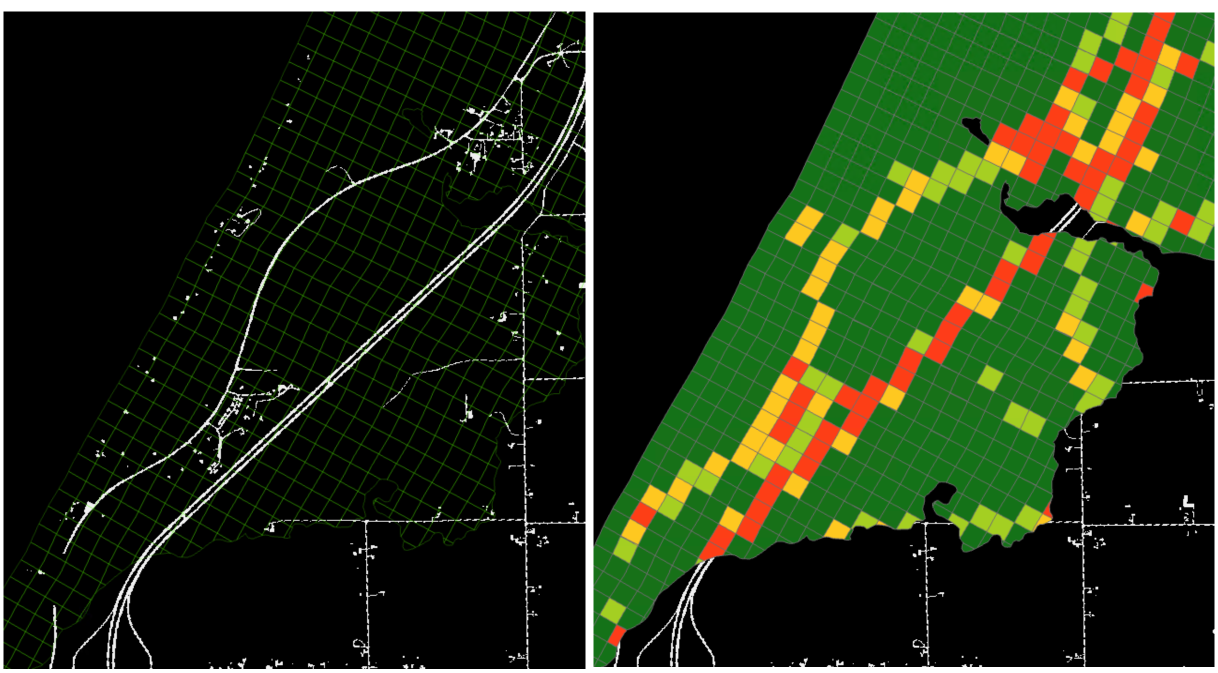


Figure 18. Impervious surface calculated through C-CAP data.

The scores from each of these attributes were added together to a maximum possible score of 16, with a higher score indicating a healthier dune complex. Data were presented as map layers symbolized by the percentage of total possible score, calculated by dividing the cumulative score from all attributes by the total possible score of 16.

6.2.3 Beach Functionality

For dune beach functionality, team members led by Dr. Guy Meadows reviewed each of the MDCs using available aerial imagery and the merged DEM layer to evaluate the six criteria described in section 6.1.2.2 and Table 5. This consisted of reviewing these geospatial data sources to establish whether a sandy beach is present, how many sand bars are present (from multiple images to document long-term condition) (Figure 19), does sheltering exist in any direction, whether a barrier to sand supply exists in any direction, whether dunes of any size exist adjacent to the beach, and whether the foredune or back beach is vegetated. This information was recorded in a spreadsheet, with a TOTAL field added to record the numeric scores possible in Table 5 up to a maximum of 8, with an "additional notes" field. Table 6 shows some example records from the Beach Functionality Scores spreadsheet. The scores were further reviewed by Dr. Ethan Theuerkauf at Michigan State University for consistency. They were then integrated into the data set for evaluation by the project team in making CDA determinations.

Figure 19. Sandbars visible through aerial photograph interpretation.

Table 6. Example Beach Functionality Data Set

Site	Geo-morphology	Sand Bars	Wave Energy	Sediment Supply	Dunes	Biological	Total
MDC	Is a sand beach present?	How many sand bars are present?	Is the site free from sheltering in all directions?	Is the site free from barriers to sand supply in all directions?	Are dunes present?	Is the fore or back beach vegetated?	Total Score
1	Y	2	N	N	Y	N	4
2	Y	3	N	Y	Y	Y	7
3	Y	2	Y	Y	Y	Y	7
4	Y	3	N	Y	Y	Y	7
5	Y	2	N	N	Y	N	4
6	Y	3	N	N	Y	N	5
7	Y	2	Y	Y	Y	Y	7
8	Y	3	Y	Y	Y	Y	8
9	Y	3	Y	N	Y	Y	7
10	Y	2	N	N	Y	Y	5

6.3.3 Field Assessment

Attributes of each MDC were evaluated through field verification during the 2025 growing season (June 9-September 30). Surveys were completed in most MDCs to validate existing remote-sensing and field data (MNFI 2025) and to collect new information needed to support Critical Dune Area (CDA) mapping decisions. MDCs on the Manitou Islands, Fox Islands, and Hog and Garden Islands were not visited, but had recently been visited by MNFI for other projects, so relevant data from those surveys was incorporated into the assessments. Field assessments focused primarily on evaluating the condition of each natural community. While habitat boundaries (MDC/CDA/EO) were checked in the field, size was evaluated in GIS and landscape context was assessed through aerial imagery supported by field observations. A standardized field data collection form was developed in Survey123 to ensure consistency.

Prior to fieldwork, survey objectives were created based on a desktop review of each MDC. These objectives guided surveyors toward collecting the most relevant data for determining CDA designations. Tasks included verifying CDA, EPC, MDC, and natural community EO boundaries; assessing existing or potential natural community EOs; and examining areas with attributes that may warrant designation or de-designation.

Three survey types were conducted:

1. **Field Assessments** – Comprehensive data collection in publicly accessible areas.
2. **Perimeter Assessments** – Visual evaluations from property boundaries where access was restricted.
3. **Follow-up Visits** – Additional site visits when initial data was insufficient to support a designation decision.

Surveyors collected point data throughout each MDC based on survey objectives and site conditions. Points were used to (1) mark access locations, (2) propose adjustments to CDA/MDC/EPC boundaries, and (3) document natural community conditions. Photographs were recorded with each point.

- **Access points** assisted with navigation and planning for potential return visits.
- **Boundary points** provided justification for retaining or modifying existing boundaries.
- **Condition points** included vegetation and structural attributes, as well as threats to ecological integrity. These points, combined with existing natural community data and aerial interpretation, formed the core dataset describing diversity, quality, and function across each MDC.

Natural community summaries documented species composition, structural characteristics, and indicators of ecological processes. Surveyors selected a natural community type from a dropdown list, which generated community-specific data fields. Species composition was recorded across vegetation strata (supercanopy, canopy, subcanopy, tall shrub, and groundcover), noting dominance (50-100% cover), abundance (30-50%), or commonness (15-30%). Diameter-at-breast height (DBH) was documented for selected and representative trees. Standing dead (snags) and coarse woody debris were recorded using standardized categories.

Surveyors also documented threats to ecological integrity, including altered hydrology, deer browse, dumping, dune stabilization, fire suppression, fragmentation, logging evidence, shoreline development, nutrient and sediment loading, pedestrian overuse, pollution, sand mining, offroad vehicle disturbance, and invasive species. Invasive species observations followed Midwest Invasive Species Information Network (MISIN) protocols, with photographs and standardized entries describing area covered, density, and treatment status

(MISIN 2025). These data were packaged for direct export to the MISIN database.
Additional observations were recorded to capture context not reflected in structured data fields. Surveyors also provided general notes that could influence final designation decisions, including recommendations for areas to consider for designation or de-designation. At the end of each survey, the team noted whether a revisit to the MDC was necessary.

6.3.4 Expert Consensus Review

Both field and geospatial data were gathered and analyzed by subsets of the project team, based on their fields of expertise. However, as mentioned throughout this report, dunes are complex systems and CDA criteria can be multifaceted and sometimes be specific to the geographic and landscape setting of the individual dunes. Interpretation of the data, and ultimate CDA determination, therefore, requires collaborative input from a broad range of individuals.

The project team conducted an in-person expert review of the data at the EGLE and MNFI offices in Lansing, MI on November 5 and 6, 2025. During this time, each MDC and 1989 CDA was reviewed and discussed. The team reviewed, analyzed, and interpreted the combined geospatial and field data and ultimately made determinations about corrections to 1989 CDA boundaries, de-designation of 1989 CDAs, and designation of new CDAs. The team present during these meetings is listed below, and follow-up reviews were completed virtually as needed following the in-person meetings.

To guide the conversations, the review team used the following principles:

- Any change to a 1989 CDA or designation as new 2026 CDA had to be made with 100% agreement from the project team. If there was disagreement after data was discussed and analyzed, or a decision could not be made due to uncertainty, the default was to make no change to the dune system under review.
- A change to a 1989 CDA or designation as new 2026 CDA can only be made if there is clear and defensible data to support the decision. This included both geospatial and field data. If data was not fully available to support a decision, there was no change made to a 1989 CDA and no new 2026 CDA was proposed.

Table 7. Expert Consensus Review Panel

Organization	Role
EGLE	
Zach Chamberlin	EGLE Project Manager
GEI	
Brian Majka	GEI Project Manager
Erin White	GIS Specialist
Asia Rasch	Ecologist
Blake Short	Ecologist
Jerald Brown	Ecologist
Michigan Technological University	
Colin Brooks, PhD	Remote Sensing and GIS Analyst
Jeremy Graham	Remote Sensing and Geospatial Scientist
Guy Meadows, PhD	Coastal Dynamics and Engineering
Ryan Navarre	GIS Analyst
Samuel Berger	GIS Analyst
Abby Jenkins	Research Scientist
Michigan Natural Features Inventory	
Tyler Bassett, PhD	Botanist
Rachel Hackett, PhD	Botanist
Danielle Smith	Botanist
Abraham Stone	Botanist
Michigan State University	
Alan Arbogast, PhD	Geographer and Dune Specialist
Orbis Environmental	
Brad Slaughter	Botanist

Figure 20. Expert Consensus Review

7. Geospatial and Field Assessment Results

A comprehensive description of each mapped dune complex is provided in Appendix E. These descriptions describe the physical and ecological conditions at each site and summarize the collective geospatial and field analysis at each MDC. The descriptions are provided in the following format and one description, with associated data, maps, and photographs, has been completed for each of the 212 MDCs.

1. **Mapped Dune Complex Identification Number:** The identification of the MDC
2. **Associated 1989 Critical Dune Areas:** The 1989 CDA that either intersected the MDC or is located adjacent to the MDC, in the event that a 1989 CDA lies completely outside of an MDC
3. **County:** The county(s) where the MDC is located.
4. **Associated Great Lake:** The Great Lake adjacent to the MDC
5. **Local Unit of Government(s):** Any local unit of government (LUG) that has jurisdiction in any part of the respective MDC
6. **Dune Overview:** A written description of the location of a given MDC, which also includes an overview of the morphology of the dunes in the MDC. When appropriate, the morphology of the dunes in the associated 1989 CDAs are also described.
7. **Dune Statistics Summary:** A table summarizing geospatially derived statistics for each MDC and 1989 CDA. Each table contains a summary of dune heights, shore length, and area.
8. **Dune Health and Beach Functionality:** A table summarizing the dune health and beach functionality scoring for each MDC and CDA.

9. **Dune Ecology:** A written description of the natural communities located within the MDC. A description of the diversity, quality, and function of the MDC as a whole is given, as well as a description of each natural community when they are dune-associated and relevant. Data for the dune ecology section was derived from field assessments as well as written descriptions of element occurrences (EOs) developed by MNFI during previous mapping efforts. Data is not reported when information was not available due to a lack of existing data or site access.
10. **Critical Dune Recommendation and Discussion:** A written description as to whether dunes within an MDC or 1989 CDA is recommended for designation as CDA, not recommended for designation as CDA, whether a 1989 CDA line should be corrected based on the current high resolution topography/bathymetry, or if a 1989 CDA or portion of a 1989 CDA should be de-designated as CDA. .
11. **Maps:** Four maps of each MDC are provided that depict different characteristics of the dune system.
    a. **Dune Morphology:** The Dune Morphology Map shows hillshaded topography and local units of government. The MDC and 1989 CDA (if applicable) or shown. Statistics are reported for dune height and size.
    b. **Dune Health:** The Dune Health Map shows an aerial photo with the dune health score for the MDC and the 1989 CDA (if applicable), as well as the local units of government. Individual metrics and scoring are also reported for Hardened Shoreline, Road Density, and Impervious Surface.
    c. **Dune Ecology:** The Dune Ecology Map shows an aerial photo with the mapped element occurrences (EOs) for natural communities, along with the MDC, 1989 CDA (if applicable), and local units of government. EOs are not depicted on maps for confidentiality reasons, but are noted the MDC description of Dune Ecology.
    d. **Critical Dune Recommendation:** The Critical Dune Recommendation map shows an aerial photo with the MDC, 1989 CDA (if applicable), and recommended CDA (if applicable).
12. **Site Photos:** Representative photographs taken within each MDC. Photographs were only taken from publicly accessible locations or in locations where private landowner access was granted, which limited photo documentation in some locations.

8. Recommended Critical Dune Areas

The recommended 2026 CDA Atlas is provided in Appendix F. This atlas shows both the 1989 and recommended 2026 CDAs, along with hillshaded relief to depict the changes that were made.

The recommended CDA Atlas includes new CDAs, corrected lines, and has de-designated areas that do not meet the aforementioned criteria for designation. Land ownership and area summaries are provided in Tables 9 and 10.

Table 9. Summary of 1989 CDA, all MDCs, and Recommended 2026 CDA

Metric	1989 CDA	Recommended 2026 CDA
Number of CDAs*	123	83
Private Ownership	28,351 ac	49,930 ac
Federal Ownership	20,909 ac	39,688 ac
State Ownership	22,432 ac	53,359 ac
County Ownership	493 ac	1,400 ac
Local Unit of Government Ownership	1,024 ac	2,019 ac
Non-Governmental Organization Ownership	1,099 ac	3,248 ac
Total	**74,308 ac**	**149,644 ac**

*Fewer CDAs are recommended because, when appropriate, 1989 CDAs were merged if they were connected as part of the same dune system.

Table 10. Summary of 1989 CDA, all MDCs, and Recommended 2026 CDA

Ownership Type	1989 CDA	Recommended 2026 CDA
Acres of Critical Dune on Public/NGO Land*	45,957 ac	99,714 ac
Acres of Critical Dune on Private Land*	28,351 ac	49,930 ac

*Data calculated using the Michigan Department of Environment, Great Lakes, and Energy Conservation and Recreation Lands (CARL) dataset

The recommended CDA determinations were graphed based on dune height, dune health, and beach functionality to validate the use of the designated criteria in the recommending CDAs (Figure 16). Ecological integrity was not graphed because the ecological estimates are not based on pure quantitative analysis. The graphs indicate an overall preference for dune height, dune health, and beach functionality as described in the defined criteria. Outlying sites in the below graphs are likely designated or not designated based on ecological characteristics or localized site-specific conditions.

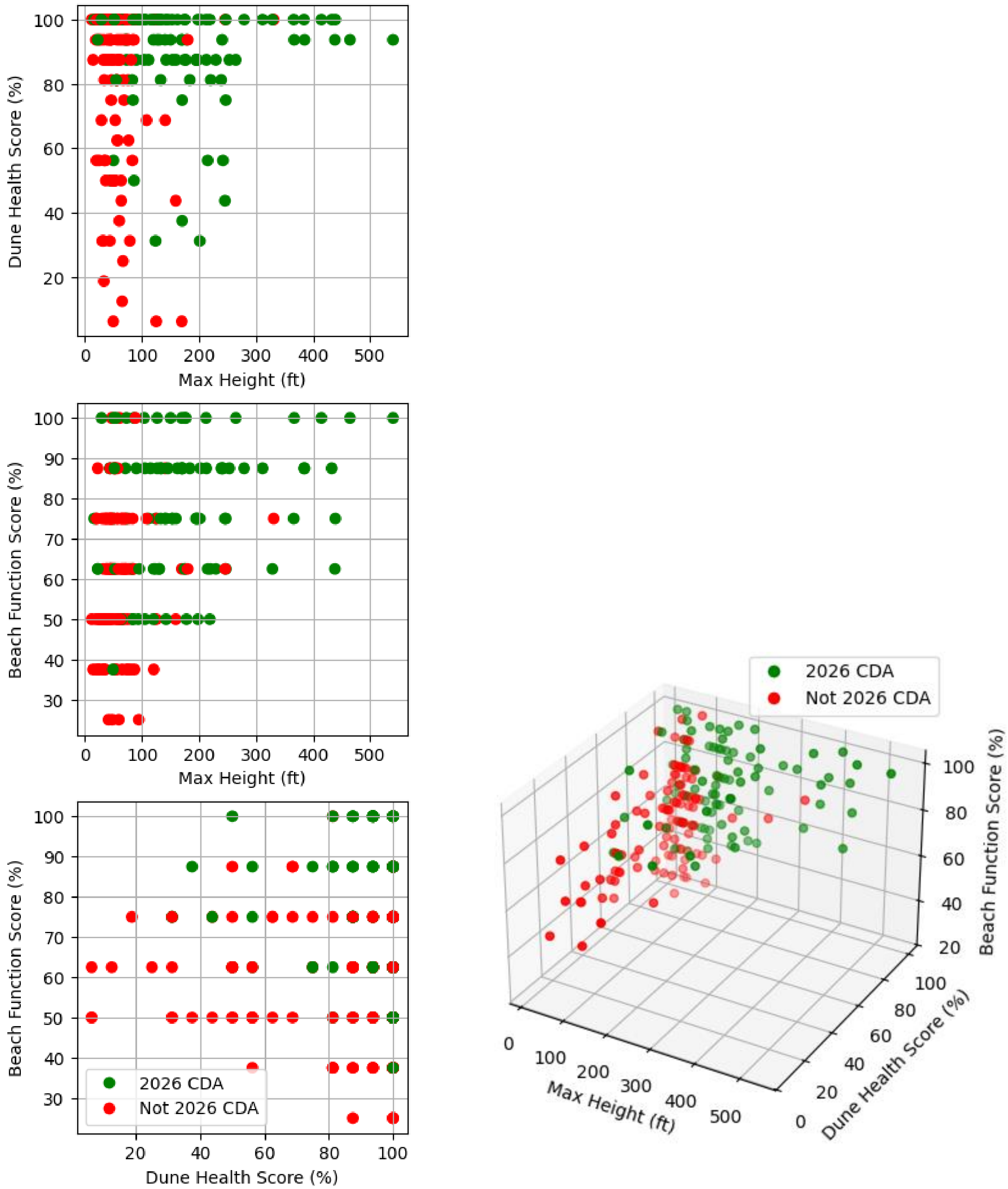


Figure 21. Recommended CDA Evaluation

9. Conclusion

This report and the resulting recommended 2026 atlas of critical dunes fulfills the requirements of the contract. Our study evaluated all Michigan dunes based on morphology utilizing modern, high-resolution elevation data that is consistent with previous efforts to delineate critical dunes. The study also evaluated dune-associated natural communities both within and outside of 1989 CDAs for diversity, quality, and function. It also included an evaluation of dune health and ecological integrity in 1989 CDAs using several parameters to identify areas of potential de-designation. The recommends a revised CDA that contains the dunes with the highest diversity, quality, and functions, including the tallest, highest quality dunes along with high-quality rare or imperiled dune associated natural communities. The recommended 2026 CDA is representative of the true extent of critical dunes in Michigan and consistent with the goals of Part 353.

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Appendix A. Report on a Natural Features Inventory of Michigan's Designated Sand Dunes

Appendix B. Valuing Michigan's Coastal Dunes

Appendix C. Spatial Data to Improve Coastal Resiliency and Better Inform Local Decision Making

Appendix D. Exemplary Plant Communities Included in 1989 Atlas

Appendix E. Mapped Dune Complex Summaries

Appendix F. Recommended Critical Dune Areas