Estimating climate-driven impacts on the suitability of Great Lakes shoreline habitat for Michigan's at-risk species

Prepared By:

Bassett, Tyler J., Nicole J. Smith, Logan M. Rowe, Helen D. Enander, and Michael J. Monfils. Michigan Natural Features Inventory, Michigan State University Extension, PO Box 13036, Lansing, MI 48901-3036

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We collectively acknowledge that Michigan State University occupies the ancestral, traditional, and contemporary Lands of the Anishinaabeg – Three Fires Confederacy of Ojibwe, Odawa, and Potawatomi peoples. In particular, the University resides on Land ceded in the 1819 Treaty of Saginaw. We recognize, support, and advocate for the sovereignty of Michigan's twelve federally recognized Indian nations, for historic Indigenous communities in Michigan, for Indigenous individuals and communities who live here now, and for those who were forcibly removed from their Homelands. By offering this Land Acknowledgement, we affirm Indigenous sovereignty and will work to hold Michigan State University more accountable to the needs of American Indian and Indigenous peoples.

Cover: Sand and gravel beach, foredune, and interdunal wetland backed by boreal forest at Vermillion, Luce County, MI. Photo by Tyler J. Bassett.

EXECUTIVE SUMMARY

Fluctuations in Great Lakes water levels are well-represented in the historical record, extending as much as one meter above or below baseline norms, and generally lasting a few years to at most two decades. Both baseline levels and fluctuations around them are likely to shift and become more extreme in the coming decades, due in no small part to changing patterns of precipitation, lake-effect snow, temperature, evaporation, and ice cover associated with global climate change. These changes present challenges for and pose threats to such disparate interests as the Great Lakes shipping industry, ecosystem services such as municipal and industrial water supply, and biodiversity, including several rare species that depend upon coastal ecosystems. Importantly, lake-level changes are occurring in the broader context of other anthropogenic global change factors related and unrelated to climate change that threaten species and ecosystems, including nutrient loading, invasive species, and the effects of weather extremes like temperature and precipitation that are unrelated to lake-level change. There is considerable uncertainty regarding how climate change will impact variation in Great Lakes water levels over the coming decades, and how species may respond, confounding conservation planning.

To address this growing need, we developed a GIS model that maps changing Great Lakes levels in Michigan consistent with a range of climate change predictions, and analyzed how those changing lake levels would affect the size of coastal ecosystems and increase or decrease habitat for 13 at-risk species. Our goal was to identify which species, natural communities, and coastal regions are more likely to suffer negative impacts from predicted Great Lakes water level fluctuations, and which may see improved outcomes. By identifying the species, communities, and regions most likely to be affected by lake-level changes, we aim to provide natural resource managers with tools to respond more rapidly and effectively to those changes as they occur. A key assumption is that we are able to predict outcomes for species based on how their habitat is affected by changing lake levels. Specifically, our objectives were to: 1) Model the impact of changing Great Lakes water levels on habitat availability for at-risk plant and animal species, across the range of fluctuations predicted based on climate modeling; 2) Assess how at-risk plant and animal species may respond to changes in habitat availability due to modeled lake-level change (i.e., decline, increase, or disperse), and; 3) Develop a list of conservation priorities - species, communities, and coastal regions, that are most in need of monitoring, restoration, and conservation.

We used a single surface raster, or bathtub inundation model, to model lake-level rise and lake-level decline. This method uses water-level height combined with topography (elevation) to model the extent of inundation. We modeled a series of Great Lakes water levels as predicted by the late-21st century and mapped inundation along the Michigan Great Lakes shoreline using the USGS 3D Elevation Program (3DEP) standard LIDAR-derived 1-Meter Digital Elevation Model (DEM) data merged with high-resolution topobathymetry elevation (TBDEM) data, producing a single seamless coastal elevation dataset. We modeled the late- rather than mid-21st century predictions, which are generally more extreme, to prepare resource managers for more extreme scenarios with greater impacts to species. Our approach differed from and expanded upon similar recent efforts by combining the use of finer-scale DEMs (e.g., 1-meter vs. 3-meter), both water-level increase and recession along the entire coast of Michigan in our modeling framework, and hydrological enforcement to allow flow through bridges, culverts, and road-stream intersections. Recent efforts have applied all of these approaches, but not in the same model. Annual lake-level changes for each of the Great Lakes resulting from net basin supply (NBS) changes were predicted by two regional climate models—rising lake levels under the RCM-CNRM model and falling lake levels under RCM-MIROC5. For each RCM model, we calculated lake-level change to relative to baseline averages, baseline high (+ 1 m), and baseline low (- 1 m).

To facilitate inferences about how these predicted lake-level fluctuations may impact at-risk species, we developed a stand-level coastal ecosystem dataset using data from Michigan Natural Features Inventory (MNFI), Michigan Department of Natural Resources, United States Forest Service, United States Fish and Wildlife Service (USFWS), and National Park Service. Each stand in this dataset was either cross-walked to or original mapped according to the MNFI natural community classification, which contains 80 natural communities grouped under one of five broad classes – primary (e.g., bedrock, bare soil), subterranean/sink (e.g., karst features), palustrine (i.e., wetlands), terrestrial (i.e., uplands), and palustrine/terrestrial (i.e., wetland/upland habitat complexes). Classes are further sub-divided into between one and seven groups, with each group containing between one and nine natural communities. This dataset covered a small proportion of Michigan's Great Lakes shoreline but included 68 different ecosystem types or natural communities. Then, we intersected spatial occurrence data for 13 at-risk species with this dataset to calculate proportional association of each species with the 42 of the 68 natural communities that those species were known to utilize. We selected 13 species for which representative spatial data were available, amongst species prioritized by USFWS and other agencies and based on relevance to regional action plans including the MI Wildlife Action Plan, Great Lakes Restoration Initiative Action Plan, and Upper Mississippi / Great Lakes Joint Venture Waterfowl, Waterbird, and Landbird Habitat Conservation Strategies. These species included one reptile - eastern massasauga (*Sistrurus catenatus*, Federal and State Threatened); three insects - blazing star borer moth (*Papaipema beeriana*, Special Concern), Hine's emerald dragonfly (*Somatochlora hineana*, Federal and State Endangered), and Lake Huron locust (*Trimerotropis huroniana*, State Threatened); four birds - black tern (*Chlidonias niger*, State Threatened), king rail (*Rallus elegans*, State Endangered), piping plover (*Charadrius melodus*, Federal and State Endangered) and common tern (*Sterna hirundo*, State Threatened); five plants - eastern prairie fringed orchid (*Platanthera leucophaea*, Federal Threatened and State Endangered), Pitcher's thistle (*Cirsium pitcheri*, Federal and State Threatened), dwarf lake Iris (*Iris lacustris*, Federal and State Threatened), Michigan monkey flower (*Mimulus michiganensis*, Federal and State Endangered), Houghton's goldenrod (*Solidago houghtonii*, Federal and State Threatened). These species also differed by coastal ecosystem preferences, are variously restricted to Great Lakes coastal habitats vs. inland habitats, represent a range of taxonomic groups, and represent a range of life-history traits that are likely to influence their response to lake-level fluctuations. We then modeled inundation and expansion of each natural community with rising and falling lake levels, and used the proportional association of each species with each natural community to infer change in habitat area for each species.

We also explicitly evaluated the spatial variation of impacts to coastal ecosystems and at-risk species populations in two ways. First, because our analysis was based on the small proportion of shoreline covered by the ecosystem dataset, we performed an analysis of areal change in 500 m square "fishnet" grid cells covering the entire study area, which we refer to as the fishnet analysis. Each 500 m fishnet grid was intersected with the classified inundation layers and we calculated the area and percent change of inundation status as we did with the habitat stands. We inspected the results visually to inform an expert assessment of specific coastal regions that vary in their inundation and expansion across lake-level scenarios. Second, we conducted individual analyses of habitat change and impacts to at-risk species at three separate focal areas representing different coastal geomorphologies, Wildfowl Bay in the Saginaw Bay, Waugoshance Point in Wilderness State Park, and the Drummond Island region. This helped us to better understand how the regional distribution of natural communities, at-risk species, and lake-level fluctuations result in different contexts for making conservation decisions.

Modeled lake levels differed most from the baseline levels in the Huron-Michigan basin, receding by 23 cm under the MIROC5 scenario, and rising 49 cm under the CNRM scenario. The Erie basin was predicted to rise 38 cm and recede by 11 cm under the CNRM and MIROC5 scenarios, respectively, while the Superior basin experienced the most minimal modeled changes, rising by 13 cm and receding by 10 cm under the CNRM and MIROC5 scenarios, respectively. All scenarios except CNRM-High (i.e., CNRM levels relative to Baseline-High) predicted significant inundation or expansion (>10%) for at least one primary group, with significant impacts observed sporadically in palustrine groups and rarely in terrestrial groups. Palustrine groups were heavily inundated under CNRM-High, with most experiencing over 10% change on average. Although primary natural communities experienced greater predicted inundation and expansion on average in all but the CNRM-High scenario, the communities that were most impactful to at-risk species were often palustrine natural communities. Inundation and expansion was most extensive and frequent for species associated with Great Lakes marsh, coastal fen, lakeplain wet prairie, and related communities.

The predicted responses of potential habitats for at-risk species to Great Lakes water-level fluctuations over the coming decades range from significant habitat gain to significant loss, with limited impacts predicted for some species. Species associated primarily with palustrine ecosystems exhibited substantial predicted habitat losses across CNRM scenarios, including king rail, black tern, common tern, eastern prairie fringed orchid, blazing star borer, and Hine's emerald dragonfly. Under MIROC5 scenarios, these species are also predicted to gain significant habitat area, especially Hine's emerald dragonfly. Species associated with habitat complexes that include a mixture of terrestrial (primarily forested), palustrine, and primary coastal communities generally showed little predicted vulnerability to habitat loss under CNRM scenarios and significant potential for habitat gain under MIROC5 scenarios. We reasoned that reductions in habitat size due to inundation for these species were generally offset by large areas of un-inundated habitats that could theoretically serve as refugia. These species included eastern massasauga, Michigan monkey flower, dwarf lake iris, and Houghton's goldenrod. Finally, despite large predicted impacts to primary communities overall, species associated with primary coastal communities (i.e., beaches, dunes, and bedrock systems like cobble shores) experienced limited predicted habitat gains under low water scenarios and limited habitat losses under high water scenario, including Lake Huron locust and piping plover. Pitcher's thistle was predicted to lose or gain even less habitat area, amounting to appreciably no change.

While our model captures broad patterns of how at-risk species may be affected by habitat inundation and expansion as Great Lakes water levels fluctuate, it does not explicitly account for several ecological and demographic processes that are likely to modify realized habitat quality and species responses. As a result, modeled habitat inundation and expansion does not necessarily equate to less and more habitat, respectively. In particular, invasive species dynamics in ecosystems and several life-history traits of at-risk species may substantially modify or override the habitat gains and losses predicted by lake-level change alone. Also, the ranges of some at-risk species are more geographically restricted than the extent of the natural communities used to model impacts to the species, so some impacts may be overstated. Together, these unmodeled processes suggest that realized outcomes for species and ecosystems will almost certainly differ from modeled projections, particularly in systems where invasive species pressure is high, or where dispersal and persistence are strongly constrained by a range of ecological factors. Incorporating these and other considerations into future modeling and monitoring efforts will be essential for translating predicted habitat change into effective conservation and management actions. The applicability of these predictions should be bolstered by in-depth knowledge of the species and places being managed, and should not be considered a substitution for that knowledge.

Nevertheless, there are some broad and consistent patterns that provide a foundation for setting conservation priorities. We center our recommendations on natural communities and coastal zones with specific ecosystem complexes to encourage management approaches that support multiple species, including but not limited to those considered here, and to discourage management approaches that benefit one species at the expense of others. Specifically, prioritizing management in Great Lakes marsh, lakeplain wet and wet-mesic prairie, limestone cobble shore, sand and gravel beach, coastal fen, interdunal wetland, open dunes, and wooded dune and swale complex is predicted to best improve conservation outcomes for the 13 at-risk species we evaluated. This "coarse filter" approach can be augmented by a "fine filter" focused on individual species when it appears the "coarse filter" approach falls short of achieving conservation goals.

Finally, managers in each coastal region are likely to face conflicting priorities, where focusing on one species or natural community may reduce protections for another. In these cases, managers may choose to bolster coastal populations of at-risk species or shift resources to non-coastal populations, emphasize management for coastal populations of a species in one region over another, or de-emphasize coastal management in a region if inland conservation targets take higher priority.

As the effects of climate change continue to intensify throughout the 21st century, both normal lake levels and the fluctuations around them are predicted to exceed historic extremes. The results of the modeling exercise reported here provide a framework for managing near-shore ecosystems and the at-risk species that depend upon them in the context of these extremes. Importantly, we hope these results provide a basis for conservation of places, ecosystems, and species along Great Lake shorelines over the coming decades.

We envision a broad array of end users of this model, both in conservation and in other arenas such as land-use planning and eco-tourism. The applications of the model to conservation also extend beyond our Objectives 2 and 3, where we propose to provide general guidance on a suite of focal species and large-scale predictions about changing natural communities. For example, modeled lake levels can certainly be applied at finer scales by managers interested in specific geographic areas, or species not included in our analyses. The model will be useful for stakeholders outside of conservation as well. Changing lake levels also threaten cultural resources, including infrastructure, coastal development, and the capacity of the lakeshore to support tourism.

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INTRODUCTION

Dramatic changes to Great Lakes water levels are altering coastal ecosystems, due in no small part to changing patterns of precipitation, lake-effect snow, temperature, evaporation, and ice cover due to climate change (Mackey 2012, Notaro et al. 2105a, Notaro et al. 2015b, ELPC 2019). These changes present challenges for and pose threats to such disparate concerns as the Great Lakes shipping industry, ecosystem services such as municipal and industrial water supply, and biodiversity, including several rare species that depend upon these habitats (Gathman et al. 2005, Angel and Kunkel 2010, Kahl and Stirrat 2012, Steinman et al. 2017, Hohman et al. 2021). Importantly, lake-level changes are occurring in the broader context of other anthropogenic global change factors related and unrelated to climate change that threaten species and ecosystems, including nutrient loading, invasive species, and the effects of weather extremes like temperature and precipitation that are unrelated to lake-level changes (Vitousek et al. 1997, Bellard et al. 2012, ELPC 2019).

Figure 1. Tawas Point State Park, in northern Lake Huron, in 2021 during high lake levels. Inundated signage and bench, and tree mortality, highlight the extent and impact of high lake levels. Photo by Logan M. Rowe.

There is considerable uncertainty regarding how climate change will impact variation in Great Lakes water levels over the coming decades, and how species will respond, confounding conservation planning (Notaro et al. 2015a). Great Lakes water levels experienced record highs from 2018 to 2021, on the heels of below average levels from 1998 to 2013 (Figure 1). Historical records indicate that extreme high- and low-water conditions in the Great Lakes typically persist for years to, at most, one to two decades, rather than long enough to drive permanent ecosystem conversion (Gronewold and Stow 2014, Notaro et al. 2015a). As a result, species responses to lake-level change are shaped not only by the magnitude of water-level fluctuations, but also by their duration and frequency, complicating predictions of long-term vulnerability (Wilcox and Nichols 2008). Furthermore, water level changes have made some rare species more vulnerable to population reductions or local extinctions while others are less vulnerable and species like marsh birds may even benefit (Mortsch et al. 2006, Hohman et al. 2021). This uncertainty regarding the direction and magnitude of lake-level change and how it will affect species and ecosystems presents a conundrum for conservation planning. Resource managers are increasingly called upon to decide whether to devote resources to species that are currently vulnerable but may not be in the future, species that may become more vulnerable in the future, or any number of scenarios. Conserving rare species will depend on our ability to predict how species will respond to these changes and enact timely management that is adaptable to changing conditions.

A large portion of rare and declining species in the Great Lakes region occur within coastal ecosystems in Michigan. The Michigan Natural Features Inventory (MNFI) manages the state's Natural Heritage Database (NHD), containing over 25,000 occurrences of 'elements of biodiversity' (hereafter, element occurrences or EOs) (MNFI 2026). These elements include nearly 800 at-risk plant and animal species and 80 natural communities or ecosystem types. Approximately 23.7% of all element occurrences in the NHD occur within the federal Coastal Zone Management shoreline area (MNFI 2026), representing 75.6% of Michigan's natural community types and 64.8% of rare plant and animal species (Cohen et al. 2025, MNFI 2026). Given the diversity of natural communities and rare species in the coastal zone, responses to lake level fluctuations are expected to differ widely. Natural communities that occur directly adjacent to the Great Lakes are more likely to be affected by lake-level fluctuations, including wetland ecosystems with submergent and emergent vegetation, and sparsely vegetated lakeshore communities including aeolian sand dunes, beaches of sand and gravel, and bedrock and cobble lakeshore communities. Natural communities directly inland from lakeshore communities are also sensitive to lake-level fluctuations when they are hydrologically linked to the Great Lakes (e.g., via water table depth), and because wind speeds and the chance of soil erosion changes with lake levels. Occurrences of every upland forested natural community in Michigan can be found in or adjacent to dunes and lakeshore bluffs, as well as multiple wetland types.

These natural communities provide habitat for multiple federally- and state-listed species, including several United States Fish and Wildlife Service (USFWS) focal species and focal species of various regional conservation plans, including the MI Wildlife Action Plan (MWAP), GLRI Action Plan, and Upper Mississippi / Great Lakes Joint Venture (UMGLJV) Waterfowl, Waterbird, and Landbird Habitat Conservation Strategies (Soulliere et al. 2017, 2018, 2020, Henehan et al. 2026). For example, federally listed and conservation-priority species such as piping plover (*Charadrius melodus*), common tern (*Sterna hirundo*), and king rail (*Rallus elegans*) are closely tied to dynamically changing beach, dune, and marsh habitats and are focal species within multiple federal and regional conservation frameworks, including the GLRI Action Plan and UMGLJV Waterbird and Waterfowl Habitat Conservation Strategies (Soulliere et al. 2017, 2018). Similarly, Great Lakes endemic and shoreline-dependent plants such as dwarf lake iris (*Iris lacustris*), Pitcher's thistle (*Cirsium pitcheri*), and Houghton's goldenrod (*Solidago houghtonii*), as well as invertebrates like the Lake Huron locust (*Trimerotropis huroniana*) and Hine's emerald dragonfly (*Somatochlora hineana*), are identified as Species of Greatest Conservation Need under the Michigan Wildlife Action Plan and are priorities for state and regional conservation planning efforts (Henehan et al. 2026). Additional species identified under the Michigan Wildlife Action Plan like eastern prairie fringed orchid (*Platanthera leucophaea*) and blazing star borer (*Papaipema beeriana*), are not Great Lakes endemic but rely significantly on natural communities in the coastal zone. Many of these species rely at least in part on coastal habitats maintained by periodic disturbance associated with lake-level fluctuations, making their long-term viability highly sensitive to changes in the frequency, magnitude, and duration of Great Lakes water-level variation.

These and other at-risk species likely respond differently to lake-level fluctuations. The ability for a species to respond to prolonged or dramatic fluctuations (e.g., 100 + mm) of Great Lakes water levels largely depends on its ability to either adapt to a changing environment or disperse to suitable habitat and is contingent on the specificity of habitat requirements and the physical traits of each organism. For example, animals that rely on specific host plants may have a harder time adapting to changes if their larval food source is not evenly distributed across the coastal zone, such as blazing star borer moth whose larvae feed exclusively on species of blazing star (*Liatris* spp.). Water level rise can reduce habitat availability for species when they have very limited habitat requirements, such as coastal bluffs and aeolian sand dunes, which are expected to decrease in size due to erosion during high-water level events (Volpano et al. 2020, van Dijk 2021). For example, the federally and state threatened Pitcher's thistle and state threatened Lake Huron locust rely entirely on Great Lakes dune ecosystems for completing their life cycle (Rabe 1999, Ellison et al. 2026a). High water levels directly threaten shoreline ecosystems through inundation, such as the cobble shore nesting habitat of federally threatened piping plover, or the nesting habitat of the state threatened common tern on small islands in the Great Lakes that are readily inundated during high water.

Still other species may benefit from rising lake levels if events create new habitats. This has been demonstrated with marsh birds in parts of the Great Lakes including American bittern (*Botaurus lentiginosus*), common gallinule (*Gallinula galeata*), American coot (*Fulica americana*), sora (*Porzana carolina*), Virginia rail (*Rallus limicola*), and pied-billed grebe (*Podilymbus podiceps*) (Hohman et al. 2021). Other species may benefit from lower lake levels, for example expanding nesting habitat of piping plover and common tern. Finally, multiple interacting factors like nutrient loading from agricultural runoff and invasive species introduce hard-to-predict contingencies. Invasive species such as invasive common reed (*Phragmites* *australis* subsp. *australis*) respond favorably to the disturbances associated with fluctuating water levels, particularly in areas with nutrient-rich agricultural runoff, quickly occupying exposed shores as lake levels recede (Wilcox 2012). As a result, expanded coastal habitat due to low lake levels may rapidly become unsuitable for many species due to these invasions.

Predicting how Great Lakes water levels will fluctuate over the next few decades, and whether the overall trend will be rising or falling, is fundamentally challenging. It is especially hard to predict how the Earth's changing climate will shift the timing and nature of weather events in the Great Lakes region, specifically because of the complexity with which the Great Lakes moderate weather patterns. Furthermore, it is particularly challenging to predict how changing weather patterns will manifest in hydrological differences, both Great Lakes water level fluctuations and overall long-term trends (MacKay and Seglenieks 2013, Notaro et al. 2015a, ELPC 2019, Gronewold and Rood 2019, Briley et al. 2021, VanDeWeghe et al. 2022). Climate change effects observed in the Great Lakes basin include rising air temperatures, reduced cloud cover, more frequent heavy precipitation events, rapid lake warming, and reduced lake ice cover, which has supported a positive trend in lake-effect snowfall (Notaro et al. 2015a,b). Unexpected effects from global climate change in other parts of the world may also become a factor for the Great Lakes. For example, there is growing evidence that changes in Arctic ice are influencing the proliferation of weather systems important to precipitation in the Great Lakes basin (Francis and Vavrus 2012). Recent models of future lake levels are highly variable, predicting sizeable increases to large declines, or little net change in lake levels (Angel and Kunkel 2010, Hayhoe et al. 2010, Gronewold et al. 2013, Notaro et al. 2015a, Gronewold and Rood 2019, Briley et al. 2021). One reason for this variability is that internationally recognized global climate modeling efforts (i.e., the Coupled Model Intercomparison Project, or CMIP) do not include or poorly represent the interaction between the Great Lakes, land, and atmosphere (Angel and Kunkel 2010, Notaro et al. 2013, 2015a, 2015b, Briley et al. 2017, Gronewold and Rood 2019, Briley et al. 2021).

The uncertainty and variation in predicting lake-level fluctuations is also inherent in modeling frameworks. To predict future lake levels, a suite of models is needed to simulate the multiple components of lake hydrology known as net basin supply (NBS), simulate flow between hydrologically connected lakes, and simulate human-controlled flow and diversions, all of which are combined with global climate model (GCM)-based prediction scenarios. Each component of this framework contributes a unique source of uncertainty. Notaro et al. (2015a) conducted what we conclude to be the most comprehensive and accurate effort to date, using two regional climate models specific to the Great Lakes. Under one climate scenario, they projected annual lake-level increases ranging from +75 mm (3 inches) for Lake Superior to +180 mm (7 inches) for Lakes Michigan–Huron by the mid twenty-first century and from +134 mm (5 inches) for Lake Superior to +420 mm (1.4 ft) for Lakes Michigan–Huron by the late twenty-first century. In contrast, the other scenario predicted lake-level declines, ranging from -24 mm (1 inch) for Lake Superior to -132 mm (5 inches) for Lakes Michigan–Huron by the mid-twenty-first century and from -97 mm (4 inches) for Lake Superior to -296 mm (1 ft) for Lakes Michigan–Huron by the late twenty-first century. In other words, "water resource managers need to prepare for the large interannual variability in lake levels already seen in the historical record, along with a potential expansion of the spread in lake levels to greater extremes" (Notaro et al. 2015a). More recently VanDeWeghe et al (2022) analyzed Great Lakes water levels for future scenarios using regional climate models and a more robust simulation of plausible NBS monthly components, and found that future Great Lakes water levels are characterized by substantial interannual and decadal variability superimposed on broader shifts in average conditions, with both high- and low-water extremes remaining plausible across scenarios rather than converging toward a single stable regime. Their analyses suggest that changes in variability and the frequency of extreme events may be as ecologically important as changes in long-term means, with continued oscillation between periods of elevated and reduced water levels shaping coastal environments. Results of all future scenarios suggest an increase in long-term average water levels across all the Great Lakes.

Despite the uncertainty across models, most predictions indicate significant deviations from historical trends. The long-term historical trend (1918 to present) shows fluctuations of less than one meter above or below the long-term average for that period (USACE 2026). Models predict an increase or decrease of *average* lake levels of as much as one meter over the next century, so fluctuations around the future average levels could easily exceed two meters higher or lower than the historical average (Notaro et al. 2015a). Considering the wide range of species and ecosystems potentially affected by fluctuating Great Lakes water levels, it is also fundamentally challenging to form broad predictions about how at-risk species will fare under any one scenario for future Great Lakes water levels. Conservation planners therefore need tools to predict across the full range of potential outcomes for lake-level change over the coming decades, and an increasingly robust ability to predict and estimate how conservation targets may be affected by that range of outcomes.

To address this growing need, we developed a GIS model that maps changing Great Lakes levels in Michigan consistent with a range of climate change predictions. Then, we analyzed how those changing lake levels would affect the size of coastal ecosystems and increase or decrease habitat for 13 at-risk species representing a range of habitat preferences, fidelity to coastal vs. inland habitats, taxonomic groups, and life-history traits that are likely to influence how they respond to lake-level fluctuations. Our goal was to identify which species, natural communities, and coastal regions are more likely to suffer negative impacts from predicted Great Lakes water level fluctuations, and which may see improved outcomes. By identifying the species, communities, and regions most likely to be affected by lake-level changes, we hope to provide natural resource managers with tools to respond more rapidly and effectively to those changes as they occur. A key assumption is that we are able to predict outcomes for species based on how their habitat is affected by changing lake levels. Specifically, our objectives were to: **1)** Model the impact of changing Great Lakes water levels on habitat availability for at-risk plant and animal species, across the range of fluctuations predicted based on climate modeling; **2)** Assess how at-risk plant and animal species may respond to changes in habitat availability due to modeled lake-level change (i.e., decline, increase, or disperse); and **3)** Develop a list of conservation priorities - species, communities, and coastal regions, that are most in need of monitoring, restoration, and conservation.

METHODS

We used GIS modeling to estimate how a range of scenarios for changes to Great Lakes water levels will impact existing and potential habitat for at-risk species in Great Lakes coastal ecosystems in Michigan. We constructed seamless inundation models consistent with several lake-level rise and decline scenarios with high resolution (1-meter) LiDAR digital elevation models (DEMs; land elevation) and topobathymetric elevation models (TBDEMs; water depth). Then, we intersected these lake-level scenarios with a spatial ecosystem dataset including natural community data from the Michigan Natural Heritage Database (NHD; MNFI 2026) and stand-level data from multiple state and federal agencies and assessed impacts across ecosystems and upon specific coastal regions based on the extent of impacts to ecosystems. Finally, we inferred impacts on at-risk species based on their proportional association with each ecosystem type, and used the predicted impacts on species and ecosystems to develop conservation priorities for responding and adapting to fluctuating Great Lakes water levels over the coming decades.

Objective 1: Modeling the impact of Great Lakes water levels on coastal ecosystems

Our first objective was to model the impact of changing Great Lakes water levels on coastal ecosystems across the range of fluctuations predicted by regional climate models. We estimated the change in area of Michigan coastal ecosystems that would result from different lake levels that are consistent with climate change predictions. Objective 1 proceeded in three stages: 1) modeling values based on two different GCMs each relative to baseline average, low, and high water levels, for total of six modeled values, 2) developing a novel spatial ecosystem data layer and intersecting predicted lake levels with that data layer to predict how changing lake levels may impact different natural communities, 3) evaluating which natural communities and coastal regions may be affected more dramatically.

Definition of study area

In order to facilitate elevation data gathering and define the populations of habitats and species occurrences to be included in the analysis, we consulted existing maps of Michigan Great Lakes shoreline to define a coastal region (i.e., we did not rely on the coastline defined by any of the inundation scenarios mapped later in the analysis). We examined the NOAA Continuously Updated Shoreline Product (CUSP) (NOAA National Geodetic Survey 2024) as well as the NOAA U.S. Great Lakes Hardened Shorelines Classification 2019 (NOAA Office for Coastal Management 2026) for suitability and determined that combining these datasets would offer the best coverage of Great Lakes islands, detail of river outlets, and detail of lakes bordering the Great Lakes coast for defining the study area. We buffered both shorelines by 1km, merged the buffers, and dissolved them. To this buffer, we also added any land regions within 100 m of the maximum inundation level that were included in the online NOAA Lake Level Viewer (NOAA Office for Coastal Management 2024) that were spatially connected to the shoreline buffer. Small holes were removed from the final polygon. Thus, the final study area was defined as a 1-km shoreline buffer in most regions, with additional low-lying regions included inland of the buffer in select regions of the state with potential for Great Lakes inundation (primarily, the

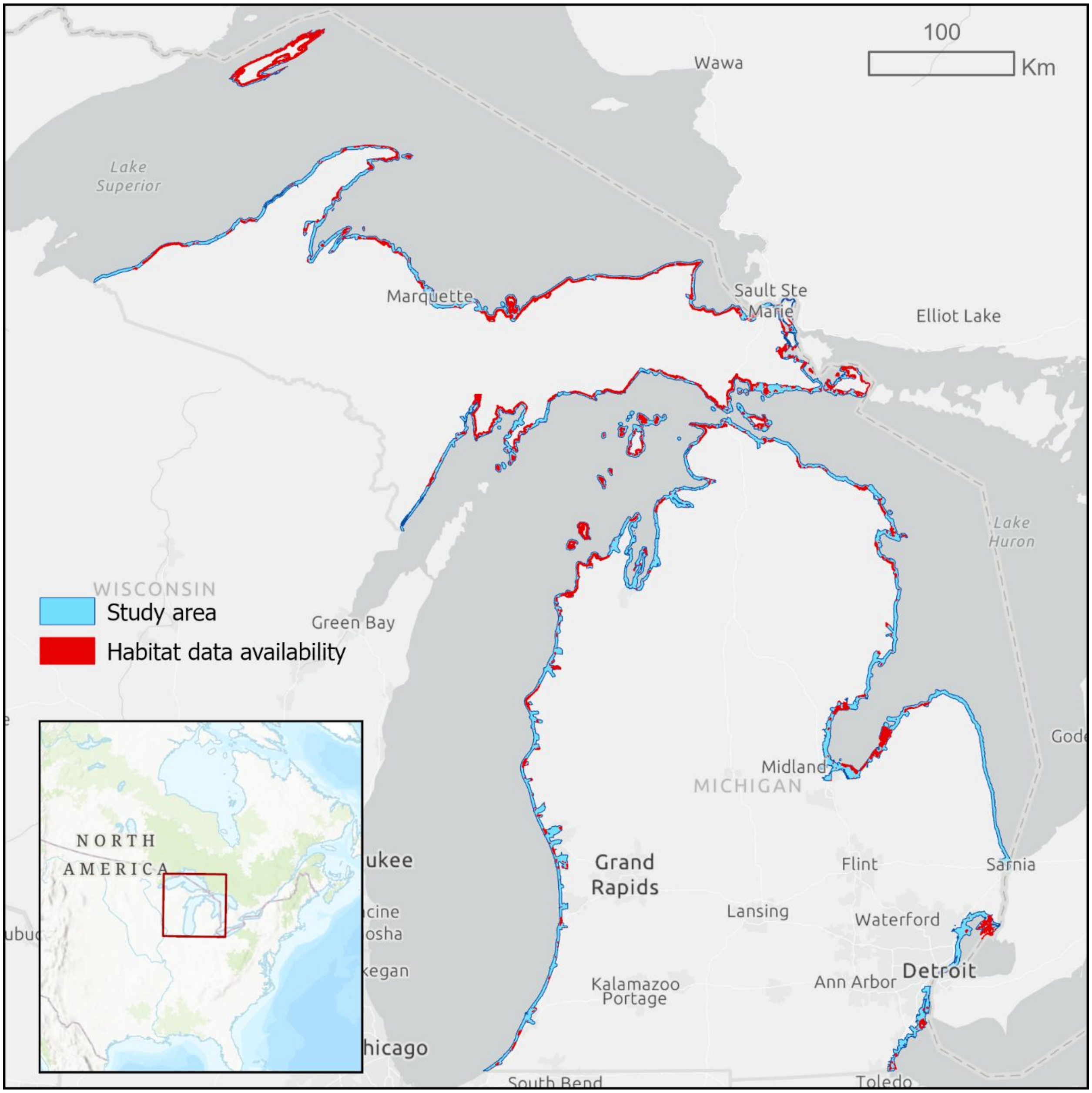

Figure 2. Study area defined by 1-km buffer around shoreline, inclusion of low-lying areas near Saginaw Bay, elevation data availability, and vertical datum transformation applicability. Habitat data (natural community labels) availability shown in red. Note: *Lake St. Clair and Detroit River region (Sarnia to Toledo) not modeled*. Basemap: Esri, TomTom, FAO, NOAA, USGS, NRCan, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS, Esri, USGS.

Saginaw Bay region) (Figure 2). This 1-km shoreline buffer with additional low-lying regions defined the search area for finding topobathymetric and topographic data in the state. The final study area was further determined by elevation data availability and the region in which the VDatum vertical transformation was available. We also used this buffer region to clip the habitats and species dataset later in the analysis (see *Generating and modeling coastal ecosystems*).

Upon visual inspection of the defined study area, we noted that two sizeable Great Lakes islands were missing from the study area due to missing shoreline delineations – Granite Island (87°24.576'W 46°43.241'N) and Tahquamenon Island (84°56.930'W 46°31.890'N), both in Lake Superior. Neither had habitats or project species data mapped (see *Generating and modeling coastal ecosystems* and *Species selection and intersection with ecosystems*, below). Otherwise, inclusion of Great Lakes islands in the study area bounds was judged to be comprehensive (though not all islands had elevation data available). The Lake St. Clair and Detroit River region was original included in the study area and had topobathymetric data available. However, it could not be transformed into the IGLD85 due to lack of transformation values in that region. Therefore, we dropped the region from the analysis.

Developing bathtub inundation model

We used a single surface raster, or bathtub inundation model, with tidal-orthometric datum conversion to model lake-level rise and lake-level decline (Poulter and Halpin 2008, Murdukhayeva et al. 2013, NOAA 2015). This method uses water-level height combined with topography (elevation) to model the extent of inundation. We modeled a series of Great Lakes water levels as predicted by the late-21st century and mapped inundation along the Michigan Great Lakes shoreline using the USGS 3D Elevation Program (3DEP) standard LIDAR-derived 1-Meter Digital Elevation Model (DEM) data (Arundel et al. 2015) merged with high-resolution topobathymetry elevation (TBDEM) data, producing a single seamless coastal elevation dataset.

When we initiated the project, existing modeling efforts were limited to efforts published before the publication of LiDAR-derived TBDEM data with 1-m horizontal resolution for essentially all of the Great Lakes shoreline of Michigan. The NOAA Lake Level Viewer, for instance, provides inundations with 3-m horizontal resolution derived from datasets gathered in 2017 (NOAA Office for Coastal Management 2024). New missions for Lake Erie (in 2020), Lake Michigan (2020), Lake Huron (2018-2019), and Lake Superior (2019) allowed us to improve the resolution and coverage along the state shoreline. Therefore, we compiled the latest datasets into a new seamless high-resolution shoreline elevation model in order to generate the most spatially accurate predictions for habitat impacts (see *Objective 2*, below). Additionally, we incorporated hydro-enforcement of the elevation model using best-available culverts, bridges, and road crossings to permit inundation of areas connected by flow through these features. Coincident this project, the Michigan Department of Environment, Great Lakes, and Energy (EGLE) sponsored a project focused on state-defined 'Critical Dune Areas' that also compiled a seamless 1-m shoreline elevation product for the state comparable to ours, without hydro-enforcement (MDEGLE 2026).

Table 1. Topobathymetric and topographic data sources incorporated in the inundation model

NOAA Digital Coast Dataset Name	Mission ID	Mission Date	Provider	Combined Topo RMSE (cm)	Combined Bathy RMSE (cm)
2020 USACE NCMP Topobathy Lidar DEM: Lake Erie (MI,OH)	9971	2020	USACE NCMP	10	15
2012 USACE NCMP Topobathy Lidar DEM: Lake Erie (MI, NY, OH, PA)	9434	2012	USACE NCMP	8	15
2019 USACE NCMP Topobathy Lidar DEM: Lake Huron, MI	9944	2019	USACE NCMP	10	15
2018 USACE NCMP Topobathy Lidar DEM: Lake Huron, MI	9657	2018	USACE NCMP	10	15
2013 - 2015 USACE NCMP Topobathy Lidar DEM: Lake Huron (MI)	7380	2013	USACE NCMP	8	15
2020 USACE NCMP Topobathy Lidar DEM: Lake Michigan (IL, IN, MI, WI)	9970	2020	USACE NCMP	10	15
2016 NOAA Topobathy Lidar DEM: Upper Lake Michigan Islands	6195	2016	NOAA	22	22
2012 USACE NCMP Topobathy Lidar DEM: Lake Michigan (MI, WI)	9268	2013	USACE NCMP	15	15
2012 USACE NCMP Topobathy Lidar DEM: Lake Michigan (IL, IN, MI, WI)	9265	2012	USACE NCMP	15	15
2015 USACE LRE Topobathy Lidar DEM: St Marys River, MI	6232	2015	USACE	20	20
2019 USACE NCMP Topobathy Lidar DEM: Lake Superior (MI, MN, WI)	9185	2019	USACE NCMP	10	15
2009 USACE NCMP Topobathy Lidar DEM: Isle Royale, MI	9485	2009	USACE NCMP	20	20
USGS 3DEP Seamless 1-Meter Digital Elevation Model	N/A	Multiple	USGS	23	N/A

All 41 of the Great Lakes shoreline counties in Michigan (including coverage of many Great Lakes islands) had high-resolution (1-meter) TBDEMs available (NOAA 2023), with LiDAR source acquisition years from 2009-2020 (Table 1). Where TBDEM data was not available, typically for islands or low-lying regions inland of TBDEM area, we procured USGS 3DEP topographic DEMs (USGS 2023). Elevation was referenced to a common vertical datum using the free vertical datum conversion software VDatum (v4.1.2; NOAA 2020). The International Great Lakes Datum of 1985 (IGLD85) is the current vertical control reference system that defines water levels within the Great Lakes. The vertical datum of the DEMs is the North American Vertical Datum of 1988 (NAVD88), the official vertical datum for the U.S. in the National Spatial Reference System (NSRS) since 1993. Because the height of the primary tidal benchmark for IGLD85 was held fixed as the constraint in NAVD88, IGLD85 and NAVD88 are essentially the same except that IGLD85 values are given in dynamic height units, and NAVD 88 values are given in Helmert orthometric height units (Zilkoski 1992). The estimated vertical uncertainty (standard deviation) of the transformation between NAVD88 and IGLD85 is provided by NOAA as 20 cm.

After unifying the elevation values to the IGLD85 vertical reference system, we filled the TBDEMs where missing data occurred. Missingness in the TBDEM reflected underwater regions where the water turbidity or depth prevented the penetration of LiDAR to the lake bottom. Filling these voids with the lowest adjacent elevation value (water surface) prevented topographic data from replacing them (erroneously) in the mosaic. We then mosaicked the input elevation data such that the latest TBDEM was used first, then older TBDEM elevation values, and then DEM elevation values only if no TBDEM data was available for a cell. After mosaicking, the missing TBDEM cells were restored such that both a filled and unfilled version of the elevation model were created.

We also hydrologically enforced the coastal elevation model to allow flow through bridges, culverts, and road-stream intersections. Elevation data derived from LiDAR present challenges for hydrologic modeling as the elevation surface includes bridges and elevated road features obscuring water flow underneath. We used the National Hydrography Dataset High Resolution (USGS 2024), Michigan Department of Transportation (MDOT) culverts (MDOT 2025b), MDOT bridges (MDOT 2025a), and Michigan Geographic Framework roads dataset (MDOT 2015) to identify potential locations for “cuts” for flow enforcement.

In areas low enough to potentially inundate, we intersected the flowline layer with the roads layer. At each intersection point, we visually examined the elevation model along with high-resolution true-color and near-infrared aerial imagery from the National Agricultural Imagery Program (USDA FPAC-BC-GEO 2022) and Michigan Imagery Solution (MCSS 2025) to judge whether a stream appeared to pass under the road. Stream channels or low regions on both sides of the road were taken as evidence of flow and the point was accepted as a “cut” location. If necessary, the point was spatially adjusted to match the DEM or imagery to avoid misdirecting flow of inundating waters. We buffered stream location locations by 20 m, culverts by 5 m, and bridges by 20 m and merged them. Zonal statistics were used to calculate the lowest elevation within the buffered polygon and then we mosaicked the zonal statistics raster with the filled DEM to lower the raster cells in the buffered “cut” locations for hydro-enforcement.

We did not evaluate other barriers such as trails, rails, or driveways as candidates for flow enforcement. In the Saginaw Bay region, due to the shallow, low-lying topography combined with extensive infrastructure in the coastal zone far beyond the extent seen in the rest of the state, we additionally cut all roads into the DEM using the lowest elevation of each road segment. This was done as most roads near the coast were lined with ditches and numerous driveways with culverts evident when we inspected the elevation model and aerial imagery.

In the bathtub inundation model, a land surface raster cell is considered flooded if it has an elevation value less than or equal to the water surface height for the model scenario. To account for topographic features that may prevent inundation of inland areas, only raster cells adjacent to the lake or adjacent to other inundated cells were included. To perform this calculation, we performed a distance accumulation after calculating a raster in which each cell above the modeled water height was set to NoData and the rest (below water) were set to a constant cost (cost = 1). We used the "Create Inundation" tool in an ArcGIS toolbox (Balstrøm and Kirby 2022) to implement the calculations for each climate scenario as well as the baseline scenarios. The inundation source cells were defined as a line approximately 500 m offshore. We later adapted their tool to use with the z-score values used in the uncertainty modeling. The inundation analysis used here does not account for inundation not resulting from Great Lakes water levels—for instance, a cell that is obviously in a river (receiving water flow from higher ground) may appear to be "not inundated" in our maps. This project evaluates relative change that is not biased by this mapping artifact.

Identifying lake-level scenarios for modeling

Notaro (2015a) described the annual lake-level changes for each of the Great Lakes resulting from net basin supply (NBS) changes predicted by two regional climate models—rising lake levels under the RCM-CNRM model and falling lake levels under RCM-MIROC5. Predictions were provided for the mid-21st century as well as the late-21st century. We modeled the late-21st century predictions, which are generally more extreme, to prepare resource managers for more extreme scenarios with greater impacts to species. Notaro et al. (2015a) provided predictions of lake-level changes resulting from NBS changes for each of the scenarios versus a baseline period of 1948-2006 from a Great Lakes monthly hydrologic dataset, as well as absolute lake-level heights under each scenario. As we could not reproduce their baseline water heights, we used the absolute lake-level heights in order to calculate differences versus baseline water heights that we defined. We calculated those baselines using a long-term average for a period extending back to 1918 by referencing the U.S. Army Corps of Engineers 1918-2023 long-term average data, which provided annual lake-level average water heights during that period (USACE 2026). We also used the USACE dataset to examine inter-annual variation and extrema during the 1918-2023 period for each lake. To incorporate lake-level variability, we chose to model three baseline lake levels: average years ("Baseline Average") that correspond to the long-term average, high water years ("Baseline High," 1 meter above average), and low water years ("Baseline Low," 1 meter below average). For each of the RCM-CNRM and RCM-MIROC5 predictions, we applied the difference between the scenario height and the long-term average to all three baseline values. This resulted in nine scenarios and six comparisons versus baseline for each lake basin (Table 2). In other words, the difference between the RCM-CNRM water height and the baseline for Lake Superior is maintained as 13 cm for each of the following comparisons: average year at baseline versus average year in RCM-CNRM, high water year at baseline versus high water year in RCM-CNRM, and low water year at baseline versus low water year in RCM-CNRM.

Table 2. Lake-level scenarios used to simulate inundations and expansions

		Lake level (meters above sea level)			Lake-level difference (meters vs. matching baseline)		
Level	**Lake**	**USACE long-term average**	**RCM-CNRM late-century**	**RCM-MIROC5 late-century**	**USACE long-term average**	**RCM-CNRM late-century**	**RCM-MIROC5 late-century**
Average water	Superior	183.42	183.55	183.32	0.00	0.13	-0.10
	Huron-Michigan	176.45	176.94	176.22	0.00	0.49	-0.23
	Erie	174.18	174.56	174.07	0.00	0.38	-0.11
High water	Superior	184.42	184.55	184.32	1.00	0.13	-0.10
	Huron-Michigan	177.45	177.94	177.22	1.00	0.49	-0.23
	Erie	175.18	175.56	175.07	1.00	0.38	-0.11
Low water	Superior	182.42	182.55	182.32	-1.00	0.13	-0.10
	Huron-Michigan	175.45	175.94	175.22	-1.00	0.49	-0.23
	Erie	173.18	173.56	173.07	-1.00	0.38	-0.11

Modeling inundation uncertainty

We incorporated an uncertainty simulation of the model and map inundation uncertainty, based on the root mean square error (RMSE) of the data source, to visually provide the user with a tool to aid in appropriate interpretation of the model results (Schmid et al. 2013, NOAA 2015). We reviewed the metadata for each topobathymetric elevation data source to record the vertical accuracy (95% confidence) or RMSE values that were reported for each mission. Most missions reported vertical accuracy for topographic values, for shallow field of view (FOV) bathymetric values, and for deep FOV values. Some only reported a joint topo/bathy accuracy or RMSE. We took the highest uncertainty for each of the topographic or bathymetric value types and converted all values to be stated as RMSE. Elevation values from topographic-only data sources were merged earlier in the project such that their original missions were not easily identifiable anymore, but the vast majority of the values used came from the projects tagged as "MI_FEMA_2019_C19" (Michigan FEMA 2019 project including 19 counties) or the "mi_13county_2015_c16" (Michigan 2015 project including 13 counties) projects. We applied the higher of the uncertainty values for the two projects (24.5cm fundamental vertical accuracy for the 2015 project) to all topographic-derived cells regardless of source, assuming this degree of uncertainty was characteristic regionally along the shore.

We combined the reported elevation uncertainty with the datum transformation uncertainty for all datasets that we needed to transform to the IGLD85 vertical datum. The transformation uncertainty is given as 20 cm RMSE by NOAA and we used the root-sum-of-squares to calculate

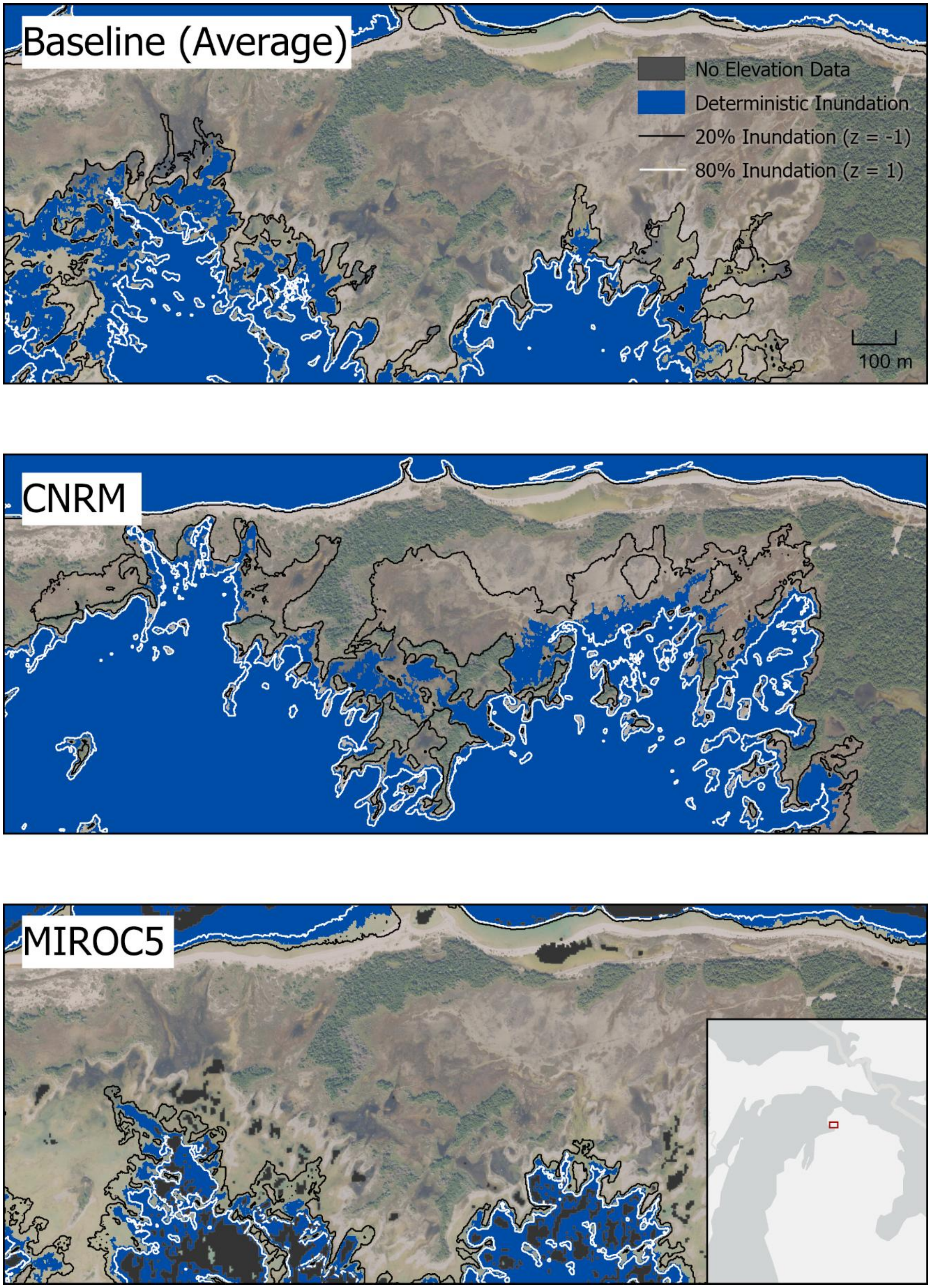

Figure 3. Example of uncertainty analysis from Waugoshance Point at Wilderness State Park. Aerial imagery from USDA Farm Service Agency.

the combined uncertainty. The maximum combined uncertainty values are compiled in Table 1. We then used the footprints from the statewide elevation raster mosaic to apply the uncertainty values as constants across each data source region. This resulted in two rasters, one with topographic uncertainty and one with bathymetric uncertainty. To apply the smaller topographic uncertainty values to cells that could not have been inundated regardless of the topobathymetric mission date, we used the high water levels of 2019 to create an elevation mask. Cells more than twice the combined topographic RMSE of 23 cm were identified as "dry" cells and the rest as "wet" cells (95% confidence). This mask was used to combine the two topographic and bathymetric uncertainty rasters into one that provides uncertainty for each cell dependent on its data source and topo/bathy context. For any cell with no elevation data, we assigned the maximum possible uncertainty of 23 cm RMSE so that an uncertainty value could be applied to filled elevation cells (Figure 3).

We used the uncertainty raster and the filled elevation rasters to calculate z-score rasters following the z-score mapping method described by Schmid et al. (2013). The following equation was applied for each cell to create a z-score map for each scenario.

$$score_{(X,Y)} = \frac{(inundation_{(water\ surface)} - elevation_{(X,Y)})}{RMSE_{(elevation\ data)}}$$

We then modified the inundation methods to use z-scores (which have a sign inverted from the raw elevation values) as the basis for the inundation status of the cell. We used "water levels" of z = -1 to and z = 1 to map contours for 15% confidence of inundation and 85% confidence of inundation (1 sigma), respectively, for each of the baseline and future water level scenarios. Cells with missing elevation data were restored to "NoData" values for scenarios below the baseline average after the inundation calculation--this is, as with the deterministic inundation calculations, they were assumed not to inhibit inundation of other areas even though their true elevation is unknown. An example of the resulting mapped uncertainty contours is shown for the baseline (average), CNRM scenario (average), and MIROC5 scenario (average) near Waugoshance Point in the Wilderness State Park (Figure 3).

Generating and modeling coastal ecosystems

We generated a stand-level ecosystem dataset to model impacts to coastal ecosystems and infer impacts to at-risk species based on their dependence on those ecosystems for habitat. Each stand in this dataset was typed to one of 68 of the 80 natural community types as described in the MNFI natural community classification (Cohen et al. 2015, 2025). This classification describes all historical Michigan native ecosystems, most of which still occur in the contemporary landscape, and is based on a combination of data derived from statewide and regional surveys, ecological sampling and data analysis, literature review, and expert assessment. These natural communities are sub-divided into one of five classes – palustrine, palustrine/terrestrial, primary, subterranean/sink, and terrestrial – each of which is further sub-divided into between one and seven groups, with each group containing between one and nine natural communities (Cohen et al. 2015, 2025). For example, the palustrine class contains a bog, fen, forested wetland, marsh, shrub wetland, and wet prairie group, each containing between two and nine natural communities.

We generated this dataset using polygons of natural community element occurrences from the NHD combined with forest stand maps from the Michigan Department of Natural Resources, Huron-Manistee and Hiawatha National Forests, United States Fish and Wildlife Service, and Sleeping Bear Dunes and Pictured Rocks National Lakeshores (Hop et al. 2010, 2011; USDA 2024 a, b; MDNR 2025; MNFI 2026). Natural community EOs were evaluated from the early 1980s to present and were either mapped to 1:24,000 scale paper topographic maps (USGS quads) and later digitized, or mapped digitally using field-collected GPS data or boundaries determined from aerial imagery interpretation. Natural community EOs were classified following the MNFI natural community classification through expert determination (Cohen et al. 2015, 2025). Forest stand maps developed by the Michigan Department of Natural Resources (DNR), United States Forest Service (USFS), United States Fish and Wildlife Service (USFWS), and National Park Service (NPS), used to guide forestry, prescribed fire, invasive species control, and other management decisions, were derived from multiple sources. The Michigan Forest Inventory (MiFI) database (MDNR 2026) includes stand-level data for State-owned public land in Michigan administered by the Wildlife Division (DNR-WLD), Forest Resources Division (DNR-FRD), and Parks and Recreation Division (DNR-PRD). We also utilized stand maps developed by USFS foresters and ecologists for the Hiawatha and Huron-Manistee National Forests (USDA 2024a,b), and by NPS ecologists for Sleeping Bear Dunes and Pictured Rocks National Lakeshores (SLBE and PIRO) (Hop et al. 2010, 2011). Finally, we utilized stand maps developed by MNFI for surveys in USFWS National Wildlife Refuge (NWR) lands on Great Lakes islands (e.g., Cohen et al. 2023). Each forest stand was cross-walked to an MNFI natural community through expert determination using a combination of the stand's original cover type label (vegetation classification label) as well as the classes from a GIS overlay of the stands with the following ancillary ecological datasets: historic (circa 1800) vegetation type, landform, physiographic region, and LANDFIRE Existing Vegetation Type. For MiFI, all DNR-WLD and some DNR-PRD stands were surveyed by MNFI ecologists and typed to a MNFI natural community in the field. All DNR-FRD and the remainder of the DNR-PRD stands were labeled using the crosswalk determination. Finally, all NPS, USFWS, and USFS stands were assigned an MNFI natural community remotely through interpretation of aerial imagery, ancillary ecological datasets, and stand data.

Once the various source datasets had a natural community label applied to each stand, the stands were merged into one dataset for further processing. Stands could overlap both within and between data sources originally and were allowed to overlap in the final natural community dataset. However, federal stands with no natural community label were dropped from the dataset, and stands with "Not Applicable" labels (non-natural vegetation such as residential or cultivated lands) were erased if coincident with a natural community found in another data source. Stand boundaries from the merged dataset were then dissolved if the natural community type label was equal (regardless of data source). The stands were then clipped to the study area resulting in the final ecosystem dataset. Polygons < 1 ha, usually slivers resulting from the merger, were removed. Stands retained overlaps in the final dataset only when they had different natural community labels, which was permitted because some of the best quality labels respect the complexity of the systems by mapping overlapping stands—such as cliffs nested within forest types, or individual communities precisely mapped within broadly-mapped wooded dune and swale complexes (Albert and Comer 2010). Habitat stands have been mapped on a subset of coastal public lands (Figure 2), resulting in a well-distributed but partial and non-uniform coverage of shoreline habitat observations available for inference of inundation impacts.

Coastal ecosystems were typically mapped using the shoreline in effect at the time of the mapping update. To allow consideration of how habitats could expand into baseline unvegetated areas revealed by receding waters, we simulated a habitat expansion in the lakeward direction. Habitats were classified as permitted to expand or not based on an expert determination (Table A1). For example, forest types were not permitted to expand because forested ecosystems require decades to develop, and periods of both inundation and expansion along Great Lakes shorelines are generally sub-decadal, so we assumed that any area of expansion adjacent to forests would be inundated again long before forest development could occur (Figure 4). Among bedrock communities, bedrock lakeshores and cobble shores fluctuate in size as they are inundated and exposed (e.g., expanded), while cliffs, bluffs, and glades are not assumed to fluctuate with lake levels. We used a distance allocation analysis to allocate lake regions to the nearest habitat (Euclidean distance). The original habitat boundaries were retained in the final result by overlaying them on top of (ArcGIS “Update” analysis) the regions mapped by the distance allocation, then the expansion area and the original area were dissolved. We added a “Not Mapped” polygon where there were no mapped habitats to enforce habitat expansion along edges of mapped areas to only allow habitats to expand outward roughly perpendicular to the shoreline (Figure 4). However, if mapped habitats were within 100 m of the shoreline, any unmapped areas were preserved as empty spaces in order to allow the habitat nearest the shoreline to expand into that region and beyond the shoreline depending on the water level.

We estimated impacts to coastal ecosystems by calculating the percent change in area for each coastal ecosystem due to the extent of inundation or expansion under each model scenario. Each inundation scenario raster dataset was converted to a single, seamless, wall-to-wall vector dataset for the entire coastal study area. The resulting polygons were labeled as one of three classes: above Great Lakes water level, below Great Lakes water level, and elevation data unavailable. In the inundation analysis, we assumed that cells were inundated at the baseline average water level when they had missing bathymetric data, since the reason for the missingness was water turbidity or depth preventing detection of the lake bottom. The missing regions were filled with the lowest surrounding elevation value (the water level at the time of in-situ mapping) before the inundation analysis. For scenarios with water levels above the baseline average, we treated them as “water rises” scenarios and assumed those regions were inundated. For “water rises” scenarios, the inundation polygons were spatially intersected with the habitats as-mapped. The area and percentage of each habitat polygon that was inundated or above water was calculated for all scenarios.

For scenarios with water levels below the baseline average, we treated them as "water recedes" scenarios and preserved the missing data in order to label those regions as having uncertain inundation status, or unfilled elevation data. For these scenarios, we spatially

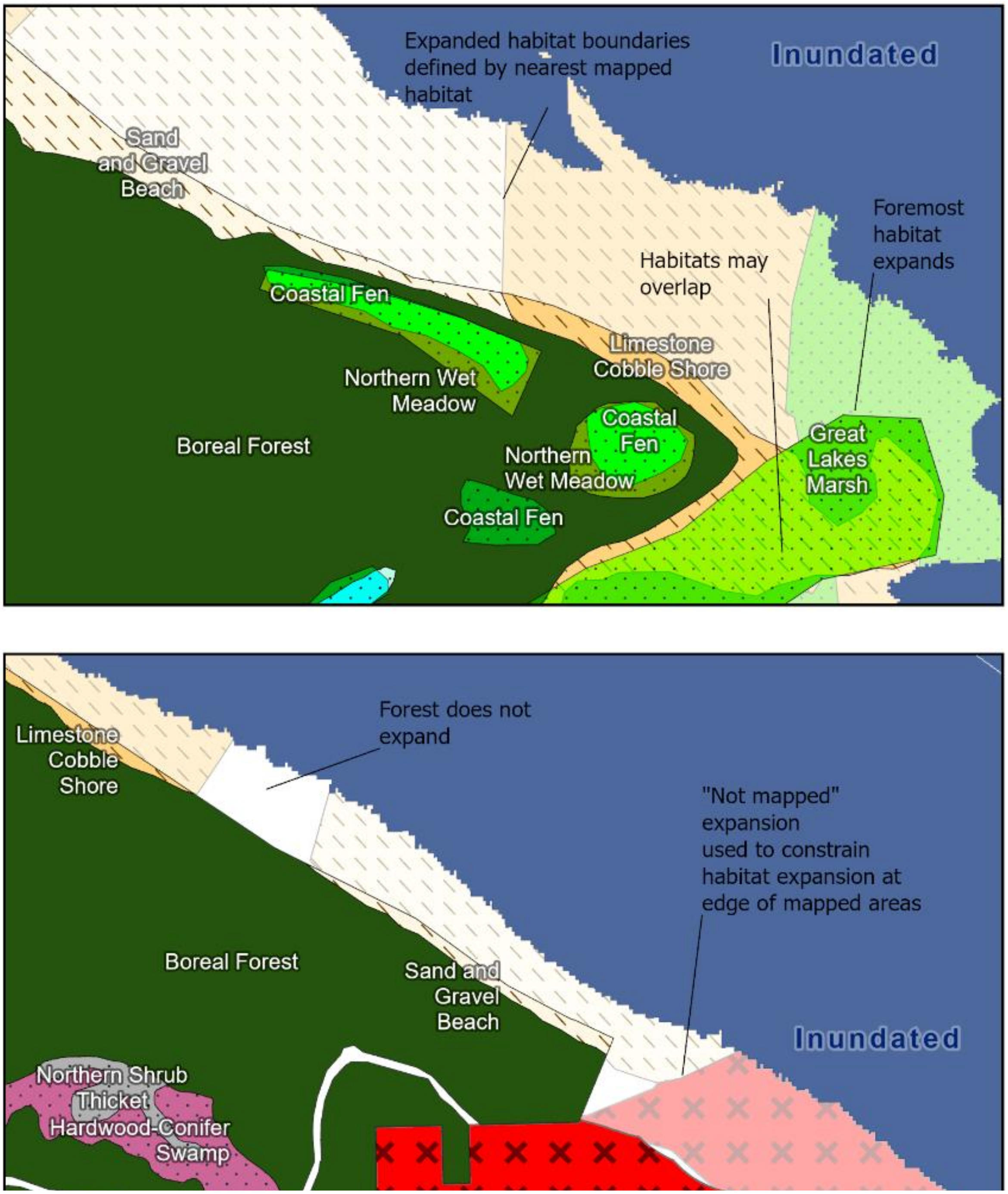

Figure 4. Example of habitat expansion scenarios across natural community types. The top panel illustrates how adjacent and overlapping natural communities expand. The bottom panel illustrates how "not mapped" polygons and communities not "allowed" to expand constrain expansion of adjacent communities.

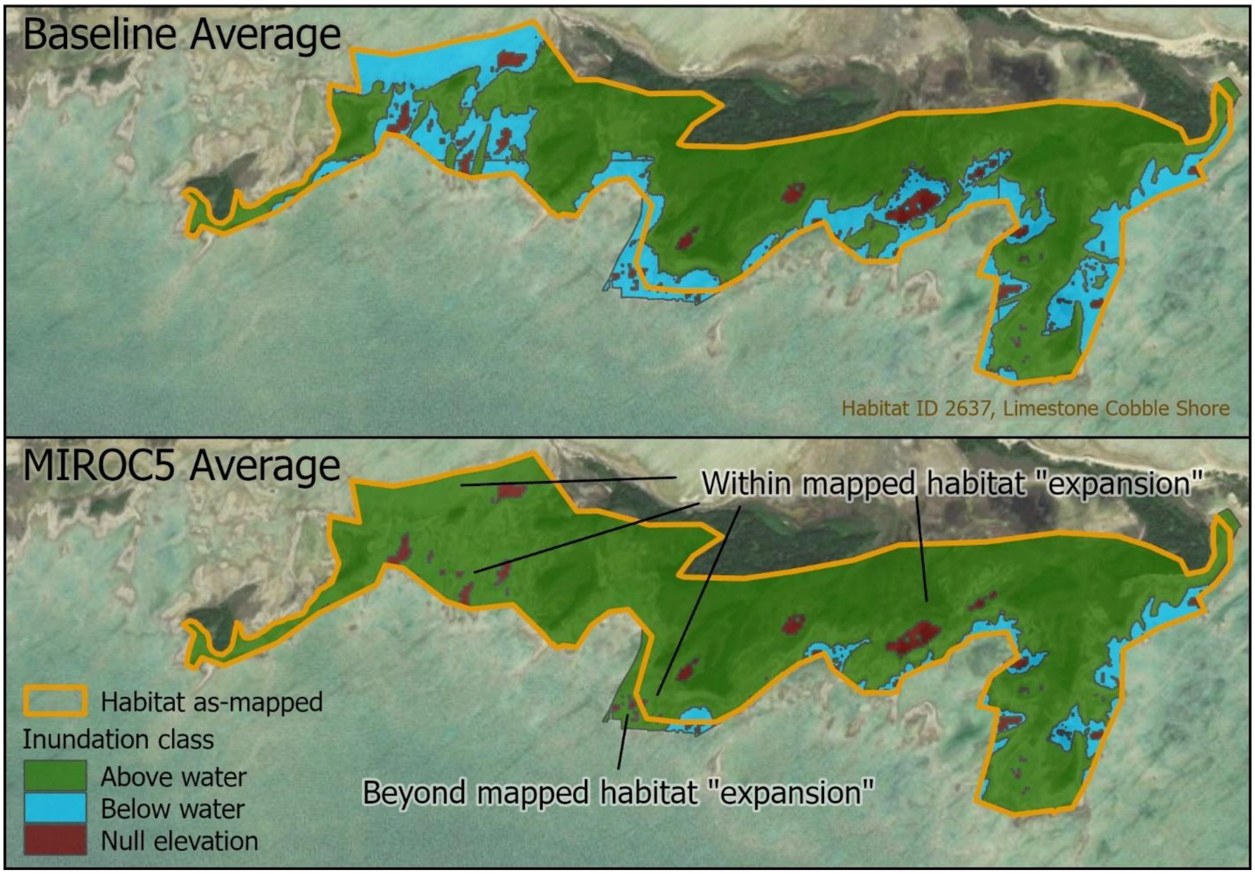

Figure 5. Habitat "expansion" may convert both areas within and beyond the habitat extent. Compared to the baseline average, the MIROC5 "average" projected water levels result in conversion of the inundated regions at the west end and along the south margin of this limestone cobble shore natural community. The projected water levels also cause the dry portion of the shore to protrude slightly beyond the originally mapped extent. This habitat is reported to have 33% "expansion" comprising of both the conversion of area within the original extent (primarily, in this case) and protrusion beyond it. Mapped natural community extents (here, the orange line) reflect in-situ consideration of the shoreline as it appeared on the survey date for each natural community. We used the above water area of the natural community in the baseline scenario as the basis for the percentage change for each paired scenarios comparison involving water levels below the long-term average, in order to standardize the delineation of the lakeward side of the natural community. Aerial imagery credits: Vantor.

intersected the unfilled inundation polygons with the "expanded" habitat polygons. The area and percentage of each habitat polygon that was inundated or above water was calculated for all scenarios and excluded the missing regions from any area calculations. We used the area of the habitat above water in the baseline scenario as the denominator for the "water recedes" percent change calculations in order to adjust for variability in how the original polygon mapping delineated the shoreline (Table A2). While mapping ambiguities are also found on the landward side of the mapped stands, these boundaries usually abut other mapped habitats and reflect a terrestrial mapping bias, so we did not theorize how habitats might expand in a landward direction. Finally, because habitat expansion was calculated relative to each baseline scenario, expansion could occur *within* a natural community polygon if the relevant baseline condition predicted inundation (Figure 5).

Once the intersections were summarized as area and percent change between scenarios, we calculated summary statistics for the natural community (habitat) class statewide in the coastal zone. Positive percent-change values were interpreted as habitat expansion, indicating an increase in habitat area as water levels recede or shift. Conversely, negative values were interpreted as habitat contraction, reflecting loss of habitat area under conditions of higher or more persistent inundation.

Evaluating impacts at focal areas

We also analyzed the regional variation of inundation and expansion of coastal ecosystems, to assess the regional variation in predicted impacts. Because natural communities were only mapped in a small fraction of the Michigan coastline, we performed an analysis of areal change in 500 m square grid cells covering the entire study area (hereafter, fishnet grid). Each 500 m fishnet grid was intersected with the classified inundation layers and we calculated the area and percent change of inundation status as with the habitat stands.

We inspected the results visually to inform an expert assessment of specific coastal regions that vary in their inundation and expansion across lake-level scenarios. First, we mapped the degree of change for each of the six scenario combinations at the 500 m grid-cell level and visualized each cell as occurring in the following categories: minimal change (-0.50 to 0.50 standard deviations), some change (-0.50 to -1.50, 0.50 to 1.50), significant change (-1.50 to -2.50, 1.50 to 2.50), and dramatic change (< -2.50, > 2.50). Then, we visually inspected the map in ArcGIS Pro at a resolution of 1:1,000,000 and recorded areas where cells indicating significant or dramatic change were concentrated (Figures B1-6).

Based on this visual inspection, we selected three focus areas in Michigan to demonstrate regional variability in Michigan's coastal habitats. These focal areas contain mapped natural community polygons and polygons for the at-risk species evaluated in Objective 2: 1) Wildfowl Bay, 2) Wilderness State Park, and 3) Drummond Island (Figure 6).

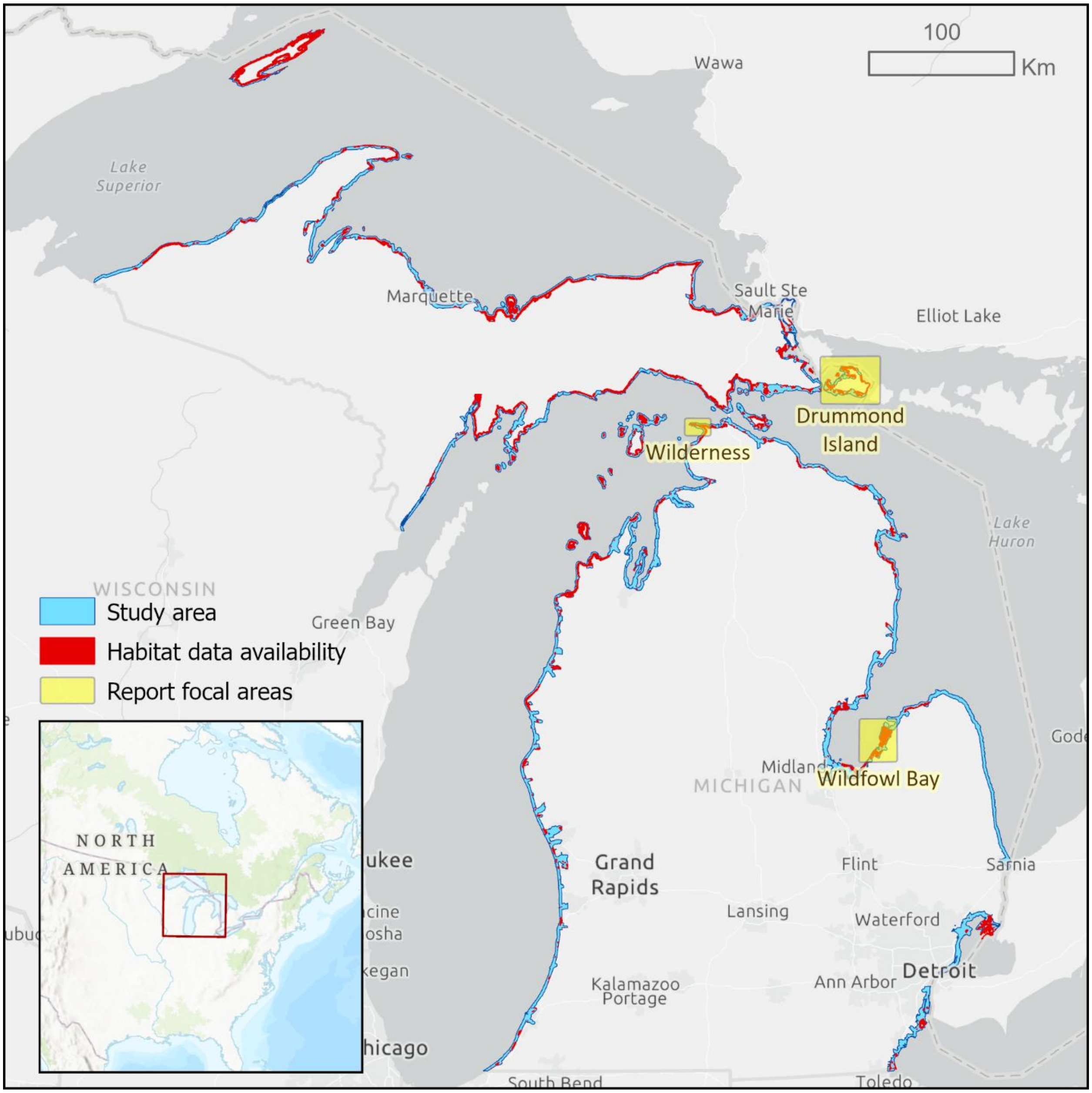

Figure 6. Study area indicating location of focal areas. See Figure 2 for additional details.

Habitat change at each focal area was assessed using percent-difference values representing the proportional change in natural community area. Rather than analyze across all six scenarios, analysis focused on the average percent-change metrics for each natural community across high, low, and average scenarios for each GCM (CNRM and MIROC5). Values from both climate scenarios were evaluated to identify which natural communities experienced the greatest magnitude of change, regardless of direction. Natural communities showing the largest positive values were classified as exhibiting the greatest degree of expansion, while those with the largest negative values were identified as exhibiting the greatest degree of inundation. These comparisons allowed for direct evaluation of natural community sensitivity to predicted water-level changes and provided a basis for interpreting which communities were likely to expand or contract under future conditions, and (Objective 2) better understand how different at-risk species may respond to climate change differently in different regions.

Objective 2: Assess how changes to coastal ecosystems will impact habitats for at-risk species

Our second objective was to assess the impact of lake-level change on at-risk species due to habitat loss and gain, both indirectly by associating each species with the ecosystem polygons assessed in Objective 1 and directly by assessing the impact on select species using spatial data for those species. Objective 2 proceeded in four stages: 1) Select focal at-risk species and calculate proportional association with each natural community type; 2) calculate the proportional impact to species via the impact to natural communities modeled under Objective 1; 3) explicitly intersect modeled lake levels with at-risk species EO polygons and estimate direct impact to those species; and 4) inspect impacts to at-risk species within the three focal areas examined under Objective 1.

Species selection and intersection with natural communities

We selected 13 species for which representative spatial data were available, amongst species prioritized by USFWS and other agencies and based on relevance to regional action plans including the MI Wildlife Action Plan (MWAP), Great Lakes Restoration Initiative (GLRI) Action Plan, and Upper Mississippi / Great Lakes Joint Venture (UMGLJV) Waterfowl, Waterbird, and Landbird Habitat Conservation Strategies (Soulliere et al. 2017, 2018, 2020, Henehan et al. 2026) (Table 3). These species also differ in coastal ecosystem preferences, are variously restricted to Great Lakes coastal habitats vs. inland habitats, represent a range of taxonomic groups, and represent a range of life-history traits that are likely to influence how they respond to lake-level fluctuations. The species included in this analysis are found in aquatic and marsh habitats (hereafter, marsh); emergent meadows, fens, and grasslands (hereafter, meadows); primary substrates including bare sand and bedrock (hereafter, primary); and upland and swamp forests, often in ecosystem complexes with a multiple forested and non-forested natural communities (hereafter, complexes). We grouped these species into broad habitat categories to assist with generalization of results and to describe the variation in habitat preferences across species, but we also describe how these categories also generally map well onto MNFI classes, groups, and natural communities. As described here, marsh and meadow communities are classified under the palustrine class, primary communities under the primary class, and habitat complexes under a mix of palustrine and terrestrial classes.

Table 3. At-risk species evaluated during this study. MWAP = Michigan Wildlife Action Plan; GLRI = Great Lakes Restoration Initiative; UMGLJV = Upper Mississippi / Great Lakes Joint Venture Waterfowl, Waterbird, and Landbird Habitat Conservation Strategies [1]GLRI focal species include all marsh breeding birds, of which black tern and king rail are a subset. See Appendix C for G-rank and S-rank definitions.

		Status					
Common Name	**Scientific name**	**Federal**	**State**	**G/S-rank**	**MWAP**	**GLRI**	**UMGLJV**
Piping plover	*Charadrius melodus*	E	E	G3S2	X	X	
Black tern	*Chlidonias niger*		T	G4G5S2	X	X[1]	X
Pitcher's thistle	*Cirsium pitcheri*	T	T	G3S3	X	X	
Dwarf lake Iris	*Iris lacustris*	T	T	G3S3	X	X	
Michigan monkey flower	*Mimulus michiganensis*	E	E	G1S1		X	
Blazing star stem borer	*Papaipema beeriana*		SC	G3?S2	X		X
Eastern prairie fringed orchid	*Platanthera leucophaea*	T	E	G2G3S1	X	X	
King rail	*Rallus elegans*		E	G4S2		X[1]	X
Eastern massasauga	*Sistrurus catenatus*	T	T	G3S3	X	X	
Houghton's goldenrod	*Solidago houghtonii*	T	T	G3S3			
Hine's emerald dragonfly	*Somatochlora hineana*	E	E	G2G3S1	X		
Common tern	*Sterna hirundo*		T	G5S2	X		X
Lake Huron locust	*Trimerotropis huroniana*		T	G4S2S3	X		X

We selected two waterbirds that are associated with marshes, black tern (*Chlidonias niger*, State Threatened) and king rail (*Rallus elegans*, State Endangered). These species nest and forage in both coastal and inland freshwater marshes, typically with sparse to moderately dense emergent vegetation such as cattails (*Typha* sp.) or bulrushes (*Schoenoplectus* spp.) (Currier 2000, Rabe 2001). Both species are generally distributed across the lower peninsula and eastern upper peninsula (Figure 7). King rail is concentrated in the southern lower peninsula, including several inland observations, whereas black terns are more restricted to Great Lakes coastal habitats, which comprise at least half of that species' breeding observations (Currier 2000, MNFI 2026). These species are associated with several MNFI natural communities in the marsh group of the palustrine class.

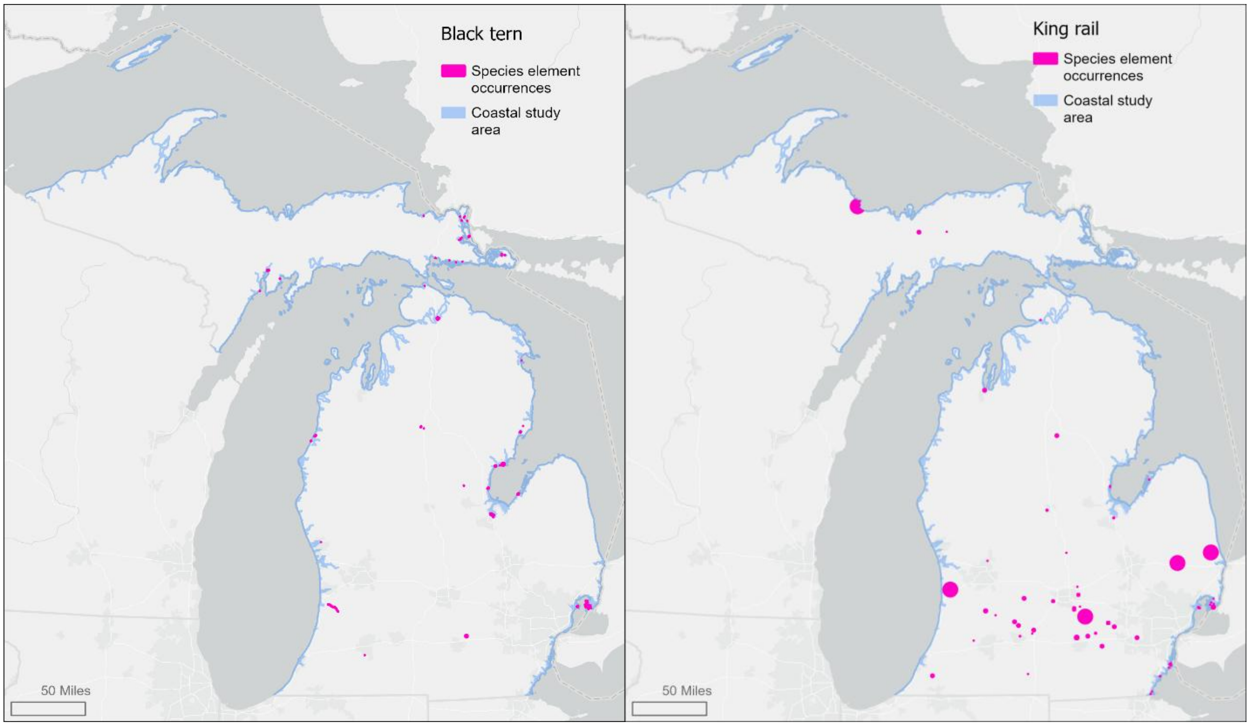

Figure 7. Element occurrences for black tern (*Chlidonias niger*, left) and king rail (*Rallus elegans*, right) in Michigan. Data from MNFI (2026).

We selected two insect species associated primarily with grass and sedge meadows and prairies, the blazing star borer moth (*Papaipema beeriana*, Special Concern) and Hine's emerald dragonfly (*Somatochlora hineana*, Federal and State Endangered), as well as one plant species, eastern prairie fringed orchid (*Platanthera leucophaea*, Federal Threatened and State Endangered). Blazing star borer and eastern prairie fringed orchid occur inland in peatlands, with the former species occurring wherever their larval host plant blazing star (*Liatris* spp.) occurs at high enough densities to support blazing star borer populations, which also includes inland dry prairies and savannas (Cuthrell 1999a, Ellison et al. 2026b). Among coastal ecosystems, however, they co-occur almost exclusively in lakeplain prairies, which are found in seasonally wet lacustrine deposits in level topography in the southeastern lower peninsula of Michigan (Figure 8). Lakeplain prairies are in the wet prairie group of the palustrine class of the MNFI natural community classification. Hine's emerald dragonflies occur in minerotrophic (i.e., groundwater-influenced) peatlands in calcareous substrates such as coastal and northern fen, and are restricted to coastal and near-coastal ecosystems, primarily in the Straits of Mackinaw region of northern Lakes Michigan and Huron (Cuthrell 1999b; Figure 8). These MNFI natural communities are in the fen group of the palustrine class.

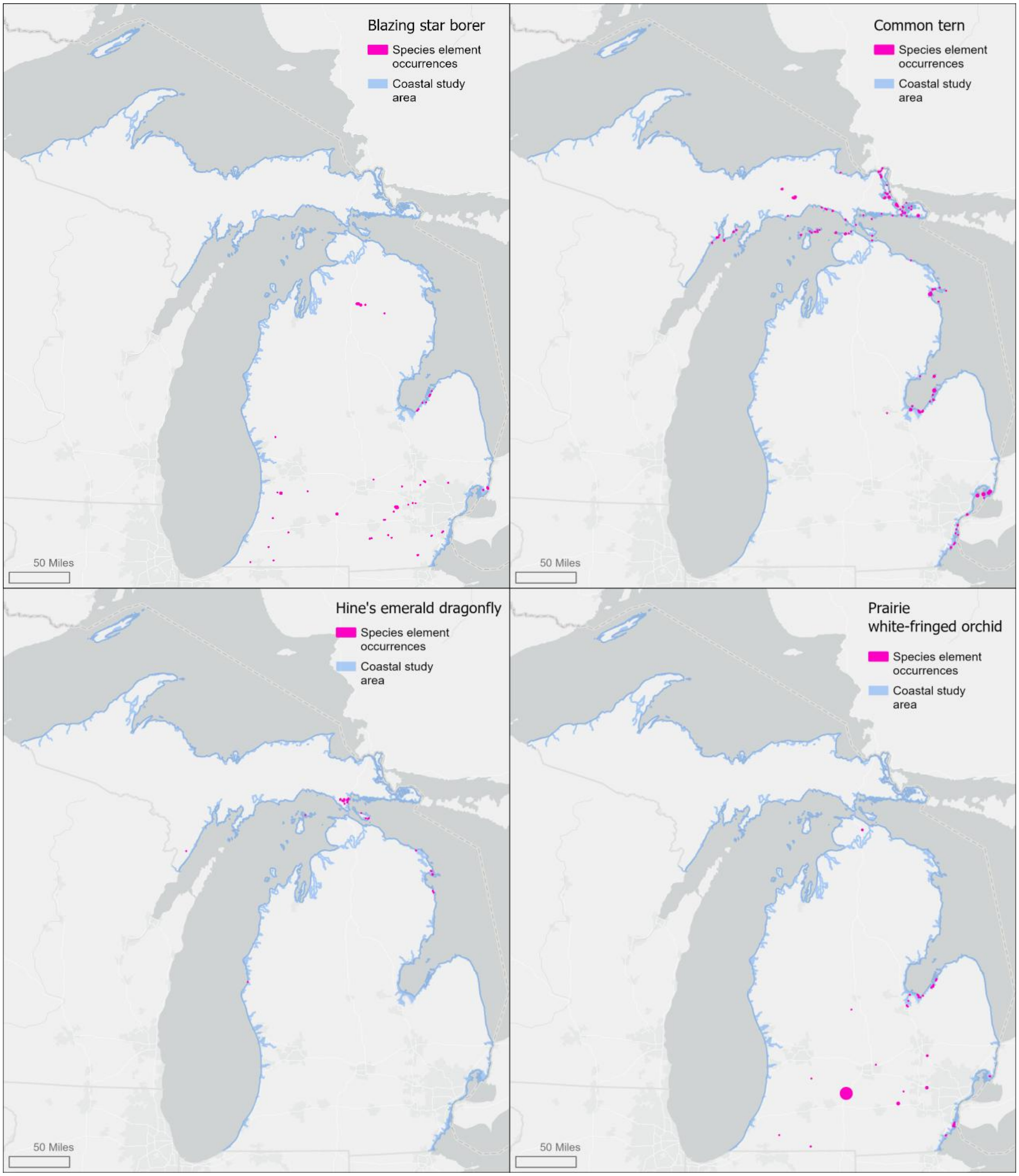

Figure 8. *Clockwise from upper left:* Element occurrences for blazing star borer (*Papaipema beeriana*), common tern (*Sterna hirundo*), eastern prairie fringed orchid (*Platanthera leucophaea*), and Hine's emerald dragonfly (*Somatochlora hineana*) in Michigan. Data from MNFI (2026).

We selected four species with habitat preferences for primary communities, including piping plover (*Charadrius melodus*, Federal and State Endangered) and common tern (*Sterna hirundo*, State Threatened), Pitcher's thistle (*Cirsium pitcheri*, Federal and State Threatened), and Lake Huron locust (*Trimerotropis huroniana*, State Threatened). Piping plover and common tern occur in sparsely-vegetated coastal ecosystems (Hyde 1997, 1999). The former nests in cobble, particularly in wide beaches with nearby riverine or marsh habitat for foraging, whereas the latter prefers isolated islands and peninsulas, and typically nest in large colonies for protection from predators. The MNFI natural communities where piping plover and common tern occur are mostly in the sand/cobble shore group of the primary class. Pitcher's thistle and Lake Huron locust are both entirely restricted to large sand dune complexes and therefore are limited by areas where prevailing winds are conducive to dune formation (Rabe 1999, Ellison et al. 2026a). Open dunes is a MNFI natural community in the dunes group of the primary class. Both species occur throughout the shores of northern Lakes Michigan and Huron and eastern Lake Superior, while the range of Pitcher's thistle also wraps around the southern shores of Lake Michigan and extends into Indiana, Illinois, and Wisconsin (Figure 9).

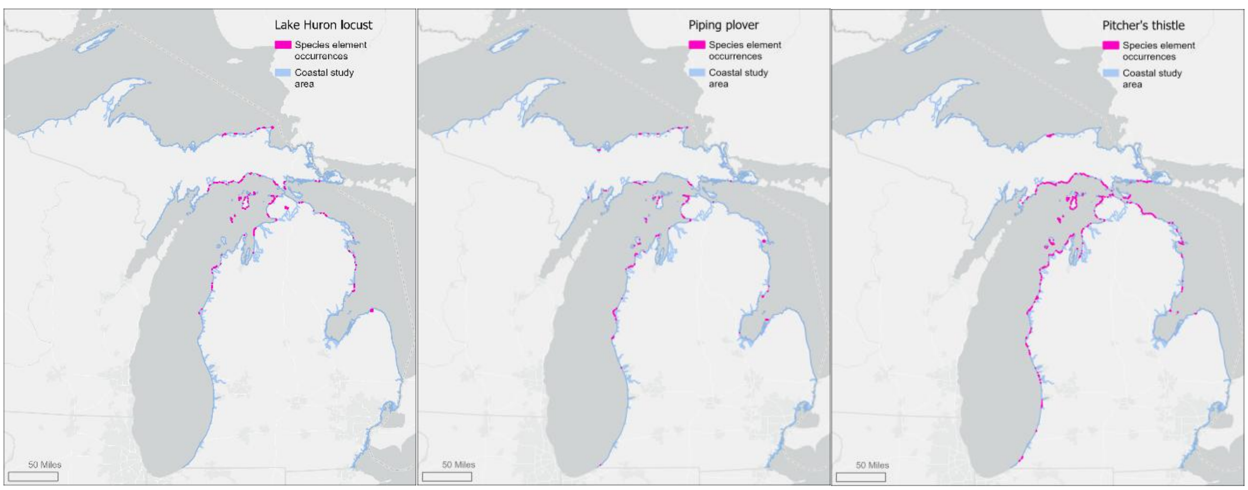

Figure 9. *Left to right*: Element occurrences for Lake Huron locust (*Trimerotropis huroniana*), piping plover (*Charadrius melodus*), and Pitcher's thistle (*Cirsium pitcherii*) in Michigan. Data from MNFI (2026).

Finally, the four remaining species, dwarf lake Iris (*Iris lacustris*, Federal and State Threatened), Michigan monkey flower (*Mimulus michiganensis*, Federal and State Endangered), Houghton's goldenrod (*Solidago houghtonii*), and eastern massasauga (*Sistrurus catenatus*, Federal and State Threatened), are typically associated with ecosystem complexes that include primary, meadow, and marsh ecosystems, as well as patches of forest. Each of these species has a range of different habitat associations, and occur across multiple MNFI natural community groups, in multiple classes. Dwarf lake iris and Houghton's goldenrod are largely endemic to the dolomitic Niagara escarpment that runs through the Straits of Mackinac along northern Lakes Michigan and Huron, generally found in calcareous coastal sands, cobble, and exposed limestone

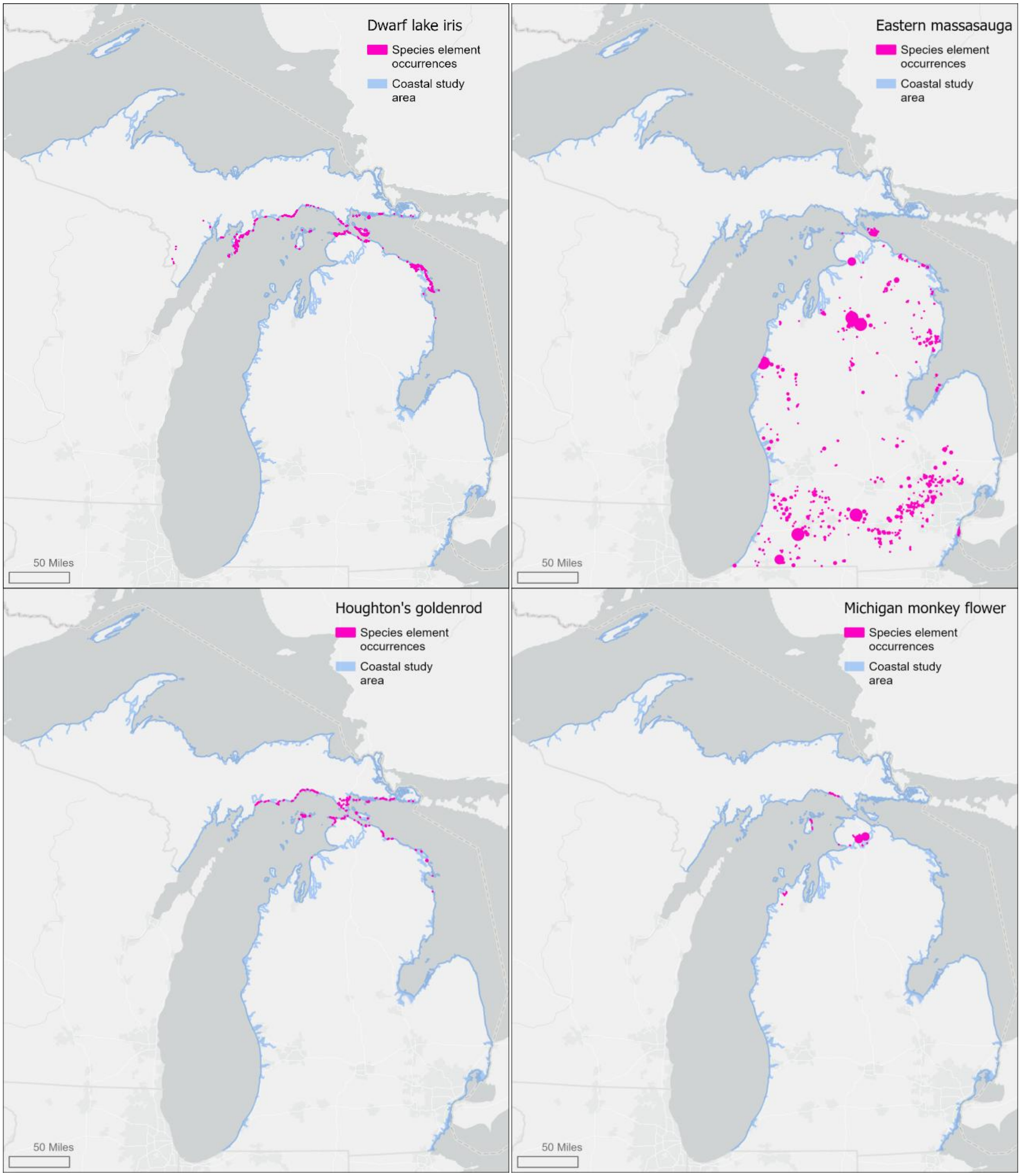

Figure 10. *Clockwise from upper left:* Element occurrences for dwarf lake iris (*Iris lacustris*), eastern massasauga (*Sistrurus catenatus*), Michigan monkey flower (*Mimulus michiganensis*), and Houghton's goldenrod (*Solidago houghtonii*) in Michigan. Data from MNFI (2026).

pavements (Figure 10; Penskar et al. 2026, Stone et al. 2026b). Dwarf lake iris is frequenty associated with a sparse to dense canopy of northern white cedar (*Thuja occidentalis*) across that range of substrates. Houghton's goldenrod prefers interdunal swales with little to no canopy and a high water table, but occurs across a range of moist coastal ecosystems from calcareous beaches to adjacent forest openings. Michigan monkey flower is found in a different suite of alkaline conditions, typically in partial shade in cool, marly groundwater seeps in inland swamps of northern white cedar on organic soils, but also at the coastal outlets of those seeps in or near the northern Lake Michigan coast (Stone et al. 2026a). Eastern massasauga is unique among the species we selected, occupying large territories that encompass an especially broad habitat diversity (Lee and Legge 2013). Occurring across the Lower Peninsula in home ranges as small as 1.3 ha (3 acres) in southern Michigan to 16.7 ha (41 acres) in northern Michigan, this species utilizes a range of wetland and upland habitats throughout its life history, including bogs, fens, sedge meadows, various upland grasslands, and hardwood and conifer forests.

We calculated the likelihood that each species would occur in each natural community by intersecting spatial data of element occurrences for each species from the NHD with the processed natural community stands, excluding all "N/A" classed polygons (Table A3; MNFI 2026). While the use of natural community types by at-risk species is well documented, the spatial representation of high-quality occurrences of each natural community is limited to EOs that have been thoroughly surveyed in the field and entered into the NHD (Cohen et al. 2015, 2025). Most species have habitat requirements that are broader than the landscapes with the greatest ecological integrity represented by natural community EOs, so relying on natural community EOs alone would not provide adequate spatial representation to accurately model habitat change. Therefore, incorporating the MiFI, USFS, and NPS stand maps, where stand data was used to crosswalk each stand to an MNFI natural community, incorporates a much broader geographic range and therefore a broader inference about how lake-level changes will affect habitat for at-risk species.

Species element occurrences are a merger of individual observations over time with varying spatial accuracy levels, the lowest of which can express uncertainty on the scale of over 1000 m (e.g., 19th-century museum specimens, vague oral reports). We created modified element occurrence boundaries that excluded these areas of low spatial accuracy before calculating the habitat linkage to focus the linkage weights on the best-mapped species and natural community co-locations. For each species, we used a spatial intersection analysis to tabulate area of each natural community intersecting the modified element occurrence polygon.

Habitat-based analysis

For each species, we calculated the percent area associated with each natural community by summing the total area of each natural community intersecting polygons for that species and dividing that sum by the total area of all of the mapped natural communities intersecting polygons for that species. The resulting percentages were used as likelihood weights inferring how areal change in each community would affect habitat for each species. For each species in each scenario, we calculated the percent change in habitat area, using the following formula:

$\sum_{i=1}^{n} \%change_{community1} * weight_{community1} + \%change_{community2} * weight_{community2}$ + . . . for the *n* natural communities in which that species is found.

The natural community dataset represents *potential* habitat for Great Lakes coastal species. To the extent that populations increase with habitat area, the change in area of natural community polygons is a proxy for the change in potential focal species population sizes (Preston 1962). We interpreted inundation to represent loss of habitat and expansion to indicate gain of habitat (although see *Which species are predicted to lose habitat?* in *Discussion*). When interpreting the degree of impacts represented by percent habitat change, we assigned a threshold of 10% habitat inundated or expanded to indicate *significant* change, and a threshold of 25% to indicate *dramatic* change. These thresholds are admittedly arbitrary, but we suggest that intuitively, a 10% change in habitat area would have "significant" impacts on population size and viability for most species and a 25% change would have "dramatic" impacts (Timpane-Padgham et al. 2017, Capdevila et al. 2020).

We also analyzed how the relationship between changes in natural community area and species habitat area were related by conducting multivariate analyses in R Studio (Posit team 2026), using the vegan package (Oksanen et al. 2026). To explore similarities among natural communities and species in percent inundation and expansion across scenarios, we constructed a natural community X scenario dissimilarity matrix using Bray-Curtis dissimilarities. We projected species habitat responses and natural communities onto the same NMDS plot, and visually inspected how species clustered relative to natural community classes (palustrine, terrestrial, palustrine/terrestrial, primary). We also tested whether community classes and groups responded similarly by conducting individual PERMANOVAs with class and group as response variables, respectively. Similarly, to explore similarities among species in percent inundation and expansion across scenarios, we constructed a species X scenario dissimilarity matrix using Bray-Curtis dissimilarities, and visually inspected species clustering in NMDS plots.

Explicitly modeling species impacts

By modeling natural community polygons rather than species occurrence polygons, however, we did not directly assess the effect of lake-level changes on individual focal species populations. To incorporate population-level impacts, we also explicitly modeled impacts of lake-level fluctuations on species polygons for each of the 13 at-risk species (MNFI 2026). We used the modified species element occurrences (excluding source features with low spatial representation accuracy) that were created for the habitat-species linkage to confine the species assessment to the best-mapped data. We summarized all element occurrences for each species to calculate its percent change in area under each scenario and make difference comparisons. We made assumptions about the capacity for each natural community to expand beyond polygon boundaries or not as lake levels recede, and applied those assumptions in the habitat-based analysis (Table A1). In contrast, we did not allow species polygons to expand beyond polygon boundaries because there was no systematic way to ensure that adjacent exposed habitat was suitable for each species.

We compared the results of species-based analyses to the habitat-based analyses to provide further context to our interpretations. Species-based analyses were limited to how predicted lake levels impacted currently documented observations of each species based on their mapped locations along the shoreline, while habitat-based analyses modeled impacts to all potential habitat for each species and therefore represented a sample of potential occurrences - a broader, if more speculative, scope of inference. In other words, while the species-based analyses represent modeled impacts to where each species *is known to* occur presently, habitat-based analyses indicate locations where each species *may occur* presently and in the future. Therefore, the difference in modeled area between species-based and habitat-based analyses presents a hypothesis of how much habitat is available for each species to *disperse into* when displaced by lake level changes. For example, if the habitat-based analysis predicted less inundation or more expansion for a species than the species-based analysis under a scenario (i.e., more habitat), that would suggest opportunities for previously-documented occurrences of that species to disperse into available habitat not impacted by lake-level changes.

Objective 3: Identify conservation priorities

We compiled a list of conservation priorities by cross-referencing how changing lake levels impacted priority species, communities, and focal areas on the landscape supporting them. We calculated an "impact score":

$$\overline{species\ weights}_{community_x} * \%change_{community_x}$$

for each natural community *x* in each scenario (Tables A5, 6). The impact score generalizes the importance of each community for how the 13 species we evaluated may be impacted by lake-level changes. We then assigned a rank-order for each natural community in each scenario, and calculated a mean rank-order for each GCM (Tables A5, 6), with one indicating highest impact. Natural communities with a mean rank-order value for MIROC5, CNRM, or the mean of the two with a value lower than one standard deviation from the mean were considered to be significantly impactful to at-risk species.

We then examined the relative impacts of each scenario on both species and natural communities, in the context of impact scores, species weights, and the predicted inundation and expansion of both species and communities. This allowed is to identify communities that had disproportionate impacts on species relative to how lake-level changes affected them, and better illuminate the connections between species, communities, and the impacts of lake-level changes, for example by identifying which communities were most responsible for each species' response.

RESULTS

Objective 1: Modeling the impact of Great Lakes water levels on coastal ecosystems

Modeled lake-level scenarios

Modeled lake levels differed most from the baseline levels in the Huron-Michigan basin, receding by 23 cm under the MIROC5 scenario, and rising 49 cm under the CNRM scenario (Table 2). The Erie basin was predicted to rise 38 cm and recede by 11 cm under the CNRM and MIROC5 scenarios, respectively, while the Superior basin experienced the most minimal modeled changes, rising by 13 cm and receding by 10 cm under the CNRM and MIROC5 scenarios, respectively. Figure 11 provides an illustration of the range of outcomes across the range of lake-level scenarios at Waugoshance Point in Wilderness State Park.

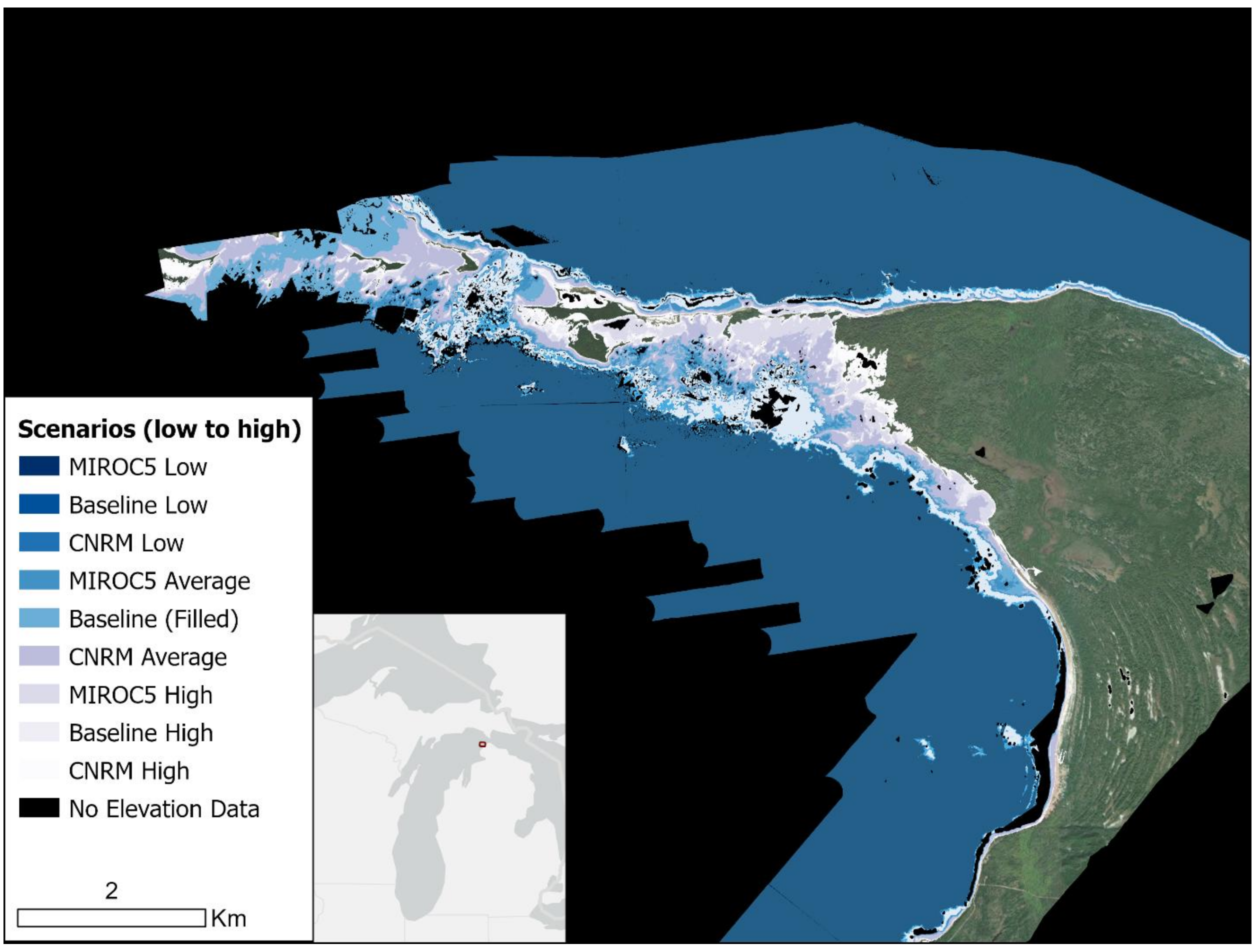

Figure 11. Waugoshance Point in Wilderness State Park, as an example of the range of inundation and expansion outcomes from the six scenarios.

Modeling coastal ecosystems

When discussing inundation and expansion of natural communities (Objective 1) and species' habitats (Objective 2), we refer to the difference between baseline and GCM scenarios by that scenario name (e.g., % change in area under 'MIROC5-Average' represents the % change under MIROC5-Average *relative* to the baseline average). Because CNRM scenarios resulted in higher lake levels relative to baseline lake levels, this translated into a loss of area for most classes, groups, and natural communities (Tables 4, A7). Conversely, the lower lake levels of all MIROC5 scenarios generally resulted in expansion of natural communities.

Table 4. Predicted inundation (negative values) and expansion (positive values) of MNFI natural community classes and groups (Cohen et al. 2025) under six scenarios. Impacts greater than 10% and the greatest impacts for a scenario when none exceeds 10% are in **bold**, as are classes and groups for which at least one scenario satisfies this condition.

Natural Community		**MIROC5**			**CNRM**		
Class	**Group**	**Average**	**High**	**Low**	**Average**	**High**	**Low**
Palustrine	Bog	0.01	0.02	0.00	-0.03	-0.05	0.00
Palustrine	**Fen**	**31.53**	6.62	0.24	-3.89	**-14.89**	-0.55
Palustrine	**Forested Wetland**	0.02	**10.68**	0.00	-0.37	**-10.98**	-0.00
Palustrine	Marsh	4.23	7.77	1.49	-2.70	**-12.42**	-2.08
Palustrine	**Shrub Wetland**	1.47	**12.74**	0.60	-0.29	**-13.62**	-0.30
Palustrine	Wet Prairie	4.78	3.35	0.00	-4.41	**-46.65**	-0.02
	Mean:	7.22	7.94	0.58	-2.03	**-15.27**	-0.80
Palustrine/Terrestrial	Wooded Dune/Swale	2.13	1.34	0.88	-0.84	-3.14	-1.62
Primary	**Bedrock Glade**	0.08	**40.35**	0.02	-0.79	-0.43	-0.02
Primary	Bedrock Grassland	0.68	0.37	0.83	-0.53	-2.99	-1.26
Primary	**Bedrock Lakeshore**	**24.37**	4.25	2.62	-2.83	-2.60	-3.37
Primary	Dunes	2.73	0.62	1.51	-1.20	-1.64	-2.86
Primary	**Inland Cliff**	1.93	**21.85**	0.33	-0.22	-0.33	-0.75
Primary	Lakeshore Cliff/Bluff	6.02	0.82	2.91	-2.02	-1.68	-3.38
Primary	**Sand/Cobble Shore**	**47.19**	**14.44**	**7.37**	**-11.75**	-4.59	**-9.50**
	Mean:	**14.37**	**14.31**	**2.60**	**-3.28**	-2.02	**-3.34**
Subterranean/Sink	Karst	0.07	0.00	0.07	0.00	-0.00	-0.07
Terrestrial	Forest	0.02	-8.50	0.01	-0.19	**-6.66**	-0.01
Terrestrial	Prairie	0.00	0.00	0.00	0.00	0.00	0.00
Terrestrial	**Savanna**	0.90	1.36	0.49	-0.91	**-12.61**	-0.99
	Mean:	0.31	5.41	0.17	-0.42	-8.09	-0.33

All scenarios except CNRM-High predicted significant inundation or expansion (>10%) for at least one primary group, with significant impacts observed sporadically in palustrine groups and rarely in terrestrial groups (Table 4). The sand/cobble shore group was consistently impacted in all non-CNRM-High scenarios, experiencing either >10% change, the highest proportional change of all groups for, or both. Among primary natural communities, limestone bedrock lakeshore and limestone cobble shore, prominent along the Niagara escarpment on the shores of northern Lakes Michigan and Huron, both experienced notable levels of inundation and expansion across scenarios, as did the broadly-distributed sand and gravel beach (Table A7). Modeled expansion under the MIROC5-High scenario was apparently also high for the bedrock glade (40.35%) and inland cliff (21.85%) groups, due to changes in northern bald (85.39%) and volcanic bedrock glade (75.51%), and volcanic cliff (86.64%), respectively. However, these communities were not allowed to expand in the model (Table A1). Other communities not allowed to expand appeared to have expanded in this (other other) scenarios, such as boreal forest (50.19% under MIROC5-High; Table A7). In these examples, the baseline scenario (USACE + 100 mm) predicted inundation, but the associated climate model scenario (MIROC5-High) predicted little to no inundation, therefore the *difference* between the two is expressed as an apparent expansion. For these natural communities, the extent of the expansion was limited to the lakeward margin of the existing natural community polygon, not beyond into topobathymetry (see Figure 5).

Palustrine groups were heavily inundated under CNRM-High, with all but the bog group experiencing over 10% change on average (Table 4). The fen, forested wetland, marsh, and shrub wetland groups all experienced between 10% and 15% inundation on average due to several natural communities in all cases. In contrast, the wet prairie group experienced 47% inundation on average, driven largely by wet prairie at 99%, although lakeplain wet and wet-mesic prairie were notable at 19% and 21% inundated, respectively (Table A7). These highly inundated wet prairie polygons occurred along Saginaw Bay, in an area where they would normally be classified as lakeplain wet prairie, so should be interpreted as such.

Twenty-four natural communities were predicted to be greatly impacted (at least 10% inundated or expanded) in one or more scenarios, including eight for which significant impacts were predicted in two or more of the six scenarios (Table A7). Coastal fen, in the fen group, was a standout under the MIROC5-Average scenario, predicted to expand by 157%, driving an average 32% expansion of the fen group of the palustrine class. Greater than 10% inundation was predicted for Great Lakes marsh under all three CNRM scenarios, the only community greatly impacted under all three scenarios under one of the GCMs.

Evaluating impacts within focal areas

Regions with significant or dramatic changes of area in response to modeled lake levels, unsurprisingly, tended to be those with shallow near-shore topography, bathymetry, or both (Table 5; Figures B1-6). The Saginaw Bay in southern Lake Huron was a standout region, characterized by a broad lakeplain associated with the Saginaw lobe of the Wisconsinan glaciation, with at least portions of the bay predicted to experience high levels of expansion or inundation in each of the six scenarios (Schaetzl et at. 2013). Other notable regions included the St. Mary’s River between Lakes Superior and Huron, Alpena and Thunder Bays in northern Lake Huron, and portions of Wilderness State Park in northern Lake Michigan.

We observed some patterns in predicted levels of inundation and expansion based on shoreline morphology. Embayments appeared equally likely to be significantly or dramatically inundated or expanded, including Alpena-Thunder Bay, Saginaw Bay, and Cheboygan in Lake Huron, and Escanaba, Grand Traverse Bay, and Wilderness State Park in Lake Michigan. Shorelines along islands showed a greater propensity for expansion, including Bois Blanc, Drummond, and Marquette Islands in Lake Huron and North Manitou Island in Lake Michigan. Drowned river mouths not in embayments were mostly inundated, including Lake Charlevoix, Lake Macatawa, and Manistee, Muskegon, and White Lakes (Ludington and Grand Haven experienced only expansion). Non-river mouth riparian areas, including the Detroit and St. Mary's Rivers, exhibited both inundation and expansion.

Table 5. Regions along Great Lakes shorelines in Michigan predicted to experience significant (> 1.5 standard deviations) expansion or inundation under six scenarios.

		MIROC5			CNRM			
Basin	**Region**	**Average**	**High**	**Low**	**Average**	**High**	**Low**	**Morphology**
Erie	Detroit River IWR		X			X		Riparian
Huron	Alpena-Thunder Bay	X			X		X	Embayment
Huron	Bois Blanc Island	X						Island
Huron	Cheboygan						X	Embayment
Huron	Drummond Island	X		X				Island
Huron	Marquette Island	X						Island
Huron	Saginaw Bay	X	X	X	X	X	X	Embayment
Huron	St. Mary's River	X		X			X	Riparian
Michigan	Escanaba	X		X				Embayment
Michigan	Grand Haven		X					River mouth
Michigan	Grand Traverse Bay						X	Embayment
Michigan	Lake Charlevoix				X			River mouth
Michigan	Lake Macatawa					X		River mouth
Michigan	Ludington	X						River mouth
Michigan	Manistee					X		River mouth
Michigan	Muskegon				X			River mouth
Michigan	North Manitou Island	X						Island
Michigan	White Lake					X		River mouth
Michigan	Wilderness SP	X					X	Embayment

To illustrate how the impacts of predicted water-level changes may vary regionally, we prepared case studies of change to natural community extent in three focal areas that represent variation of Great Lakes shoreline settings. To simplify interpretation, we limited comparisons to the mean values of all three lake-level scenarios for both MIROC5 and CNRM climate models. Results are presented for Wildfowl Bay in Saginaw Bay, which experienced consistently significant or dramatic impacts, Waugoshance Point in Wilderness State Park, which experienced significant or dramatic impacts in some scenarios, and for Drummond Island

Table 6. Percent inundation and expansion of natural communities in Wildfowl Bay, Wilderness State Park, and Drummond Island, under the mean of CNRM and MIROC5 scenarios. Positive values indicate natural community expansion, whereas negative values represent inundation. Impacts greater than 10% are in **bold**.

	MIROC5 (mean)			CNRM (mean)		
Natural community	**Wildfowl**	**Wilderness**	**Drummond**	**Wildfowl**	**Wilderness**	**Drummond**
Alvar	-	-	0.63	-	-	-1.59
Boreal Forest	-	0.84	0.17	-	-3.06	-0.56
Coastal Fen	-	**10.45**	-	-	**-15.01**	-
Dry Northern Forest	-	-	0.00	-	-	0.00
Dry-mesic Northern Forest	-	-	0.00	-	-	-0.16
Dry-mesic Southern Forest	0.30	-	-	-6.76	-	-
Emergent Marsh	0.12	1.63	0.00	**-30.12**	**-20.23**	0.00
Great Lakes Barrens	-	0.53	-	-	-2.69	-
Great Lakes Marsh	**16.98**	**41.89**	**18.45**	**-19.39**	**-15.79**	**-12.12**
Hardwood-Conifer Swamp	1.94	0.00	0.05	**-26.93**	0.00	-0.26
Interdunal Wetland	-	9.57	-	-	**-23.93**	-
Lakeplain Oak Openings	1.80	-	-	**-18.26**	-	-
Lakeplain Wet Prairie	6.56	-	-	**-18.62**	-	-
Lakeplain Wet-mesic Prairie	7.58	-	-	**-17.08**	-	-
Limestone Bedrock Glade	-	-	3.62	-	-	-2.85
Limestone Bedrock Lakeshore	-	-	4.61	-	-	-6.63
Limestone Cliff	-	-	1.15	-	-	-2.00
Limestone Cobble Shore	-	**27.24**	**36.68**	-	**-15.75**	-5.77
Mesic Northern Forest	0.00	0.00	0.03	0.00	0.00	-0.18
Mesic Southern Forest	4.03	-	-	-4.28	-	-
Northern Fen	-	0.78	13.59	-	-5.64	**-12.76**
Northern Hardwood Swamp	-	-	0.13	-	-	-0.19
Northern Shrub Thicket	3.05	0.00	0.00	**-25.62**	0.00	-0.10
Northern Wet Meadow	6.04	0.00	3.51	-2.57	0.00	-4.19
Open Dunes	-	**16.57**	-	-	**-15.52**	-
Poor Conifer Swamp	-	-	0.00	-	-	-0.35
Poor Fen	-	0.00	0.00	-	0.00	0.00
Rich Conifer Swamp	-	0.32	0.03	-	-4.95	-0.34
Rich Tamarack Swamp	-	0.00	0.02	-	0.00	0.01
Sand and Gravel Beach	-	**13.75**	**335.28**	-	**-24.10**	**19.32**
Southern Hardwood Swamp	1.52	-	-	**-14.51**	-	-
Southern Shrub-carr	6.05	-	-	**-16.77**	-	-
Submergent Marsh	-	0.00	-	-	0.00	-
Wet Prairie	0.00	-	-	**-33.09**	-	-
Wet-mesic Flatwoods	1.13	-	-	**-15.19**	-	-
Wooded Dune/Swale	-	0.00	-	-	-0.05	-

and associated islands, which experienced variable impacts (Table 6). These sites encompass diverse geomorphological conditions and habitat assemblages, including emergent marshes, dune and shoreline systems, bedrock-influenced coasts, and low-lying wetlands, and therefore capture a broad spectrum of potential ecosystem responses. Focusing on these areas allows for direct comparisons of natural community expansion and inundation patterns under contrasting climate scenarios, highlighting both shared sensitivities and site-specific differences in ecosystem response to lake-level fluctuations.

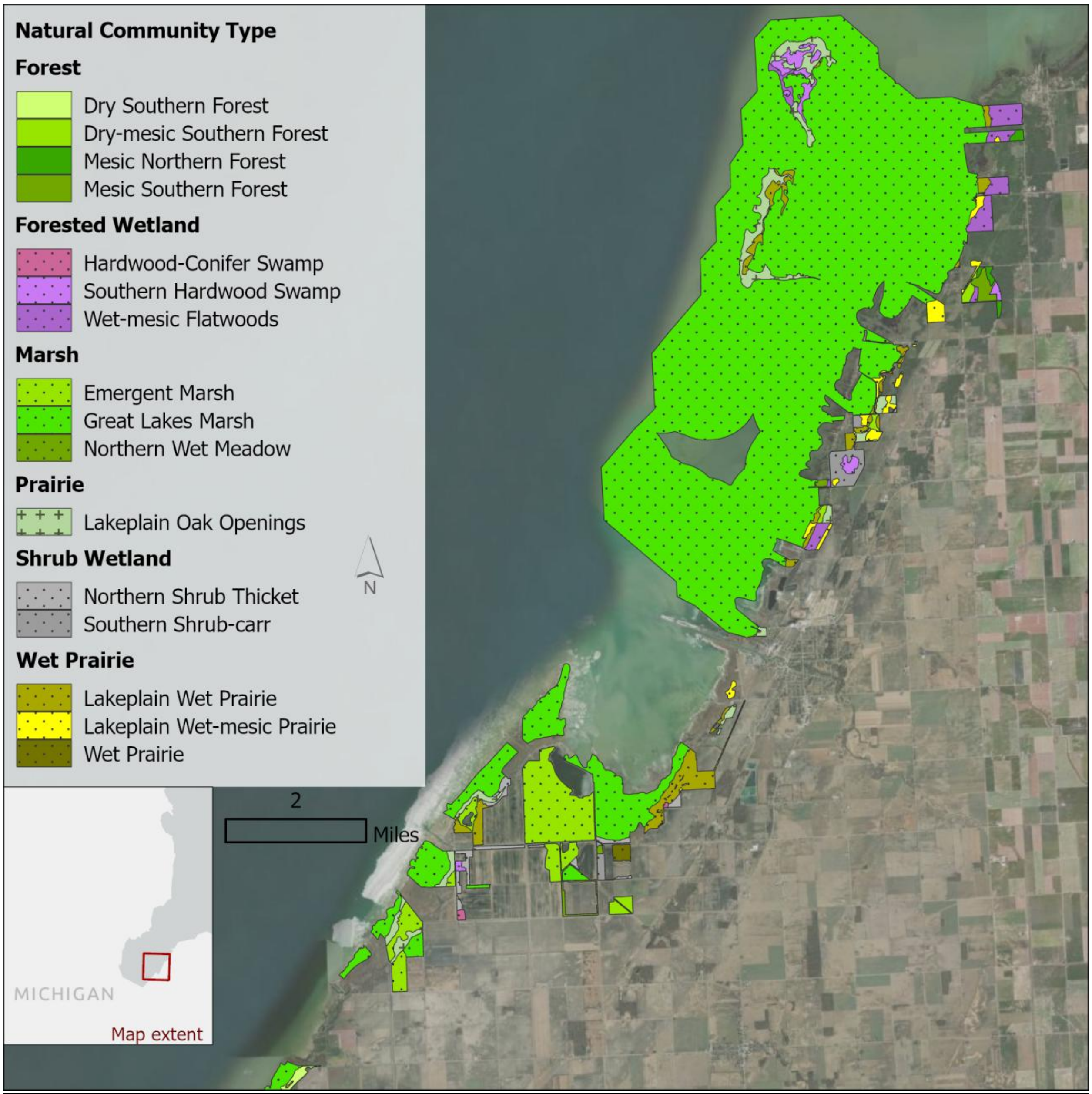

Figure 12. Natural communities documented in the Wildfowl Bay focal area.

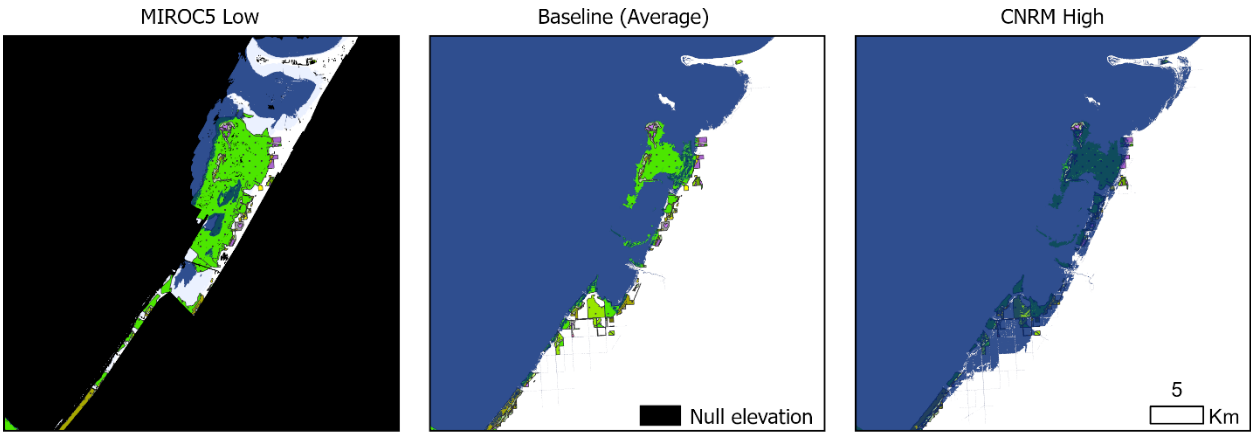

Figure 13. Inundation and expansion of natural communities at Wildfowl Bay, under average baseline conditions, the lowest water-level scenario (MIROC5-Low), and the highest water-level scenario (CNRM-High). See Figure 12 for legend to natural community type symbology. Black coloration represents areas lacking elevation data where no expansion could be modeled.

Wildfowl Bay

Great Lakes marsh was by far the most prevalent natural community at Wildfowl Bay, occupying > 80% of the modeled region (Table A8; Figure 12). Additional natural communities each occupied > 1% of the region, in decreasing abundance from 5-1% - emergent marsh, lakeplain oak opening, lakeplain wet prairie, wet-mesic flatwoods, and lakeplain wet-mesic prairie. The largest expansions in Wildfowl Bay were predicted to occur within Great Lakes marsh, which shows a 16.98% increase under the MIROC5 scenario (Table 6, Figure 13). Among prominent communities at Wildfowl Bay, notable expansions occurred within lakeplain wet prairie (6.56%) and lakeplain wet-mesic prairie (7.58%).

Significant inundation was widespread under the CNRM scenario, with 11 natural communities having > 10% of their area inundated. Predicted inundation was high for all six of the prominent natural communities, in decreasing order from emergent marsh (-30.12%) to wet-mesic flatwoods (-15.19%) and including Great Lakes marsh (-19.39%; Table 6). Less prominent communities also had significant predicted inundation, including wet prairie (-33.09%), hardwood-conifer swamp (-26.93%), northern shrub thicket (-25.62%), southern shrub-carr (-16.77%), and southern hardwood swamp (-14.51%).

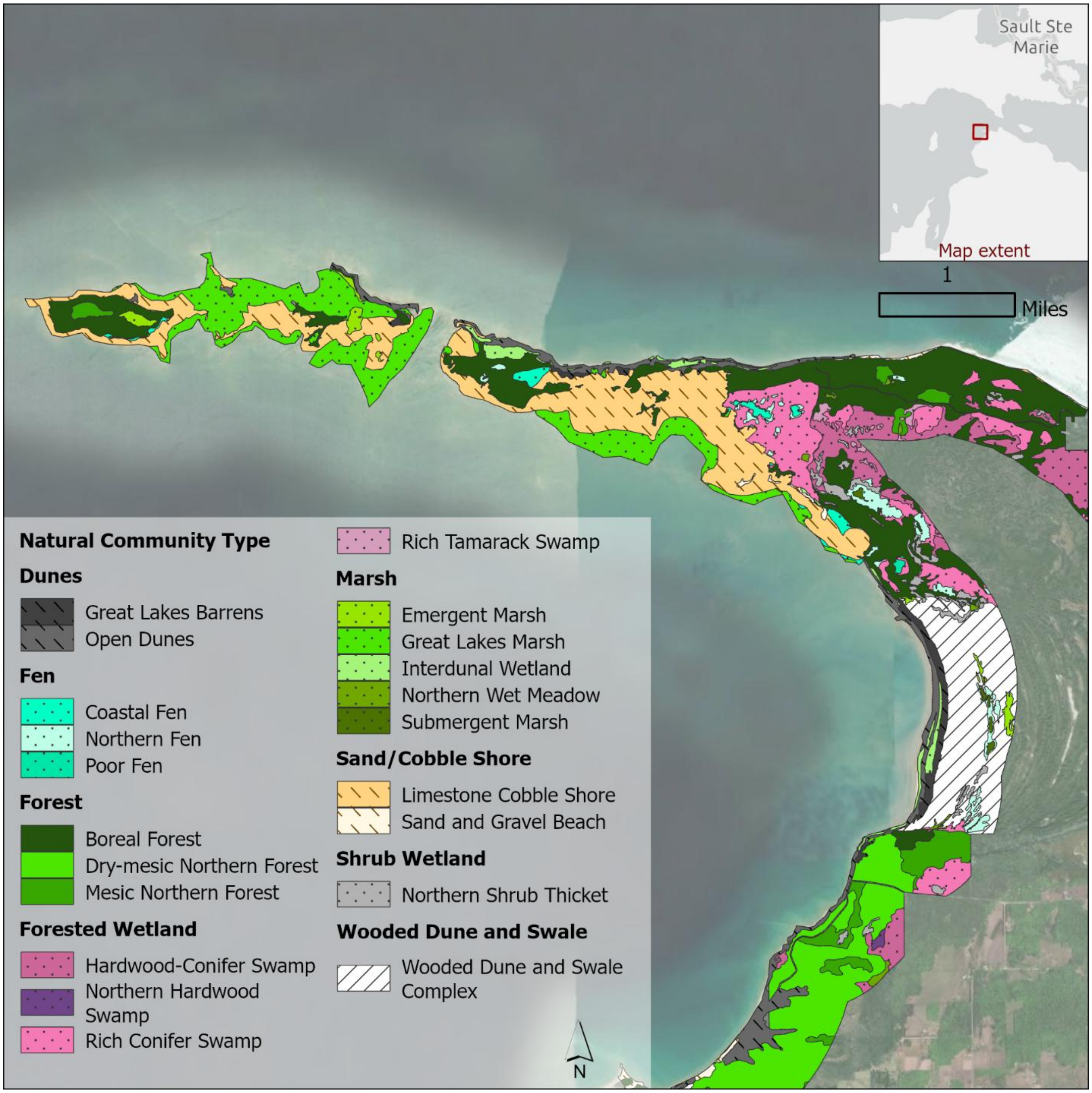

Figure 14. Natural communities documented in the Wilderness State Park focal area.

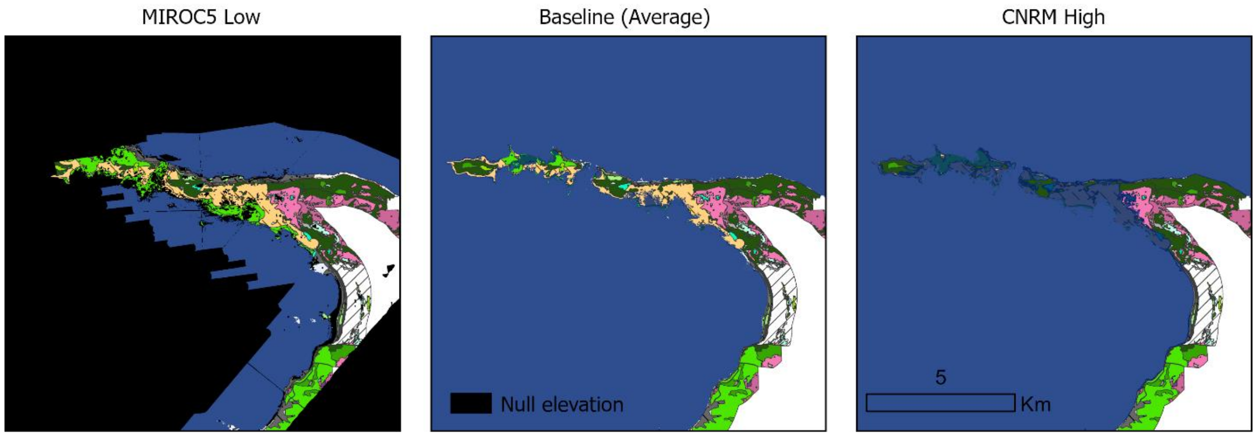

Figure 15. Inundation and expansion of natural communities at Wilderness State Park, under average baseline conditions, the lowest water-level scenario (MIROC5-Low), and the highest water-level scenario (CNRM-High). See Figure 14 for legend to natural community type symbology. Black coloration represents areas lacking elevation data where no expansion could be modeled.

Waugoshance Point (Wilderness State Park)

Great Lakes marsh was also prevalent at Wilderness State Park, occupying nearly 25% of the modeled area (Figure 14; Table A8). Boreal forest, limestone cobble shore, coastal fen, wooded dune and swale complex, and rich conifer swamp occupied 18-5% of the area in decreasing order of abundance, followed in decreasing order of abundance from 5-1% by open dunes, hardwood-conifer swamp, northern fen, northern shrub thicket, Great Lakes barrens, and interdunal wetland. The most dramatic response occurred in Great Lakes marsh, which is predicted to expand by 41.89%, representing the largest modeled expansion across all natural communities at this site (Table 6, Figure 15). Significant expansions were also predicted in limestone cobble shore (27.24%) and coastal fen (10.45%). Less prominent communities, such as open dunes (16.57%) and sand and gravel beach (13.75%), also had significant predicted expansion.

Under the CNRM scenario, largely the same community types that expanded under MIROC5 showed significant predicted inundation. The proportion of ecosystem loss was similar among three prominent communities, Great Lakes marsh (-15.79%), limestone cobble shore (-15.75%), and coastal fen (-15.01%). Predicted inundation was greater in less prominent communities, including sand and gravel beach (-24.10%), interdunal wetland (-23.93%), and emergent marsh (-20.23%).

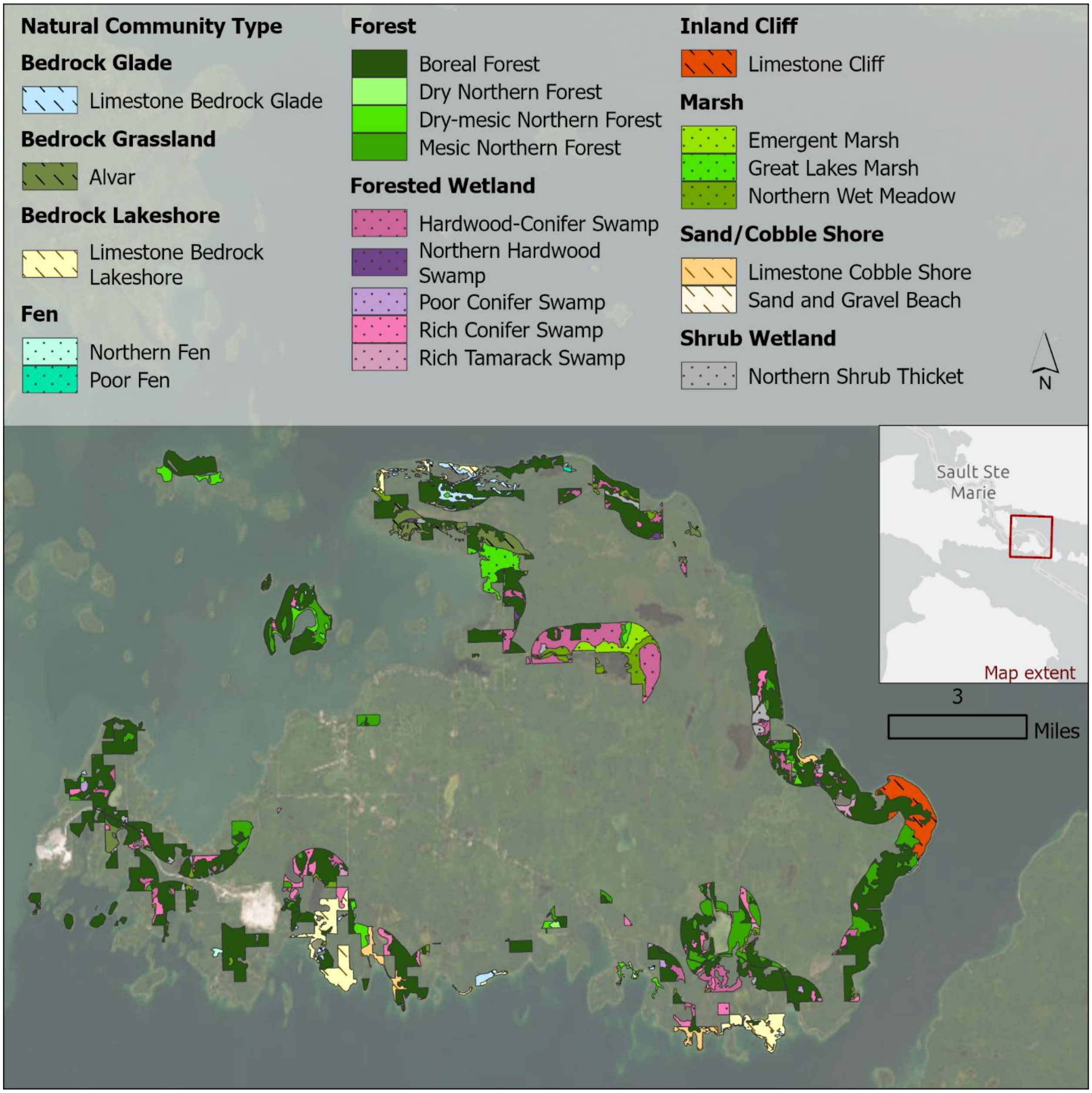

Figure 16. Natural communities documented in the Drummond Island focal area.

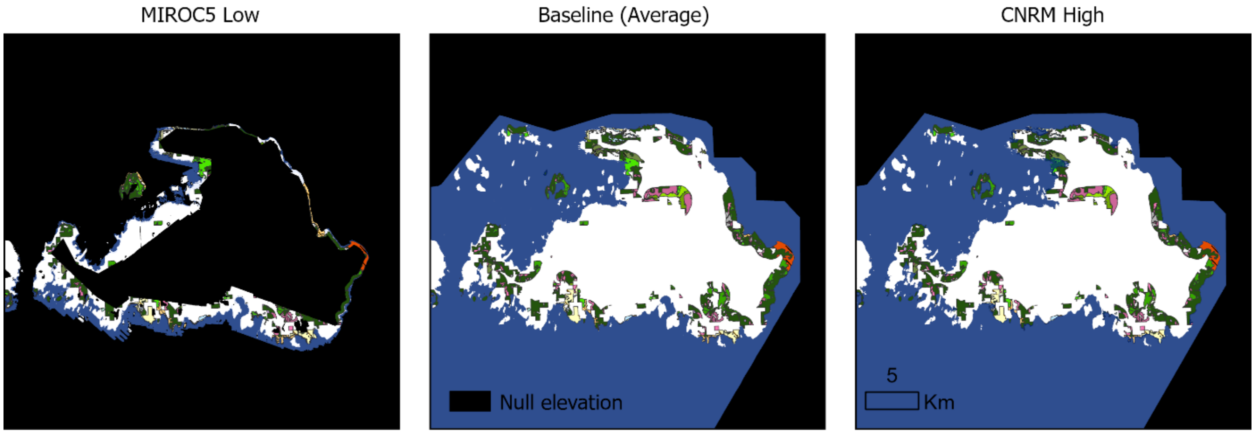

Figure 17. Inundation and expansion of natural communities at Wilderness State Park, under average baseline conditions, the lowest water-level scenario (MIROC5-Low), and the highest water-level scenario (CNRM-High). See Figure 16 for legend to natural community type symbology. Black coloration represents areas lacking elevation data where no expansion could be modeled

Drummond Island

Boreal forest was the most prevalent natural community at Drummond Island at 53%, followed in decreasing order of abundance from 9-1% by hardwood-conifer swamp, limestone bedrock lakeshore, mesic northern forest, alvar, Great Lakes marsh, northern wet meadow, rich conifer swamp, limestone cobble shore, limestone bedrock lakeshore, limestone cliff, northern shrub thicket, emergent marsh, and dry-mesic northern forest (Figure 16; Table A8). Significant expansion was predicted in two of these communities under the MIROC5 scenario, limestone cobble shore (36.68%) and Great Lakes marsh (18.45%), and in one less prominent community, northern fen (13.59%) (Table 6, Figure 17). Dramatic expansion was predicted in sand and gravel beach (335.28%), which occupied only 0.03% of the focal area and was restricted to the eastern shore of Harbor Island off the northwest shore of Drummond Island itself.

Under the CNRM scenario, significant inundation was restricted to some but not all of the same communities predicted to experience significant expansion, including Great Lakes marsh (-12.12%) and northern fen (-12.76%). Predicted inundation was moderate in two other communities, limestone bedrock lakeshore (-6.63%) and limestone cobble shore (-5.77%). Sand and gravel beach was predicted to expand by 19.32% under the CNRM scenario, which, however was erroneous. Sand and gravel beach was exclusively found on Harbor Island, which was strongly impacted by a data error that falsely predicted expansion and reversed the change sign. This data error is addressed in the Discussion as *Error 2* under *Limitations of our modeling approach and known errors.*

Objective 2: Assess how changes to coastal ecosystems will impact habitats for at-risk species

Species intersection with ecosystems

Species polygons for the 13 focal at-risk species intersected with polygons for 42 of the 68 natural communities in our ecosystem dataset (Table A3).

<u>Species by community</u>

Species varied considerably in their association with natural communities, with most species strongly associated with communities across multiple classes and groups (Table A3). Neither community class (PERMANOVA, $p = 0.54$, $R^2 = 0.07$) nor group (PERMANOVA, $p = 0.14$, $R^2 = 0.34$) predicted variation in weights across species, although there was some weak clustering of species by community class (Figure 18). Blazing star borer, eastern prairie fringed orchid, king rail, common tern, and black tern had similar weights, likely due to shared association with lakeplain wet and wet-mesic prairie, and Great Lakes marsh (Table A3). Eastern massasauga and dwarf lake iris were both frequently associated with boreal forest, and their occurrences consistently overlapped several communities with which they were weakly associated, including several hardwood and conifer swamps and northern fens, meadows, and shrub thickets (Table A3). Pitcher's thistle, Lake Huron locust, and piping plover were strongly associated with open dunes, and also clustered with Michigan monkey flower (Figure 18). These species consistently overlapped and showed weak associations with several natural communities, including several types of fens and sand and gravel beach (Table A3). Finally, Houghton's goldenrod and Hine's emerald dragonfly were both weakly to strongly associated with wooded dune and swale complexes, coastal fen, and limestone bedrock lakeshore (Table A3).

<u>By scenario</u>

Modeled impacts to at-risk species differed across scenarios within species and across species within scenarios (Table 7, Figure 19). Significant impacts (>10%) were predicted in at least one scenario for every species except Pitcher's thistle. Impacts ranged from approximately 20% inundated habitat for black tern (-20.21%) and blazing star borer (-19.70%) under CNRM-High, to more than 20% expanded habitat for dwarf lake iris (21.27%) under MIROC5-High, and for king rail (20.79%), Houghton's goldenrod (35.27%) and Hine's emerald dragonfly (105.83%) under MIROC5-Average.

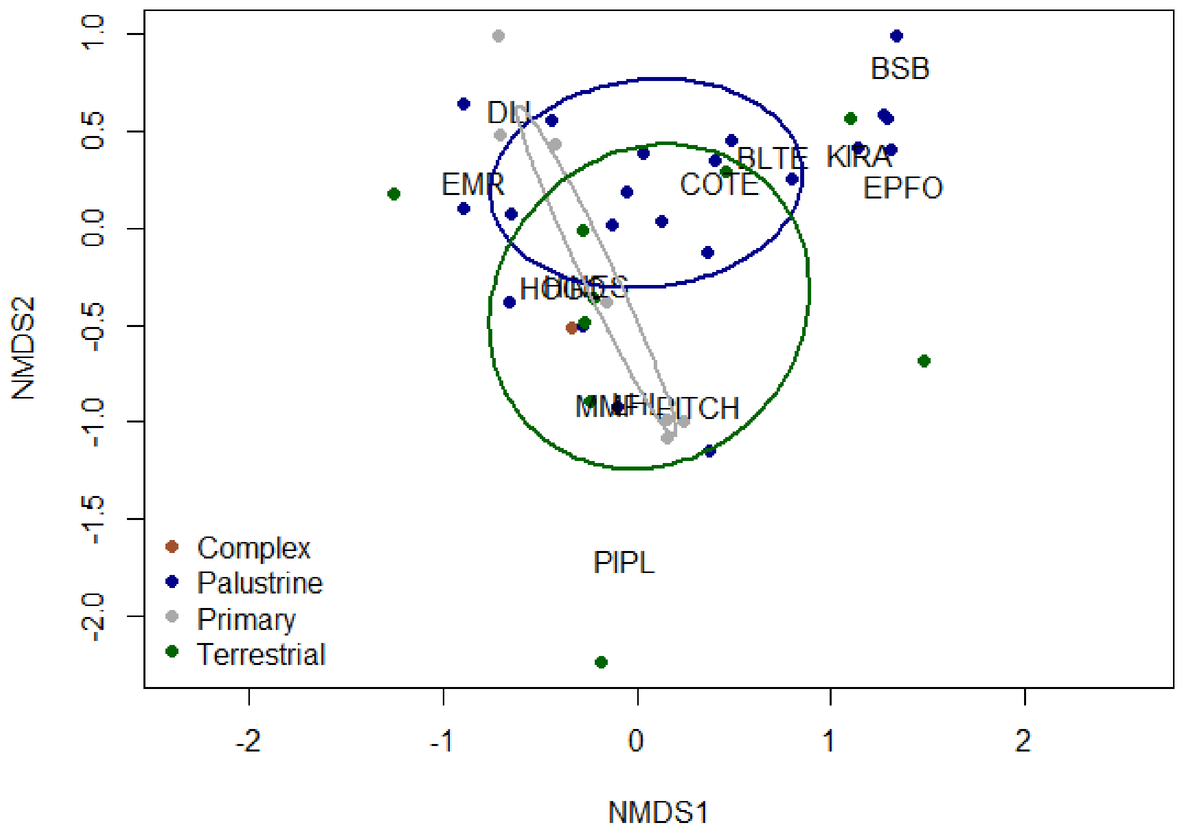

Figure 18. NMDS plot visualizing overlap of community weights of 13 at-risk species with 42 natural communities, grouped by natural community class (Complex, Palustrine, Primary, Terrestrial); K=3, Stress = 0.092, RMSE = 0.0032. See Table A3 for values. Class did not predict variation in weights across species (PERMANOVA, $p = 0.54$), but convex hulls included to aid in visualization. Complex = wooded dune and swale complex, a single community so convex hull meaningless. BLTE = black tern, BSB = blazing star borer, COTE = common tern, DLI = dwarf lake iris, EMR = eastern massasuaga, EPFO = eastern prairie fringed orchid, HINES = Hine's emerald dragonfly, HOGO = Houghton's goldenrod, KIRA = king rail, LHL = Lake Huron locust, MMF = Michigan monkey flower, PIPL = piping plover, PITCH = Pitcher's thistle. HOGO and HINES were strongly overlapping near (0,0) and LHL and MMF were strongly overlapping near (0, -1.0).

Table 7. Predicted percent change in habitat for 13 at-risk species for six climate scenarios, relative to baseline lake levels. Positive values represent habitat expansion and negative values indicate habitat inundation. Impacts greater than 10% and the greatest impacts for a scenario when none exceeds 10% are in **bold**.

		MIROC5				CNRM			
Scientific Name	**Common Name**	**Average**	**High**	**Low**	**Mean**	**Average**	**High**	**Low**	**Mean**
Charadrius melodus	Piping plover	**12.10**	2.86	2.91	5.95	-3.79	-4.26	-5.03	-4.36
Chlidonias niger	Black tern	**13.15**	5.33	3.90	7.46	-8.05	**-20.21**	-7.97	**-12.08**
Cirsium pitcheri	Pitcher's thistle	6.47	2.69	1.97	3.71	-2.12	-2.35	-3.36	-2.61
Iris lacustris	Dwarf lake iris	**12.78**	**21.27**	0.68	**11.58**	-2.30	-3.79	-1.11	-2.40
Mimulus michiganensis	Michigan monkey flower	2.50	**15.39**	1.22	6.37	-1.66	-3.29	-2.01	-2.32
Papaipema beeriana	Blazing star borer	2.75	5.04	0.00	2.60	-3.01	**-19.87**	-0.02	-7.64
Platanthera leucophaea	Eastern prairie fringed orchid	**12.86**	5.70	1.26	6.61	**-10.07**	**-18.31**	-2.47	**-10.28**
Rallus elegans	King rail	**20.79**	7.39	6.65	**11.61**	**-12.43**	**-14.69**	**-13.64**	**-13.58**
Sistrurus catenatus	Eastern massasauga	9.68	**13.77**	2.68	8.71	-5.25	-9.91	-5.26	-6.81
Solidago houghtonii	Houghton's goldenrod	**35.27**	**14.54**	2.65	**17.49**	-7.21	-6.11	-4.20	-5.84
Somatochlora hineana	Hine's emerald dragonfly	**105.83**	**15.92**	1.40	**41.05**	**-13.19**	**-15.36**	-2.55	**-10.37**
Sterna hirundo	Common tern	**16.88**	**14.78**	4.16	**11.94**	-9.10	**-11.83**	-8.24	-9.72
Trimerotropis huroniana	Lake Huron locust	**11.13**	3.34	2.97	5.81	-3.67	-4.02	-5.00	-4.23

Low water scenarios showed the least dramatic impacts, with only king rail habitat greatly impacted in both CNRM-Low (13.64% inundated habitat) and MIROC5-Low (6.65% expanded habitat). Habitats for several species were greatly impacted in the other scenarios, with six species experiencing > 10% inundation or expansion in CNRM-High or MIROC5-High, respectively, and three species experiencing > 10% inundation under CNRM-Average. The greatest number of species, nine, had habitats greatly impacted by modeled lake levels in MIROC5-Average.

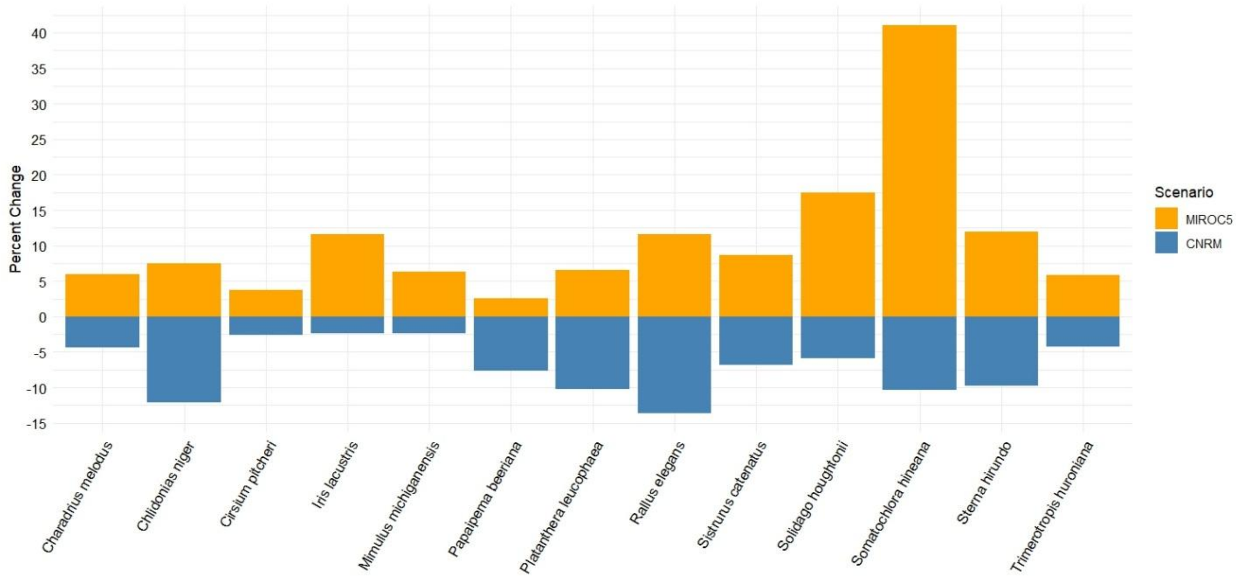

Figure 19. Mean habitat expansion (MIROC5) and inundation (CNRM) for 13 at-risk species. Percent change values are means of high, low, and average values in Table 7. See Table 7 for common names.

Across scenarios, few species clustered by area of habitat change according to Bray-Curtis similarities, but those that did were consistent with species groupings observed by habitat association (Figures 18, 20). The cluster with the greatest degree of overlap according to habitat change was Lake Huron locust, piping plover, and Pitcher's thistle. These three species also clustered together according to natural community association (Figure 18), all occurring frequently in open dunes. Other species were either not, or very loosely, clustered, and apparently randomly separated along either axis.

Pitcher's thistle was not predicted to lose or gain significant habitat, changing less than 3.50% for all but the MIROC5-Average scenario, where the species gained a moderate 6.47% of habitat area (Table 7). Significant area of habitat increase was predicted in one or two MIROC5 scenarios for piping plover, dwarf lake iris, Michigan monkey flower, eastern massasauga, Houghton's goldenrod, and Lake Huron locust, with no CNRM scenarios predicting >10% habitat loss for these species. Blazing star borer was the only species to only experience predicted habitat inundation and not expansion, losing 19.7% habitat area in CNRM-High. The remainder of the species aside from Pitcher's thistle saw mixed results, with significant gains and losses across scenarios.

Species associated with marsh habitats were roughly equally likely to gain as lose habitat (4 vs. 3 scenarios, collectively). Both black tern and king rail lost significant amounts of habitat under MIROC5 scenarios and gained significant amounts of habitat under CNRM scenarios. Species associated with meadow habitats were also roughly equally likely to gain as lose habitat (3 vs.

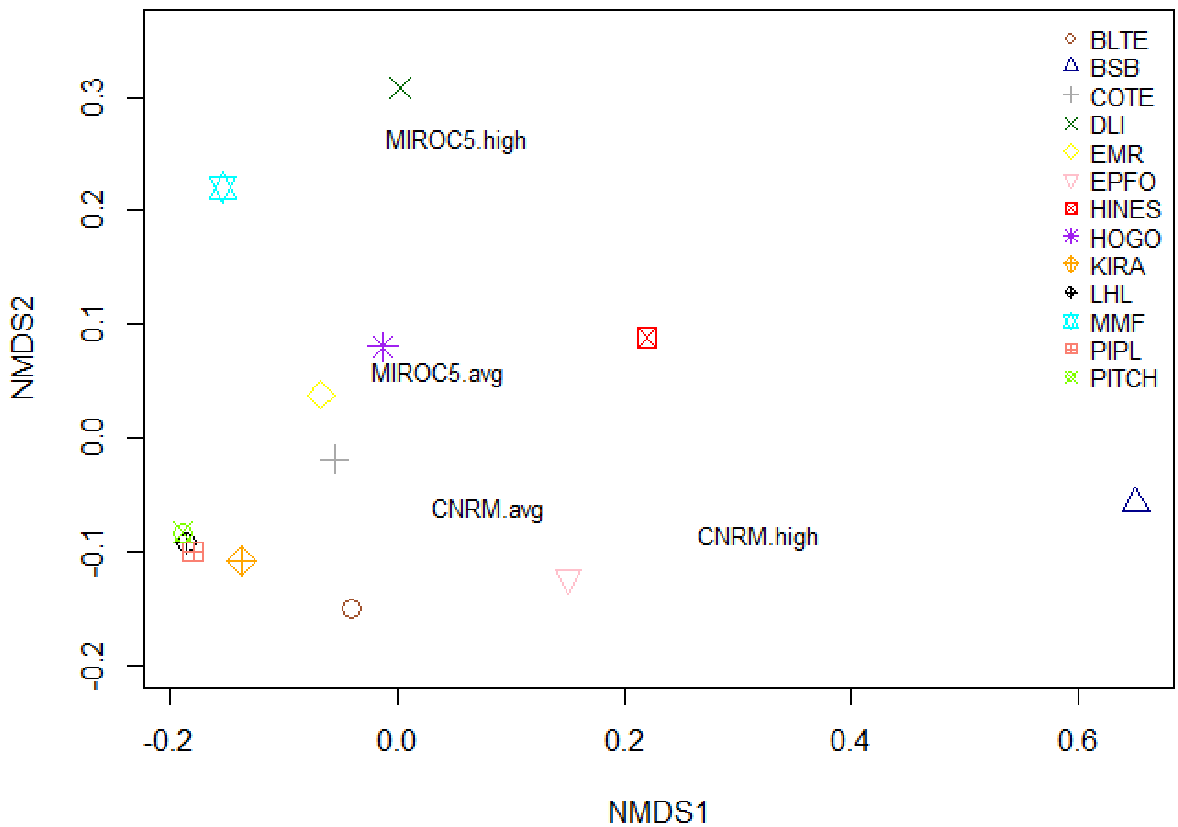

Figure 20. NMDS plot visualizing similarity in area of habitat change for 13 at-risk species across six lake level scenarios, relative to baseline scenarios; K=2, stress = 0.13, RMSE = 0.000037. BLTE = black tern, BSB = blazing star borer, COTE = common tern, DLI = dwarf lake iris, EMR = eastern massasuaga, EPFO = eastern prairie fringed orchid, HINES = Hine's emerald dragonfly, HOGO = Houghton's goldenrod, KIRA = king rail, LHL = Lake Huron locust, MMF = Michigan monkey flower, PIPL = piping plover, PITCH = Pitcher's thistle.

5). Blazing star borer, eastern prairie fringed orchid, and Hine's emerald dragonfly generally gained significant amounts of habitat under MIROC5 scenarios and lost significant amounts of habitat under CNRM scenarios. Species associated with primary habitats were more likely to gain than lose habitat, with piping plover, common tern, and Lake Huron locust gaining significant amounts of habitat under MIROC5 scenarios, and common tern losing significant amounts of habitat under CNRM-High.

Explicitly modeling species impacts

Predicted impacts under the species-based analysis were lower compared to the natural community-based analysis (i.e., less % change in area in general, with a few exceptions; Tables 8, A9). Impacts were especially restricted under the MIROC5 scenarios because we did not allow expansion of any species polygons outside mapped polygon boundaries because there was no systematic way to ensure that adjacent exposed habitat was suitable for each species. This complicated both interpretation of MIROC5 scenarios and comparisons between species-based and habitat-based analyses for MIROC5 scenarios. Consistent with the habitat-based analysis, predicted impacts were generally low for MIROC5-Low and CNRM-Low (Table A9). Significant impacts were predicted for only eastern prairie fringed orchid for MIROC5-High, and for only black tern and common tern under the MIROC-Average and CNRM-Average scenarios. In contrast, CNRM-High predicted notable inundation overall (mean = 18.14%; range = 3.09 – 54.12%), with significant inundation (>10%) for seven species and both king rail and eastern prairie fringed orchid were predicted to experience > 50% habitat inundation (Table A9).

Opportunities for dispersal, or the difference between modeled habitat area using natural community polygons and modeled occupied area using species polygons, varied among species as well (Table 8). For all species except black tern, on average across MIROC5 scenarios, modeled expanded habitat area was greater than modeled occupied area. This result should be interpreted with caution, however, given the lack of a reasonable way to estimate how species polygon area may expand. Therefore, as with natural communities that we did not allow to expand during sub-decadal time-scales between lake-level fluctuations (e.g., forests that require decades to establish, primary communities such as cliffs and glades that occur above the range of predicted lake levels), "expansion" in the species polygons was only possible out to the lakeward boundary of each polygon. We interpret this as a conservative estimate, or the minimum capacity of each population to shift in space.

Among CNRM scenarios, modeled occupied area and habitat area were very similar on average for many species, suggesting limited dispersal opportunities for those species. The average modeled difference in area was less than 1% for six species, Pitcher's thistle, dwarf lake iris, Lake Huron locust, Hine's emerald dragonfly, eastern massasauga, and piping plover, suggesting neither dispersal opportunities nor a deficit (Table 8). Modeled habitat for black tern, eastern prairie fringed orchid, king rail, and Houghton's goldenrod was 1-10% less inundated than occupied area on average, indicating notable dispersal opportunities. The remaining species, blazing star borer, eastern massasauga, and common tern, were predicted to experience a deficit in dispersal opportunities on average, albeit < 5%. Among scenarios, CNMR-High, the highest lake-levels among the six scenarios, predicted habitat-based area was greater than species-based area for 9 of 13 species (1.95 - 36.50%). In contrast, CNRM-Low predicted a dispersal deficit in all species (0.02 – 13.64%). CNRM-Average was roughly evenly split, with seven species predicted to have some dispersal opportunities, and six a dispersal deficit.

Table 8. Difference in percent change between modeled occupied area and modeled habitat for at-risk species for six climate scenarios, relative to baseline lake levels. Positive values in **bold**, indicate greater modeled habitat area vs. modeled occupied area, for both MIROC5 and CNRM scenarios, e.g., more expanded and less inundated, respectively.

		MIROC5				**CNRM**			
		Habitat-Species				**Habitat-Species**			
Scientific Name	**Common Name**	**Average**	**High**	**Low**	**mean**	**Average**	**High**	**Low**	**mean**
Charadrius melodus	Piping plover	**7.84**	-0.54	**2.40**	**3.23**	**3.40**	**2.38**	-2.95	0.94
Chlidonias niger	Black tern	-4.15	-2.81	**2.18**	-1.59	**11.60**	-1.86	-1.61	**2.71**
Cirsium pitcheri	Pitcher's thistle	**5.43**	**1.26**	**1.88**	**2.86**	0.66	**1.95**	-2.71	-0.03
Iris lacustris	Dwarf lake iris	**8.25**	**20.33**	0.67	**9.75**	-1.07	-0.70	-1.00	-0.92
Mimulus michiganensis	Michigan monkey flower	-0.43	**11.91**	**1.14**	**4.21**	**5.13**	**4.26**	-1.13	**2.75**
Papaipema beeriana	Blazing star borer	**2.75**	**2.50**	0.00	**1.75**	-2.63	**-6.26**	-0.02	**-2.97**
Platanthera leucophaea	Eastern prairie fringed orchid	**12.57**	-8.89	**1.26**	**1.64**	-5.26	**35.81**	-2.47	**9.36**
Rallus elegans	King rail	**20.79**	**5.67**	**6.65**	**11.04**	-12.43	**36.50**	-13.64	**3.48**
Sistrurus catenatus	Eastern massasauga	**9.50**	**13.63**	**2.68**	**8.60**	-5.02	**11.01**	-5.24	0.25
Solidago houghtonii	Houghton's goldenrod	**33.07**	**7.78**	**2.30**	**14.38**	0.43	**7.14**	-3.24	**1.44**
Somatochlora hineana	Hine's emerald dragonfly	**105.76**	**12.77**	**1.40**	**39.98**	-10.66	**12.76**	-2.55	-0.15
Sterna hirundo	Common tern	0.98	**10.84**	-0.64	**3.73**	**5.53**	**-4.21**	-6.62	**-1.77**
Trimerotropis huroniana	Lake Huron locust	**8.96**	-0.11	**2.41**	**3.76**	**2.32**	**3.03**	-3.16	0.73

Species responses in focal areas

The habitat-based response of at-risk species differed for each species across focal areas, between scenarios at each focal area, and across species within each scenario-focal area combination (Figures 21-23).

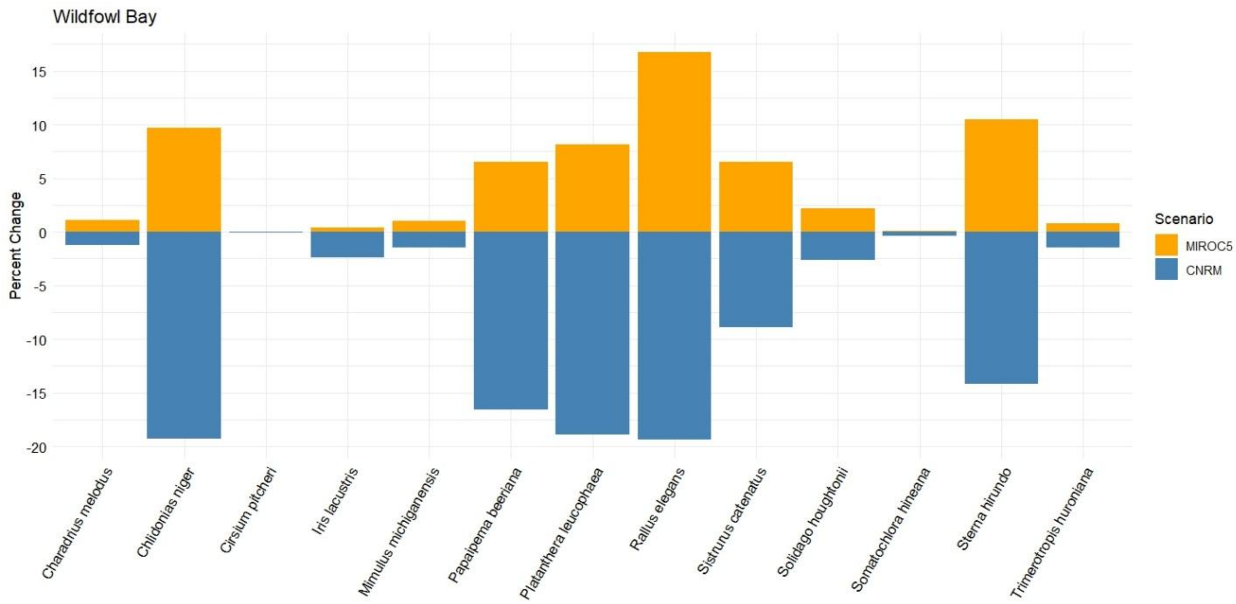

Figure 21. Mean habitat expansion (MIROC5) and inundation (CNRM) for 13 at-risk species at Wildfowl Bay. Percent change values are means of model-derived high, low, and average values. See Table A10 for raw data and common names.

Great Lakes marsh was by far the most prevalent natural community at Wildfowl Bay (>80% of the area; Table A8), with emergent marsh, lakeplain oak opening, lakeplain wet prairie, wet-mesic flatwoods, and lakeplain wet-mesic prairie also prominent (>1%). Under the MIROC5 scenario, significant habitat expansion (9.73% or more) was predicted for three species strongly linked to Great Lakes marsh (Table A3), the community that was predicted to experience the greatest amount of expansion in that focal area (16.98%; Table 6). Black tern and king rail (9.73% and 16.74%, respectively) depend upon marshes for both breeding and foraging. Common tern (10.49%) nests in primary coastal communities but utilizes marshes for foraging and rarely nesting (Nickell 1966). Significant habitat inundation was predicted for these same three species at Wildfowl Bay under the CNRM scenario, with black tern and king rail most inundated (-19.26% and -19.33%, respectively), followed by common tern (-14.15%). Significant inundation was predicted for two species associated with lakeplain prairies, blazing star borer (-16.56%) and eastern prairie fringed orchid (-18.89%).

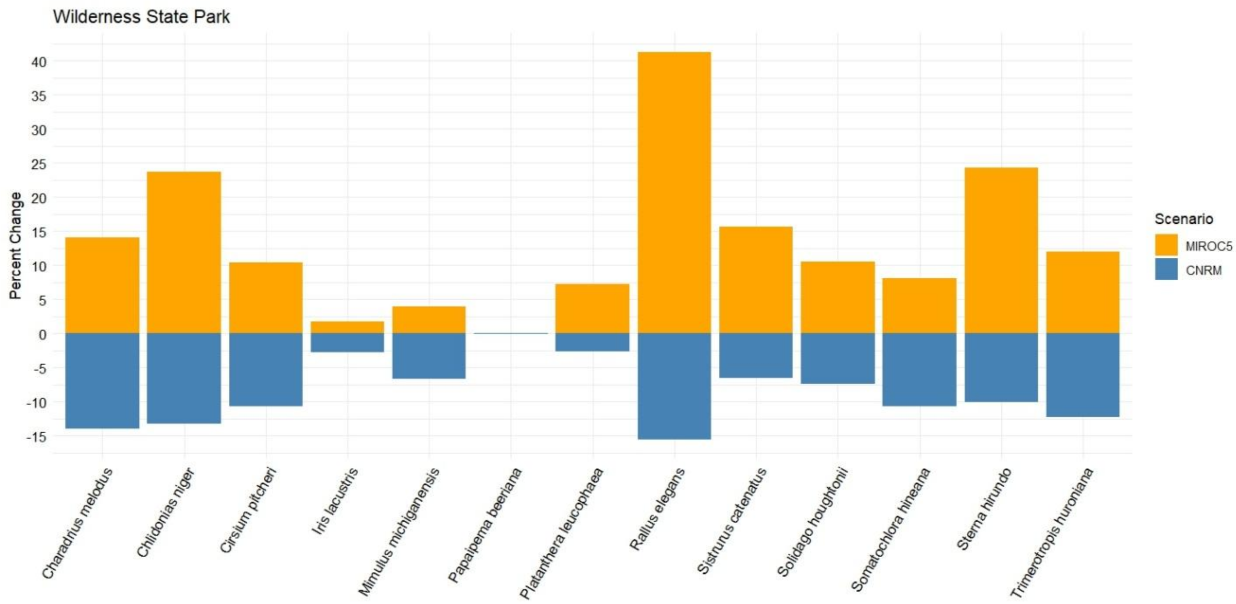

Figure 22. Mean habitat expansion (MIROC5) and inundation (CNRM) for 13 at-risk species at Waugoshance Point (Wilderness State Park). Percent change values are means of model-derived high, low, and average values. See Table A10 for raw data and common names.

Great Lakes marsh was also prevalent at Wilderness State Park, occupying nearly 25% of the modeled area, with boreal forest, limestone cobble shore, coastal fen, wooded dune and swale complex, and rich conifer swamp each occupying >5% of the area, and open dunes, hardwood-conifer swamp, northern fen, northern shrub thicket, Great Lakes barrens, and interdunal wetland occupying 1-5%. Modelling predicted significant habitat expansion for eight species under the MIROC5 scenario, especially the birds associated with Great Lakes marsh, king rail (41.23%), black tern (23.66%), and common tern (24.34%). Species strongly associated with open dunes were also predicted to gain habitat, specifically piping plover (14.07%), Lake Huron locust (11.95%), and Pitcher’s thistle (10.38%). Finally, significant gains were predicted for eastern massasauga (15.66%) and Houghton’s goldenrod (10.54%), two species linked to habitat complexes including wooded dune and swale complex and boreal forest. Most of the same species were predicted to lose significant habitat area under the CNRM scenario, including king rail (-15.54%), black tern (-13.31%), common tern (-10.08), piping plover (-13.98%), Lake Huron locust (-12.29%), and Pitcher’s thistle (-10.68%). In addition, Hine’s emerald dragonfly, closely linked to coastal fen, was predicted to lose 10.74% of habitat area.

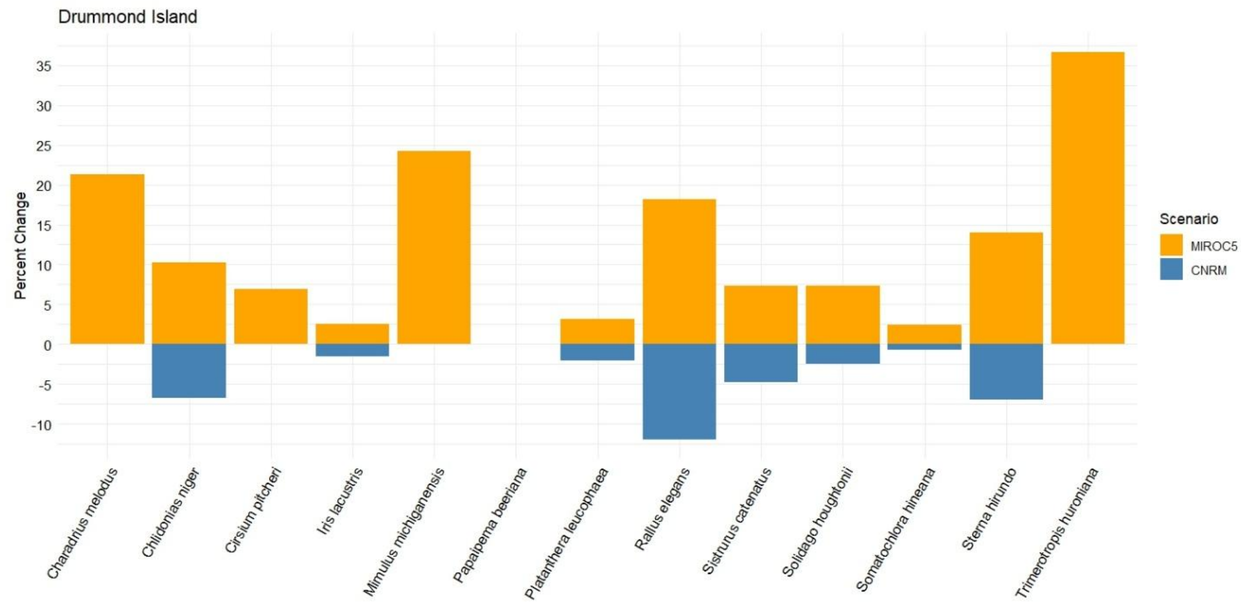

Figure 23. Mean habitat expansion (MIROC5) and inundation (CNRM) for 13 at-risk species at Drummond Island. Percent change values are means of model-derived high, low, and average values. See Table A10 for raw data and common names.

Boreal forest was the most prevalent natural community at Drummond Island at >50%, while hardwood-conifer swamp, limestone bedrock lakeshore, mesic northern forest, alvar, Great Lakes marsh, northern wet meadow, rich conifer swamp, limestone cobble shore, limestone bedrock lakeshore, limestone cliff, northern shrub thicket, emergent marsh, and dry-mesic northern forest each occupied >1%. Significant habitat expansion was predicted for six species under the MIROC5 scenario. Birds associated with Great lakes marsh were again predicted to gain habitat area, specifically king rail (18.16%), common tern (13.96%), and black tern (10.26%). The largest gains were predicted for open-dunes-associated Lake Huron locust (36.65%), with piping plover also gaining habitat (21.33%). Largely associated with rich conifer swamp, Michigan monkey flower gained a predicted 24.23% of habitat area. Significant habitat inundation under the CNRM scenario was restricted to a single species, king rail (-11.93%).

Objective 3: Identify conservation priorities

Among 42 natural communities associated with impacts to at-risk species, 12 communities disproportionately impacted habitat change under at least one scenario on average (mean rank-order value for MIROC5, CNRM, or overall < value of one standard deviation from the mean; Table 9). Among these twelve, seven were palustrine natural communities – Great Lakes marsh, coastal fen, lakeplain wet prairie, interdunal wetland, emergent marsh, northern shrub thicket, and northern wet meadow; four were primary natural communities – open dunes, limestone cobble shore, sand and gravel beach, and limestone bedrock lakeshore; and the twelfth was wooded dune and swale complex which includes a diverse mix of terrestrial and palustrine communities.

The importance of each natural community for species outcomes, the impact score, was due to varied combinations of the degree of inundation and expansion across scenarios and how strongly associated at-risk species were with that community. Great Lakes marsh was apparently the natural community most strongly linked to species' habitat outcomes, with the highest impact score in all three CNRM scenarios and MIROC5-Low, and the second highest in MIROC5-Average and MIROC5-Low. This is due both to significant inundation (mean = -13.71% across CNRM scenarios) and expansion (mean = 11.76% across MIROC5 scenarios), combined with widespread association with species. Ten species had at least a weak association with Great Lakes marsh (>1%), and four of those – black tern, king rail, eastern massasauga, and common tern – were more strongly associated with Great Lakes marsh than with any other communities (Table A3).

Changes to open dune and wooded dune and swale complex appeared to significantly impact habitats largely due to strong associations with species, despite minimal inundation and expansion. Four species had at least a weak association with open dunes, three of which were most strongly associated with that community than any other – piping plover, Pitcher's thistle, and Lake Huron locust (Table A3). Eight species were at least weakly associated with wooded dune and swale complex and Houghton's goldenrod was most strongly associated with that community (Table A3). Open dunes and wooded dune and swale complex were predicted to be neither strongly inundated (mean = -3.11% and -1.87%, respectively, across CNRM scenarios) nor expanded (mean = 2.94% and 1.45%, respectively, across MIROC5 scenarios) (Table A7).

The importance of coastal fen, limestone cobble shore, and limestone bedrock lakeshore to at-risk species overall appeared to be attributable more to the extent of expansion (mean = 59.13%, 62.69%, and 31.63%, respectively, across MIROC5 scenarios) rather than species association (mean weights of 5.63, 2.06, and 0.64, respectively). Hine's emerald dragonfly was most strongly associated with coastal fen than other communities, boosting the impact scores of that community.

The remainder of the most important natural communities were impactful due to a mix of weak to moderate species associations (associated with multiple species but weights generally < 0.10) in combination with weak to strong inundation and expansion (generally 1-10% on

Table 9. Natural communities ranked by how their degree of inundation or expansion translate to impacts for at-risk species. Rank order for each scenario (1=highest) according to “impact score” ($\overline{species\ weights}_{community_x} * \%change_{community_x}$; Tables A3, A5-6). Communities in **bold** - mean rank order for MIROC5, CNRM, or overall < one standard deviation from the mean (MIROC5, μ= 21.5, σ = 10.95; CNRM, μ= 21.5, σ = 11.05; overall, μ= 21.5, σ = 10.67).

	MIROC5				CNRM					
Natural community	**Avg**	**High**	**Low**	**Mean**	**Avg**	**High**	**Low**	**Mean**	**Overall Mean**	**Mean Weight**
Great Lakes Marsh	2	2	1	1.67	1	1	1	1.00	1.33	22.59
Coastal Fen	1	4	6	3.67	2	4	5	3.67	3.67	5.63
Open Dunes	5	11	2	6.00	5	6	2	4.33	5.17	12.53
Limestone Cobble Shore	3	10	3	5.33	4	12	4	6.67	6.00	2.06
Lakeplain Wet Prairie	4	7	17	9.33	3	2	12	5.67	7.50	7.12
Wooded Dune and Swale Complex	9	12	5	8.67	7	8	6	7.00	7.83	7.70
Sand and Gravel Beach	7	13	4	8.00	6	16	3	8.33	8.17	1.91
Interdunal Wetland	8	14	7	9.67	8	13	7	9.33	9.50	2.31
Emergent Marsh	10	17	11	12.67	10	7	9	8.67	10.67	1.88
Northern Shrub Thicket	11	8	8	9.00	17	11	11	13.00	11.00	1.30
Limestone Bedrock Lakeshore	6	16	10	10.67	11	20	8	13.00	11.83	0.64
Northern Wet Meadow	12	6	13	10.33	12	25	13	16.67	13.50	0.64
Submergent Marsh	13	24	19	18.67	18	5	18	13.67	16.17	0.96
Lakeplain Wet-mesic Prairie	17	5	26	16.00	9	3	42	18.00	17.00	6.14
Boreal Forest	42	1	14	19.00	15	17	15	15.67	17.33	6.82
Hardwood-Conifer Swamp	15	15	25	18.33	14	18	23	18.33	18.33	1.21
Northern Fen	16	23	15	18.00	25	15	19	19.67	18.83	0.40
Lakeplain Oak Openings	20	27	18	21.67	20	14	16	16.67	19.17	0.23
Limestone Bedrock Glade	14	20	24	19.33	13	26	20	19.67	19.50	0.87
Rich Conifer Swamp	41	3	23	22.33	16	10	25	17.00	19.67	7.09
Great Lakes Barrens	18	32	12	20.67	21	29	10	20.00	20.33	1.06
Mesic Northern Forest	39	9	16	21.33	19	27	17	21.00	21.17	3.49
Dry-mesic Northern Forest	21	25	21	22.33	24	28	21	24.33	23.33	1.31
Dry-mesic Southern Forest	23	31	20	24.67	26	22	22	23.33	24.00	0.75
Open Water	40	21	9	23.33	30	35	14	26.33	24.83	0.30
Floodplain Forest	25	30	30	28.33	23	9	40	24.00	26.17	0.83
Dry Northern Forest	19	34	27	26.67	22	30	26	26.00	26.33	0.78
Wet-mesic Flatwoods	29	18	41	29.33	27	19	29	25.00	27.17	0.46
Southern Shrub-carr	24	19	28	23.67	31	23	38	30.67	27.17	0.11
Limestone Lakeshore Cliff	22	35	22	26.33	32	36	24	30.67	28.50	0.01
Northern Hardwood Swamp	27	26	31	28.00	28	24	39	30.33	29.17	0.20
Southern Hardwood Swamp	26	29	42	32.33	29	21	28	26.00	29.17	0.22
Poor Fen	31	33	36	33.33	34	31	27	30.67	32.00	0.02
Rich Tamarack Swamp	37	22	34	31.00	38	38	35	37.00	34.00	0.05

Natural community	MIROC5 Avg	High	Low	Mean	CNRM Avg	High	Low	Mean	Overall Mean	Mean Weight
Poor Conifer Swamp	38	28	33	33.00	36	34	36	35.33	34.17	0.04
Bog	28	36	29	31.00	33	39	41	37.67	34.33	0.14
Mesic Southern Forest	30	37	37	34.67	35	37	33	35.00	34.83	0.00
Oak-Pine Barrens	33	40	32	35.00	40	33	37	36.67	35.83	0.19
Pine Barrens	32	38	35	35.00	37	40	34	37.00	36.00	0.00
Wet Prairie	35	42	39	38.67	41	32	31	34.67	36.67	0.00
Inundated Shrub Swamp	34	39	38	37.00	39	42	32	37.67	37.33	0.00
Intermittent Wetland	36	41	40	39.00	42	41	30	37.67	38.33	0.00

average across scenarios). In some of these instances a single species association or scenario contributed disproportionately, boosting the impact score. For example, eastern prairie fringed orchid was most strongly associated with lakeplain wet prairie (weight = 62.99), one of only 5 species associated with that community. Significant expansion of northern wet meadow was predicted under MIROC5-High (49.21%), with notably lower average expansion (mean = 17.75% across MIROC5 scenarios) and inundation (mean = -3.37% across CNRM scenarios) and no significant species associations.

Other communities ranked lower on average, despite strong associations with at least one species or significant inundation and expansion in at least one scenario, but otherwise minimal species associations and habitat change. For example, Michigan monkey flower was most strongly associated with rich conifer swamp, but inundation (mean = -0.93% across CNRM scenarios) and expansion (mean = 6.97% across MIROC5 scenarios) were generally limited in that community.

Habitat expansion or inundation of multiple communities were clearly responsible for predicted habitat gains and losses for each species; however, in many cases the fate of most species can be attributed to the most impactful communities identified in Table 9. The at-risk species predicted to gain the most habitat under MIROC5 scenarios, in declining order of habitat expansion, are king rail, black tern, common tern, eastern prairie fringed orchid, blazing star borer, and Hine's emerald dragonfly (Table 7). The modeled impacts to king rail, black tern, and common tern habitats are apparently tightly linked to the fate of Great Lakes marsh, with which all three species are strongly associated. Expansion of lakeplain wet prairie is likely the strongest driver of expanded habitat for eastern prairie fringed orchid and blazing star borer, whereas coastal fen is most tightly linked to outcomes for Hine's emerald dragonfly. We explore conservation priorities in more detail in the Discussion (*Recommended conservation priorities*).

DISCUSSION

As the effects of climate change intensify over the course of the 21st century, the amplitude, frequency, and direction of Great Lakes water-level changes are predicted to exceed previously observed extremes (Gronewold et al. 2013, Notaro et al. 2015a). Whether future lake-levels will trend higher or lower than baseline levels is unclear, leading to considerable uncertainty in how fluctuations will impact at-risk species that utilize or depend on coastal ecosystems.

Here, we modeled how fluctuating lake levels under two global climate models would affect nearshore ecosystems, and as a result, at-risk species. Below, we distill our model results into insights that we hope can form the foundation for actionable recommendations and inspire future research and monitoring that lead to more refined conclusions. First, we summarize the patterns among species and across coastal regions. Our model was a simplified first step in this effort, so we discuss how incorporating greater ecological, demographic, and analytic complexity into our model could refine the predictive value of future models. Then, we provide guidance on how best to translate our results into concrete management recommendations.

Species habitat responses

The predicted responses of potential habitats for at-risk species to Great Lakes water-level fluctuations over the coming decades ranges from significant habitat gain to significant loss, with limited impacts predicted for some species. Significant impacts are predicted under a range of contexts, including when a species is strongly associated with a single highly impacted natural community, weakly to moderately associated with multiple highly impacted communities, or strongly associated with multiple weakly to moderately impacted communities. In many cases, we highlight specific aspects of some species' biology that contextualize predicted responses to lake levels. We discuss specific contexts not accounted for in the model in a later section (see *Effects of Great Lakes water level fluctuations that are not accounted for in our model*).

Because the CNRM climate model consistently predicts higher lake-levels and the MIROC5 climate model consistently predicts lower lake-levels, the fate of at-risk species may depend on which climate model is more accurate. In general, species largely associated with nearshore palustrine ecosystems were predicted to both lose the most habitat under CNRM scenarios and gain habitat under MIROC5 scenarios, while species associated with habitat complexes gained the most habitat and lost little. None of the species predicted to gain or lose substantial amounts of habitat are entirely restricted to coastal ecosystems in Michigan. In contrast, the three species that are – piping plover, Pitcher's thistle, and Lake Huron locust – saw the least amount of predicted change in habitat area due to fluctuating Great Lakes levels.

Which species are predicted to lose habitat?

Species associated primarily with palustrine marsh and meadow ecosystems exhibited substantial predicted habitat losses across CNRM scenarios, reflecting the tendency for these natural communities to experience inundation with elevated lake levels. Predicted habitat loss across CNRM scenarios was highest (mean inundation >10%) for king rail and black tern, species that in Michigan rely on marsh habitats such as Great Lakes marsh for both nesting and foraging. It is not clear, however, whether the extent of inundation predicted by our model constitutes habitat loss or habitat gain. At first glance, greater inundation of marshes could be thought of as increasing habitat for marsh birds. In fact, recent monitoring data and associated modeling has indicated that the recent high water-level period (2018-2021) led to increases in marsh bird populations, in large part due to the increase in open water-vegetation interspersion and open water extent (Grand et al. 2020, Tozer et al. 2024). However, breeding bird density and diversity in marshes have been found to be greatest when emergent plant cover to open water ratios are approximately 50:50 (Weller and Spatcher 1965, Weller and Fredrickson 1973). Thus, extensive inundation, both in depth and duration, may decrease the availability of emergent and submergent vegetation enough to reduce habitat suitability overall. Furthermore, inundation beyond the extent observed in 2018-2021, a reasonable expectation by the end of the 21st century, may further reduce overall habitat suitability by replacing large portions of emergent and submergent zones with deep, open water.

Common tern nests in sparsely vegetated nearshore primary communities, such as sand and gravel beach, and uses adjacent open areas of the Great Lakes and coastal marshes for foraging. Mean inundation of common tern habitat across CNRM scenarios was nearly 10%. Even if increased inundation in coastal marshes increases foraging opportunities for common tern, the inundation of nesting habitat in primary natural communities along coasts and on islands slightly above mean lake levels comprises a clear threat to habitat suitabiity.

Eastern prairie fringed orchid, and to a lesser degree blazing star borer, are also among the species predicted to lose significant habitat under CNRM scenarios. In Great Lakes coastal areas, both species are restricted to lakeplain prairie communities. These communities occur from the Saginaw Bay to Lake Erie in broad, level glacial lake plains that extend inland from Great Lakes shorelines for several miles with little elevation change. As a result, large portions of habitat could be inundated with limited lake-level increase. Hine's emerald dragonfly is also restricted to glacial lakeplains and is predicted to lose >10% of habitat area under CNRM scenarios. The inundation-prone coastal fens that support most of this species' occurrences are found in narrow portions of lakeplain in the Straits of Mackinac region over limestone substrates of the Niagara escarpment. The hydrologic regime and nutrient cycles of coastal fens are primarily groundwater-driven with a minimal influence from wave action, but are fundamentally tied to the influence of Great Lakes levels on the water table (Cohen et al. 2025).

Which species are predicted to gain habitat?

Species associated with habitat complexes that include a mixture of terrestrial (primarily forested), palustrine, and primary coastal communities generally showed little vulnerability to habitat loss and significant potential for habitat gain. Both dwarf lake iris and Houghton's goldenrod were predicted to gain >10% of habitat area on average across MIROC5 scenarios. These species typically occupy a broader ecological niche so when some habitat is significantly inundated, additional minimally impacted natural communities likely provide a refuge for these species, including a mix of forested and non-forested, wetland and upland, and primary and non-primary natural communities. These clonal species have a high degree of shared association with boreal forest, wooded dune and swale complexes, limestone cobble shore and bedrock lakeshore, and Great Lakes marsh. The rhizomatous growth of these species supports both continued growth or persistence in landward habitat patches, and in minimally inundated habitat where non-inundated portions of a clone can allocate resources to inundated vegetation. Boreal forest and wooded dune and swale complex were not significantly inundated across CNRM scenarios, limiting habitat loss, and at the same time much of the predicted habitat gain for these species appears to be from expansions of limestone cobble shore and limestone bedrock lakeshore across MIROC5 scenarios.

Eastern massasauga and Michigan monkey flower have habitat associations that overlap those of dwarf lake iris and Houghton's goldenrod, and are predicted to gain >10% in the MIROC5-High scenario, despite gaining <10% of habitat area on average *across* MIROC5 scenarios (8.71% and 6.37%, respectively). Eastern massasauga is associated most strongly with Great Lakes marsh and boreal and floodplain forests, and Michigan monkey flower is associated most strongly with rich conifer swamp and mesic northern forest but also somewhat with Great Lakes marsh and sand and gravel beach. These species likely can rely on non-inundated ecosystems during high water, but may benefit somewhat from expansion of Great Lakes marsh and sand and gravel beach during low water. Eastern massasauga may be especially adaptable, able to take advantage of new foraging and breeding sites, as well as hibernacula for overwintering. Michigan monkey flower is known to disperse through fragmented clones (not via rhizomes as with Houghton's goldenrod and dwarf lake iris), but the rates at which those fragments contribute to population expansion are not known (Stone et al. 2026b).

Some species that are predicted to lose significant amounts of habitat under CNRM scenarios are also predicted to gain habitat under MIROC5 scenarios. Hine's emerald dragonfly in particular, predicted to lose > 10% of habitat area under CNRM scenarios on average, was predicted to gain > 40% of habitat area under MIROC5 scenarios on average. The coastal fen natural community that provides the bulk of habitat for the Hine's emerald dragonfly is both susceptible to inundation and has the potential to expand into lakeplains where they occur, especially when previous high water levels led to canopy mortality in landward swamps and facilitated more open conditions (Cuthrell 1999b). Similarly, eastern prairie fringed orchid was predicted to gain >10% habitat area in the MIROC5-Average scenario, despite a mean expansion of 6.61% across all MIROC5 scenarios. Just as the flat landscape this species occurs in makes its habitat inundation-prone, the limited elevation change in the lakeplain prairies supporting this species provides ample habitat area for expansion with lake-level recession.

Finally, the same marsh-associated birds that were predicted to lose significant habitat under CNRM scenarios were predicted to gain significant habitat under MIROC5 scenarios. Habitat loss and gain for king rail, black tern, and common tern appears strongly linked to inundation and expansion of Great Lakes marsh, especially for king rail which is associated almost exclusively with this natural community in the coastal zone. Just as inundation may represent habitat gain, expansion may represent habitat loss, or at least a decline in habitat suitability. For example, extreme drops in lake-levels may reduce the interspersion of emergent vegetation and open water, lower water levels below preferred depths, and eliminate vegetation structural characteristics necessary for nesting or foraging (Currier 2000, Rabe 2001).

Which species are predicted to lose or gain little habitat?

Species associated with primary coastal communities (i.e., beaches, dunes, and bedrock systems like cobble shores) experienced limited predicted habitat gains under low-water scenarios and limited habitat losses under high-water scenarios. Because these habitats are disturbance-maintained and naturally reset by fluctuating lake levels, species occupying them are adapted to, and in some cases dependent upon, even the most minimal periodic exposure and reworking of shoreline environments.

A single species, Pitcher's thistle, was predicted to neither lose nor gain significant amounts of habitat, <4% on average across both CNRM and MIROC5 scenarios. Furthermore, there were minimal differences in the habitat- vs. species-based analysis indicating neither dispersal opportunities nor deficits. That suggests the fate of this species, which is strongly tied to open dunes and dune-associated ecosystems like Great Lakes barrens, may not be determined by lake-level fluctuations, but by other factors such as climate change effects (excluding lake-level fluctuations), competition with invasive plant species, and seed predation by non-native insects (Vitt et al. 2010, Havens et al. 2012). However, our model did not take into account the erosive effects of high lake-levels, which can undercut the lakeward dune face, which Vitt et al. (2024) implicate as a primary threat to Pitcher's thistle.

Piping plover and Lake Huron locust are both also strongly associated with open dunes. Predicted loss and gain of habitat was <6% on average across CNRM and MIROC5 scenarios for both. A single scenario, MIROC5-Average, predicted >10% expansion for both species. The plover and the locust are both more strongly associated than Pitcher's thistle with sand and gravel beach, a community that was predicted expand significantly (>10%) on average across MIROC5 scenarios. Piping plover in particular is dependent on expansive, protected sections of sand and gravel beach for nesting (Hyde 1999).

The link between natural community and species responses

Although primary natural communities experienced greater predicted inundation and expansion on average in all but the CNRM-High scenario, the communities that were most impactful to at-risk species were often palustrine natural communities. Inundation and expansion was most extensive and frequent for species associated with Great Lakes marsh, coastal fen, lakeplain wet prairie, and related communities. Compared to primary communities, these palustrine systems are collectively more widespread along Great Lakes coasts in Michigan and therefore more broadly characterize Great Lakes coastal environments. Perhaps most importantly, these communities are vital for absorbing and moderating lake-level fluxes and maintaining near-shore hydrology, nutrient flows, and other ecosystem functions. In other words, inundation and expansion is central to the identity of these communities.

There is often a shelf of bedrock or sandy lake bottom that extends into the Great Lakes, certainly during average and high lake levels, but even under low lake levels. Primary communities like limestone lakeshore communities and sand and gravel beach contributed to habitat loss for some species when inundated, but provided the biggest impact through their capacity to "expand" into that shelf during low-water conditions. In particular, species occurring in habitat complexes that were largely unaffected by inundation under high-water conditions saw habitat increases with the expansion of primary communities during lake-level recession. Finally, open dunes provide a large proportion of habitat for species including Pitcher's thistle, Lake Huron locust, and piping plover, but was not significantly inundated or expanded in any of the six scenarios we modeled. The apparent stability of open dunes in our model was central to the modeled population stability of these species. This apparent stability may appear paradoxical, as dune systems are fundamentally dynamic, requiring repeated patterns of erosion and sand accumulation to maintain open, treeless conditions. Yet, it is that dynamism, characterized by shifting geomorphology, that maintains the stability of the system in the places where they occur.

Responding to regional variation of impacts to ecosystems and species

The efficacy of conservation efforts is augmented when incorporating place-based approaches that integrate local social, environmental, and economic goals (Berkes 2007, Hartig 2015, Waller and Reo 2018). By identifying which regions along Michigan's Great Lakes shorelines are more likely to be affected than others under specific scenarios, land managers and civic leaders can be prepared rather than surprised by the impacts of changing coastal zones, and navigate conflicting land use decisions before the most dire of impacts are unavoidable. These impacts include changes to ecosystems and habitat for at-risk species, which we focus on here, but may extend to infrastructure with social and economic consequences such as roads, culverts, and bridges (Meadows et al. 2025).

The detailed evaluation of impacts to ecosystems and species at the focal areas of Wildfowl Bay, Wilderness State Park, and Drummond Island provides us with a vehicle for understanding how conservation priorities may vary from region to region as Great Lakes levels fluctuate. These case studies are consistent with broader patterns in the response of ecosystems and species to predicted fluctuations, so provide a menu of sorts for how regional and local land managers across Michigan's coastal zones can adapt their planning as Great Lakes levels fluctuate over the coming decades. For example, managers may choose to bolster coastal populations of at-risk species or shift resources to non-coastal populations, emphasize management for coastal populations of a species in one region over another, or de-emphasize coastal management in a region if inland conservation targets take higher priority.

The predicted response of natural communities and at-risk species to Great Lakes fluctuations at Wildfowl Bay mirrored statewide patterns, with some of the most significant impacts being inundation of marshes and lakeplain prairies and impacts on species reliant on those communities. These responses may serve as a template for similar embayments or broad lakeplains in southeast Michigan, including Lake St. Clair, western Lake Erie, and other portions of the Saginaw Bay. The potential for habitat expansion under MIROC5 scenarios was minimal, with only Great Lakes marsh predicted to experience significant expansion. Under CNRM scenarios, significant inundation was predicted for multiple natural communities, including hardwood-conifer swamp, northern shrub thicket, southern hardwood swamp, southern shrub-carr, and wet-mesic flatwoods. However, these communities occupy a small portion of the focal area (< 1% for all but wet-mesic flatwoods, which occupied < 2%) and no at-risk species were strongly associated with them.

The natural community with the greatest extent at Wildfowl Bay as well as the greatest predicted change in area was Great Lakes marsh, alternately expanding or contracting depending on modeled conditions. Consequently, predicted habitat loss under CNRM scenarios (and to a lesser degree habitat gain under MIROC5 scenarios) was significant for marsh-associated birds black tern, king rail, and common tern. Significant inundation was also predicted for emergent marsh, which these species also utilize for foraging and occasionally nesting. Under CNRM scenarios, predicted habitat loss was high for eastern prairie fringed orchid and blazing star borer, which in the coastal zone occur largely on lakeplain wet and wet-mesic prairie and lakeplain oak openings, communities predicted to experience significant inundation under CNRM scenarios at Wildfowl Bay. Despite collectively comprising only 7.5% of the Wildfowl Bay focal area, these communities are arguably the natural communities at Wildfowl Bay with the highest overall conservation value, as they are imperiled to critically imperiled globally and critically imperiled in Michigan, and support dozens of other rare plant and animal species (Cohen et al. 2025). Lakeplain prairies have also long been threatened by invasive species that are facilitated by lake-level change, particularly invasive reed (*Phragmites australis* subsp. *australis*) (Wilcox 2012).

How should regional and local managers respond to these predictions? Regionally, managers in Wildfowl Bay (and the Saginaw Bay region in general) may choose to concentrate resources toward supporting populations of these species through habitat conservation and species monitoring, with the goal of increasing the viability of these and other species that rely on Great Lakes marsh and other coastal marshes, and lakeplain prairie and related communities. Managing for large, genetically diverse populations should confer some measure of resilience against habitat loss during high-water periods (Timpane-Padgham et al. 2017, Capdevila et al. 2020). Beyond that, restoring and maintaining natural processes (e.g., prescribed fire), native biodiversity, and connectivity in ecosystems should buffer against habitat loss (Beier and Noss 1998, Damschen et al. 2019).

Alternately, managers may conclude that the fate of coastal populations of these species is dire enough that resources for conservation of these species in non-coastal environments should be bolstered, although coastal vs. non-coastal conservation opportunities vary by species. For example, 63% (31 of 49) of documented blazing star borer occurrences in Michigan occur in fens and savannas outside the coastal zone, so conservation efforts specifically targeting that species could focus on those occurrences (MNFI 2026). In contrast, only 3% (3 of 99) documented occurrences of common tern occur outside the coastal zone (MNFI 2026). Managers may direct resources away from Saginaw Bay populations of blazing star borer and toward inland populations, while focusing on the Saginaw Bay populations of common tern because there are so few documented inland occurrences. In a modeling exercise prioritizing Great Lakes coastal wetlands for marsh bird conservation based on monitoring data and several environmental predictors, the Saginaw Bay was among the highest-ranked regions (Grand et al. 2020). Furthermore, the proportion of both open water and herbaceous wetlands were among the most important predictors of habitat quality, emphasizing the need for both in sustaining marsh bird populations. Alternately, as only 10 (10%) of documented coastal occurrences of common tern occur in the Saginaw Bay, there are other opportunities for coastal conservation in regions that may not be as impacted by lake-level fluctuations (e.g., Drummond Island). Further research to understand how predicted lake-level fluctuations will impact the distribution of these resources both within and among coastal regions will be important for prioritizing marsh bird conservation.

Wilderness State Park also showed a strong response among palustrine communities, but differed from Wildfowl Bay in that both significant expansion under MIROC5 scenarios and significant inundation under CNRM scenarios was predicted for a wider array of palustrine as well as primary communities. Significant inundation and expansion was predicted for communities that occupied a large proportion of the focal area, including Great Lakes marsh, limestone cobble shore, and coastal fen. Significant inundation and expansion were also predicted for open dunes and sand and gravel beach, neither of which occupy a large proportion of the focal area. Nonetheless, species strongly associated with all significantly impacted communities were predicted to experience significant impacts to habitat.

Planning for the consequences of climate change at Wilderness State Park may depend on which climate models are more accurate, with the most consistent pattern being either inundation or expansion for most species. Under CNRM scenarios, seven of the thirteen species may be threatened with habitat contraction while under MIROC5 scenarios, eight of the thirteen species may benefit from habitat expansion, with considerable overlap among species predicted to experience inundation vs. expansion. Species of both Great Lakes marsh (black tern, king rail, and common tern) and species of dune systems and adjacent beaches and cobble shores (piping plover, Pitcher's thistle, Lake Huron locust, common tern) are predicted to either experience significant inundation if CNRM scenarios play out or significant expansion if MIROC5 scenarios play out. This conundrum is likely most acute for black tern, king rail, and common tern. Habitat for these species - Great Lakes marsh, and to a lesser extent limestone cobble shore - are both well-represented and have significant predicted impacts here. Populations of dunes-associated species, on the other hand, may be more secure elsewhere so managers may either prioritize conservation of dunes-associated species at Wilderness State Park or de-prioritize them in favor of species associated with other natural communities. Minimal impacts are predicted statewide for open dunes and dunes-associated species in general, likely because many dune systems elsewhere achieve significantly higher elevations than those at Wilderness State Park.

Two species, Houghton's goldenrod and eastern massasauga, are predicted to gain significant habitat under MIROC5 scenarios and only lose a moderate amount of habitat under CNRM scenarios. Wilderness State Park could then be treated as a stronghold for those two species. Conservation planners could bolster habitat for these species at this and other potential strongholds. Finally, a single species, Hine's emerald dragonfly, is predicted to lose habitat under CNRM scenarios and gain a moderate amount of habitat under MIROC5 scenarios. This species, however, has never been documented at Wilderness State Park, despite a significant amount (272 hectares [673 acres]) of available coastal fen habitat. Managers may therefore wish to prioritize surveys to confirm the presence or absence of Hine's emerald dragonfly.

Drummond Island highlights yet another context within which regional conservation priorities are navigated. One of the primary conservation priorities on Drummond Island is alvar, a natural community that is globally imperiled and critically imperiled in Michigan, with most of its Michigan extent occurring on Drummond Island (Lincoln 2018, Cohen et al. 2025, MNFI 2026). The highest-quality alvar complex on Drummond Island, at 590 hectares (1450 acres), supports populations of 12 rare plant species, 7 rare mussels, 2 rare mammals, and 1 rare insect (MNFI 2026). However, very little alvar occurs in the coastal zone in this focal area (<5%) and our analysis predicted minimal expansion (< 1%) or inundation (<2%) of the alvar that *does* occur in the coastal zone. Also, a diversity of other natural communities occur in the coastal zone of Drummond Island and the other islands in the focal area. As a result, while conservation of globally imperiled alvar is a high priority for biodiversity conservation on Drummond Island, it will not factor heavily into how managers adapt conservation strategies as Great Lakes levels fluctuate. Managers may even choose to not prioritize coastal ecosystems, given the high conservation priority of alvar.

Impacts may be minimal overall in the coastal zone of the Drummond Island focal area. Predicted coastal zone impacts are generally restricted to habitat expansion, and where inundation was a concern, it was for species for which minimally inundated natural communities provide refugia. Over 50% of the coastal zone in this focal area was boreal forest, which had <1% predicted inundation or expansion, so impacts to species like dwarf lake iris that regularly occur along the lakeward margins of boreal forest may be buffered at least from inundation of the other natural communities where they occur. Significant expansion (>13%) was predicted for Great Lakes marsh, limestone cobble shore, northern fen, and sand and gravel beach, although none of these communities occupied more than 5% of the focal area under baseline conditions. The predicted expansion of sand and gravel beach was particularly dramatic at 335%. However, this community is only represented by 1.8 hectares (4.5 acres, 0.03% of the focal area) on the eastern shore of Harbor Island, so its expansion only equals a jump to 6 hectares (15 acres), still an insignificant habitat area for any affected species.

Piping plover, black tern, Pitcher's thistle, Michigan monkey flower, king rail, common tern, and Lake Huron locust were predicted to experience significant habitat expansion, from 13% to 37%, as a result of natural community expansion. Habitat expansion for piping plover, Pitcher's thistle, and Lake Huron locust was largely linked to the dramatic expansion of sand and gravel beach on Harbor Island. None of these species has ever been documented on Harbor Island, however, and recent surveys that would have been likely to detect at least Pitcher's thistle and piping plover reported neither species (Bassett et al. 2023, Cohen et al. 2023). Similarly, Michigan monkey flower has never been reported outside of the northern shores of Lake Michigan. Potential habitat for a single species, king rail, was predicted to experience significant inundation, linked to inundation of Great Lakes marsh and limestone cobble shore. However, the northern edge of the king rail's breeding range is depicted as near the tension zone of the Lower Peninsula in Michigan, with observations in northern Michigan being widely scattered spatially and temporally and no confirmed evidence of breeding in the Upper Peninsula being known from either the Natural Heritage Database (MNFI 2026) or the Michigan Breeding Bird Atlas (Putnam 2013) (Figure 7). Even if the king rail's range shifts northward with continued climate change, it is unlikely to become abundant enough to warrant being a management priority for Drummond Island.

Effects of Great Lakes water level fluctuations that are not accounted for in our model

Modeled habitat inundation and expansion does not necessarily equate to less and more habitat, respectively. While our model captures broad patterns of how at-risk species may be affected by habitat inundation and expansion as Great Lakes water levels fluctuate, it does not explicitly account for several ecological and demographic processes that are likely to modify realized habitat quality and species responses. In particular, invasive species dynamics in ecosystems and several life-history traits of at-risk species may substantially modify or override the habitat gains and losses predicted by lake-level change alone. Also, the ranges of some at-risk species are more geographically restricted than the extent of the natural communities used to model impacts to the species, so some impacts may be overstated.

We did not account for changes to the abiotic environment, and subsequent biotic responses in affected communities, due to inundation and expansion and how those responses may modify the suitability of habitat for at-risk species. Such effects may be particularly acute when ecosystems expand following a period of inundation. The rapid response of invasive species to changing lake levels, a disturbance that results in pulses of both light availability and soil nutrients, may limit the apparent benefits of habitat expansion implied by our model results (Bansal et al. 2019). The success of invasive plant species is due in part to their ability to respond to "windows of opportunity" – pulses of resources such as light and soil nutrients, particularly following reductions in biomass or soil disturbances (Davis et al. 2000). For example, lake-level recessions following periods of inundation can expose large areas of nutrient-enriched substrate that are rapidly colonized by invasive reed (*Phragmites australis* subsp. *australis*) and narrow-leaved and hybrid cattail (*Typha angustifolia* and *T. X glauca*) (Tulbure et al. 2007, Tuchman et al. 2009, Wilcox 2012). The authors and their colleagues recently observed dramatic invasions of invasive reed and narrow-leaved cattail with lake-level recession since 2021 following historic high lake-levels in lakeplain prairies and oak openings in the St. Clair delta in southeastern Michigan, a region that receives high levels of nutrient-rich urban and agricultural runoff (Hu et al. 2019; Figure 24). Without a rapid management response, invasive reed and narrow-leaved and hybrid cattail invasions in lakeplain prairie are likely to rapidly outcompete both eastern prairie fringed orchid and marsh blazing star (*Liatris spicata*), the host plant for blazing star borer in lakeplain prairies. This recent expansion of invasive plant species came after these many other coastal wetlands experienced extensive

Figure 24. Lakeplain prairie decline in St. Clair Flats State Wildlife Area in the St. Clair River Delta: 2016 before (above) and 2024 after (below) high lake-levels. Invasive reed: silver or light green (2016), brown (2024). Prairie: green (2016), dark green (2024). Arrow vectors added for reference. Note tree mortality in lakeplain oak openings (e.g., red ellipses). Photos by Jesse M. Lincoln.

colonization by invasive reed and cattails during a prolonged period of below-average water levels that occurred in much of the Great Lakes during about 1999-2014.

Changes to the abiotic environment may also include geomorphological changes linked to changing water levels. Vitt et al. (2024) report on a ten-year demographic study of Pitcher's thistle at two sites in Door County, WI, and link declines in plant survivorship and population growth rates to the effects of high lake-levels, including erosion, sand burial, and storm damage. While our model did not predict significant inundation or expansion of open dunes and therefore Pitcher's thistle, Vitt et al. (2024) suggest that reductions to habitat quality may still result and negatively impact this and other species.

We also did not explicitly incorporate dispersal ability, demographic constraints, or other life-history traits that influence whether species can take advantage of newly available habitat or persist under conditions of habitat loss or inundation. Highly mobile species, such as birds, may be able to disperse from inundated habitats to adjacent suitable coastal or non-coastal habitats. For example, while existing marsh habitat may become less suitable for marsh-associated birds due to changes to or loss of marsh vegetation during high-water years, marsh-associated birds may be able to disperse to or take advantage of adjacent or nearby areas that remain or become suitable. Indeed, throughout the shift from low (2011-2013) to high (2018-2021) lake-level years, the area of suitable marsh habitat expanded in the Great Lakes overall, leading to increases in marsh bird species richness in coastal wetlands and population increases for most marsh-obligate and marsh-facultative bird species (Hohman et al. 2021, Tozer et al. 2024).

Plant species and dispersal-limited insects may be limited by dispersal distance, habitat connectivity, or reliance on specific host plants or microhabitats. For example, seed dispersal in Houghton's goldenrod and dwarf lake iris is limited in favor of clonal expansion, so expansion into adjacent non-inundated or recently exposed habitat may not be fast enough to constitute meaningful population growth. However, clonal growth may correlate with traits that confer tolerance of inundation, such as bud-banking (Klimesova and Klimes 2007). A recent study of dwarf lake iris from peak lake levels in 2019 through lake-level recession in 2024 documented some populations persisting in shallow water, while others were eliminated due to sand and cobble deposition associated with high lake levels (Hackett et al. 2024). Anecdotal evidence suggested occasional expansion from the edge of boreal forest, but at extremely slow rates and only when limestone cobble shore was adjacent (Figure 25). In comparison, eastern prairie fringed orchid produces tiny seeds adapted to long-distance dispersal, and rapid occupation of exposed habitat during low lake-levels and adjacent habitat during high levels has been documented (Ellison et al. 2026b). Finally, species with obligate associations to particular substrates, hydrologic conditions, or host species may be unable to colonize newly exposed areas if those conditions do not develop rapidly enough, even where habitat expansion is predicted. For example, while blazing star borer may be able to disperse into adjacent, non-inundated lakeplain prairie, viability of those populations will still be limited by the presence of host plants in the genus *Liatris*.

Figure 25. Dwarf lake iris ramets, highlighted in red ellipse, slowly expanding into recently exposed limestone cobble shore at Wilderness State Park, 5/28/24. Photo by Rachel A. Hackett.

We did not control for the documented or potential distribution of at-risk species in our analysis. Instead, we assumed in our model that each species could utilize each associated natural community wherever in Michigan that community was mapped. For example, Michigan monkey flower was strongly associated with rich conifer swamp (Table A3). However, while rich conifer swamp occurs in coastal areas across the northern lower peninsula and much of the upper peninsula, Michigan monkey flower has only been documented in the northeastern lower peninsula and a small stretch of the northern Lake Michigan shoreline in the upper peninsula (MNFI 2026; Figure 10). Therefore, inferences based on impacts to rich conifer swamp outside of its potential range may be inaccurate or in the least misleading. The association of Michigan monkey flower with equally widespread mesic northern forest, sand and gravel beach, Great Lakes marsh, and other communities introduce additional error into predicted impacts to this species.

Finally, our analysis is specifically restricted to the predicted impacts of fluctuating Great Lakes levels on coastal populations of thirteen at-risk plant and animal species. Each of these species faces a myriad of threats beyond those related to fluctuating Great Lakes levels, including but not limited to overexploitation, anthropogenic development, invasive species, disease, and pollution (Hernández-Yáñez et al. 2016, Bernardo et al. 2019). Conservation strategies for these species must take all of these threats into account. Furthermore, there are a diversity of conservation priorities in the Great Lakes coastal zone beyond the 13 at-risk species we targeted, and beyond rare species conservation in general (Schriberg et al. 2025). Conservation priorities based on the modeled impact to habitat for these 13 species need to be placed in the context of a range of concerns including hunting and fishing, recreation, infrastructure, and local economies.

Together, these unmodeled processes suggest that realized outcomes for species and ecosystems will almost certainly differ from modeled projections, particularly in ecosystems and regions where invasive species pressure is high, or where dispersal and persistence are strongly constrained by a range of ecological factors. Incorporating these and other considerations into future modeling and monitoring efforts will be essential for translating predicted habitat change into effective conservation and management actions.

Limitations of our modeling approach and known errors

There are also limitations to our modeling approach. Single surface raster modeling does not model detailed components and feedbacks of inundation such as soil erosion, accretion rates, wetland and landcover conversion, wave action, and flooding from storm surge that can potentially contribute to loss of habitat area above and beyond modeled lake-level changes. Thus, predicted changes in habitat area according to our model should be viewed as conservative estimates and interpreted in a context that potentially includes these other effects. Because of these limitations, the resulting inundation surfaces can be inaccurate (Poulter and Halpin 2008, McLeod et al. 2010, Murdukhayeva et al. 2013). However, most of the previous studies using this modeling approach employed DEMs with significantly less vertical and horizontal accuracy or used LiDAR-derived DEMs that were not processed based on current USGS Base Lidar specifications (Heidemann 2018, 2019). Therefore, our model was implemented to gain accuracy compared to previous models, in addition to providing improved spatial resolution.

Five impactful errors were discovered in the GIS outputs after they were used for the analysis presented in this report. The version of data products delivered with this report contains the following known errors unless otherwise noted.

Error 1—Elevation values too high in southern Lake Erie

The elevation values of cells in the Lake Erie shoreline region south of Sterling State Park (41.918801, -83.33386 to the state border, ~ 15 miles [25 km]) are higher than expected. We verified the vDatum transformation was applied correctly and the underlying cause of the problem remains unknown. As a result, inundation extents are systematically underestimated in this region. Statistics for the southern Lake Erie region may be too biased to draw conclusions at this time.

Error 2—Missing elevation regions erroneously permitted to inhibit inundation in MIROC5 Low, MIROC5 Average, and CNRM Low scenarios

The inundation modeling step was intended to assume that missing bathymetric elevation cells could not have their own inundation status calculated but would not be permitted to inhibit flow (inundation) to regions near the shore. This decision required the use of filled rasters during the inundation modeling step. Instead, unfilled rasters were used for these three scenarios, while the filled rasters were correctly used for the Baseline Low and Baseline Average scenarios. As a result, comparisons involving these three scenarios have spatially distributed errors where the sign of the change statistic may be reversed in addition to random error in the change statistics. While distributed, these errors are most likely in areas with high missingness of bathymetric data. The effect is most pronounced in the Baseline Low to CNRM Low statistics for the St. Mary's River region.

Error 3—Water surface in topographic data used for some islands incorrectly treated as lake bottom

For the following islands, topobathymetric data was not available and topographic data was collated instead: Garden Island archipelago, Les Cheneaux islands, Bois Blanc Island and nearby Round Island, North Manitou Island, Au Train Island (no habitat data availability), and Lighthouse Island (Huron National Wildlife Refuge). The elevation cells representing the water surface should have been assigned NoData values; instead, they were retained and functionally treated as the lake bottom elevations. As a result, graphical interpretations of data may be confusing when mapping these islands. Change statistics involving all receding water scenarios (below baseline average) are biased towards inferring habitat expansion instead of showing more limited change values along with a high data missingness statistic. Water rise scenarios are not impacted.

Error 4—Baseline High to MIROC High inundation comparisons for Isle Royale

Inundation scenario shapes for Isle Royale (only) were duplicated in the MIROC5 High layer. As a result, this error caused incorrect area calculations during percent change calculations for habitats, species, and regional fishnet grids which resulted in values of approximately -100% instead of the appropriate positive values for any Baseline High to MIROC5 High comparisons. The data product was repaired but the analysis reported includes the error.

Error 5—Saginaw Bay MIROC5 High scenario lacks road enforcement

The MIROC5 High scenario inundation was calculated from an elevation raster that was missing the more permissive road/culvert burning that was included in all other scenarios for the Saginaw Bay region (labeled "Huron2" in the data products). This causes some local regions to falsely not inundate in this scenario. The delivered data product was fixed but the analysis statistics were affected.

Recommended conservation priorities

The results of our model represent predictions for how the fluctuation of Great Lakes levels will impact individual or groups of at-risk species and coastal natural communities, but lack many important geological, ecological, demographic, and analytical considerations. As such, the applicability of these predictions should be bolstered by in-depth knowledge of the species and places being managed, and should not be considered a substitution for that knowledge. Nevertheless, there are some broad and consistent patterns that provide a foundation for setting conservation priorities. Here, we outline conservation priorities supported by our results (Table 10).

We center our recommendations on natural communities and coastal zones with specific ecosystem complexes to encourage management approaches that support multiple species, including but not limited to those considered here, and to discourage management approaches that benefit one species at the expense of others (Caro and O'Doherty 1999, Jenkins et al. 2021). This "coarse filter" approach can be augmented by a "fine filter" focused on individual species when it appears the "coarse filter" approach falls short of achieving conservation goals (Noss 1987, Lemelin and Darveau 2006, Tingley et al. 2014).

Great Lakes marsh

Great Lakes marsh is the natural community that is associated most strongly with the most at-risk species in our analyses (Table A3). Great Lakes marsh was consistently predicted to be subject to significant inundation across CNRM scenarios and in many cases significant expansion across MIROC5 scenarios at a statewide level. Significant inundation and expansion of Great Lakes marsh was also predicted in all three focal areas we examined. The prevalence of Great Lakes marsh in a coastal region may therefore indicate high sensitivity to lake-level fluctuations. For example, Great Lakes marsh was dominant in the Wildfowl Bay focal area (81.97% of natural community cover), prevalent at Waugoshance Point (23.34%), and rare at Drummond Island (3.83%). The dominance of Great Lakes marsh in Saginaw Bay, along with the prevalence of other priority ecosystems like lakeplain prairie (*see below*), point to that region as a high priority for conservation as lake levels fluctuate in the coming decades (Grand et al. 2020). Other regions with concentrations of Great Lakes marsh include Thunder Bay in the northeastern lower peninsula, Munuscong Bay in the St. Mary's River connecting Lakes Superior and Huron, the Manistee River delta in the northwest Lower Peninsula, the Grand River delta in the southwest Lower Peninsula, and the Detroit River connecting Lake St. Clair to Lake Erie (Table 5).

Table 10. Conservation priorities for natural communities, species, and coastal regions in Michigan.

Natural community	Species > 10% associated	Justification	Coastal regions	Research/Monitoring
Great Lakes marsh	Six Birds - common tern, black tern, king rail; Plants - eastern prairie fringed orchid, Houghton's goldenrod; Reptile - eastern massasauga	Most associated species (12 of 13) and strongest mean association (22.59); > 10% inundated in all three CNRM scenarios, > 10% expansion in one and >5% in two MIROC5 scenarios	*Huron* - Saginaw, Munuscong, and Thunder Bays; *Michigan* - Grand and Manistee River deltas; *Detroit River*	What does expansion and inundation mean for marsh bird habitat suitability? As a habitat complex with emergent and submergent zones, how will effects of inundation and expansion vary?
Lakeplain wet and wet-mesic prairie	Two Insects - blazing star borer; Plants - eastern prairie fringed orchid	5 and 3 associated species, respectively; > 10% inundated/expanded in 3 scenarios; globally imperiled (G1?-G2) and critically imperiled in Michigan (S1)	*Huron* - Saginaw Bay; *Lake St. Clair*	How best to balance species conservation between lakeplain prairie and inland peatlands supporting same species?
Limestone cobble shore, sand and gravel beach	Two Insects - Lake Huron locust; Plants - Houghton's goldenrod	8 and 7 associated species, respectively; > 10% inundated/expanded in 4 of 6 scenarios	*Michigan/Huron* - Straits of Mackinac (including islands); *Huron* - Drummond Island	How important are these communities for buffering impacts to inland communities?
Coastal fen and interdunal wetland	Two Birds - piping plover (interdunal wetland); Insects - Hine's emerald (coastal fen)	8 and 7 associated species, respectively; coastal fen > 10% inundated/expanded in 4 of 6 scenarios	*Michigan/Huron* - Straits of Mackinac (including islands); *Michigan* - multiple regions along eastern shore	Will the effects of climate change degrade hydrologic controls (via groundwater discharge) on this community?
Open dunes and wooded dune and swale complex	Six Birds - piping plover; Insects - Hine's emerald, Lake Huron locust; Plants - Pitcher's thistle, dwarf lake iris, Houghton's goldenrod	8 associated species; regionally unique natural communities; very little predicted inundation and expansion	*Michigan/Huron* - Straits of Mackinac (including islands); *Michigan* - much of eastern shore; *Huron* - Thunder and Saginaw Bays; *Superior* - sporadically	What is the effect of dune erosion on habitat suitability following high lake levels? How do high lake levels affect hydrology of swales?

Focusing conservation efforts on Great Lakes marsh should support several at-risk species that are strongly associated with this community (Table A3), especially common tern, black tern, and king rail, and several other marsh birds. Combining adjacent meadows, prairies, and other habitat complexes in conservation planning will further bolster conservation efforts, especially for species that utilize multiple cover types like common tern and eastern massasauga, and directly for species like eastern prairie fringed orchid and blazing star borer. In addition to the species examined in this study, several other at-risk species would benefit from conserving Great Lakes marshes, such as American bittern (*Botaurus lentiginosus*, Special Concern, UMGLJV focal species), least bittern (*Botaurus exilis*, State Threatened), and common gallinule (*Gallinula galeata*, State Threatened). Great Lakes marshes may require special attention because their susceptibility to extreme changes in water levels make them vulnerable to invasive species expansion, such non-native common reed and cattails during low water periods and aquatic species like European frog-bit (*Hydrocharis morsus-ranae*) and starry stonewort (*Nitellopsis obtusa*) during highwater periods.

Lakeplain wet and wet-mesic prairie

Lakeplain wet and wet-mesic prairie are two of the more geographically restricted communities we evaluated. They are prominently featured in the Saginaw Bay in Lake Huron and the nearby Lake St. Clair, for example occupying approximately 10% of the Wildfowl Bay focal area, but are almost entirely absent from coastal regions outside of southeast Michigan. Lakeplain prairies support only five of the thirteen species we evaluated. Eastern prairie fringed orchid and blazing star borer are likely to be the primary beneficiaries of conservation efforts in lakeplain prairies. However, these communities are imperiled to critically imperiled at both global and statewide scales, and due to their landscape position (i.e., low elevation change from shoreline) very inundation-prone under CNRM scenarios. Therefore, prioritizing lakeplain prairies in the context of lake-level changes weaves together regional and global conservation priorities, elevating their value.

Limestone cobble shore, sand and gravel beach

Limestone cobble shore and sand and gravel beach are prominent along the Niagara escarpment through the Straits of Mackinac, and in adjacent coasts in northern Lakes Michigan and Huron, including on several Great Lakes Islands (Grand Traverse and Beaver Archipelagos, Manitou and Fox Islands in Lake Michigan, and Crooked, Sugar, Bois Blanc, Lime, Harbor, and Drummond Islands in Lake Huron). They are common in many of these regions, for example occupying approximately 15% of the Waugoshance Point focal area. Both communities appear dynamic under climate change, exhibiting capacity for inundation in two CNRM scenarios and expansion in two MIROC5 scenarios. Balancing development pressures adjacent to these communities with lake-level impacts will likely be crucial. Many Great Lakes islands are owned partially or wholly by federal or state agencies, with limited development pressure, so factor heavily in conservation of species that rely on these communities.

Despite supporting 9 of the 13 species we evaluated between them, each community is only strongly associated with one, Lake Huron locust in sand and gravel beach and Houghton's goldenrod in limestone cobble shore. However, they often serve as a dynamic interface between open water or coastal marshes on the one hand, and inland dune, forest, and meadow communities on the other. Both communities frequently occur adjacent to wooded dune and swale complex, with limestone bedrock lakeshore frequently associated with boreal forest and sand and gravel beach consistently associated with open dunes. Species strongly associated with those communities, are often weakly associated with and undoubtedly regularly utilize limestone cobble shore and sand and gravel beach. Therefore, conservation efforts focused on these two communities may be vital in broader regional strategies to support at least six additional species, including piping plover, pitcher's thistle, dwarf lake iris, eastern massasauga, Hine's emerald dragonfly, and common tern.

Coastal fen and interdunal wetland

Coastal fen and interdunal wetland serve a similar function to that of limestone bedrock lakeshore and sand and gravel beach, exhibiting similar dynamism, with significant predicted inundation in two CNRM scenarios and expansion in two MIROC5 scenarios. Both communities are influenced by a hydrologic regime linked to Great Lakes levels. Supporting nine at-risk species in our analysis, each is strongly associated with only one species, piping plover in interdunal wetland, and Hine's emerald dragonfly in coastal fen. Both communities also serve as an interfacing between coastal marshes and adjacent uplands. Interdunal wetlands are typically nestled in open dune complexes and both communities regularly occur adjacent to boreal forest and wooded dune and swale complexes, with coastal fen frequently transitional to Great Lakes marsh. Therefore, when managing these communities in the context of ecosystem complexes, at least eight additional at-risk species could receive conservation support, including black tern, Pitcher's thistle, dwarf lake iris, king rail, eastern massasauga, Houghton's goldenrod, common tern, common tern, and Lake Huron locust.

Open dunes and wooded dune and swale complex

As discussed above, conservation of both open dunes and wooded dune and swale complexes in the context of coastal fen, interdunal wetland, limestone cobble shore, and sand and gravel beach has the potential to support large blocks of heterogenous habitat for most of the species we evaluated, especially in areas supporting Great Lakes marsh and other coastal marshes. Here, we will focus on the specific conservation value these dune communities provide on their own, in the context of fluctuating lake levels. These are regionally unique natural communities, with the Great Lakes supporting the most extensive freshwater dune systems in the world (Hansen et al. 2020). Approximately 100 wooded dune and swale complexes are distributed along the Great Lakes shores, the only region in the world where they are found, with over half occurring in Michigan (NatureServe 2026).

Open dunes are central to the conservation of piping plover, Pitcher's thistle, and Lake Huron locust, which also rely on wooded dune and swale complexes. Dwarf lake iris, Houghton's goldenrod, and Hine's emerald dragonfly are strongly associated with wooded dune and swale complexes. Despite being restricted to the coastal zone in the Great Lakes, neither natural community was predicted to experience significant inundation or expansion. Our model did not take into account erosion of dunes during high-water periods, or hydrologic modifications in the wetland communities of dune and swale complexes. Additional research into how lake-level fluctuations will impact erosion and hydrology in these communities will be vital for making biodiversity conservation decisions in the coming decades.

Conclusions

As the effects of climate change continue to intensify throughout the 21st century, both normal lake levels and the fluctuations around them are predicted to exceed historic extremes. The results of the modeling exercise reported here provide a framework for managing near-shore ecosystems and the at-risk species that depend upon them in the context of these extremes. Importantly, we hope these results provide a basis for conservation of places, ecosystems, and species along Great Lake shorelines over the coming decades.

We envision a broad array of end users of this model, both in conservation and in other arenas such as land-use planning and eco-tourism. The applications of the model to conservation also extend beyond our Objectives 2 and 3, where we propose to provide general guidance on a suite of focal species and large-scale predictions about changing natural communities. For example, modeled lake levels can certainly be applied at finer scales by managers interested in specific geographic areas, or species not included in our analyses. The model will be useful for stakeholders outside of conservation as well. Changing lake levels also threaten cultural resources, including infrastructure, coastal development, and the capacity of the lakeshore to support tourism.

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APPENDIX A: SUPPLEMENTAL TABLES

Table A1. Designation of natural communities that were allowed to “expand” into adjacent topobathymetry under “water recedes” scenarios.

Community	Expands?	Class	Group
Exposed Unclassed	No	N/A	N/A
N/A	No	N/A	N/A
Not Mapped	No	N/A	N/A
Plantation	No	N/A	N/A
Bog	No	Palustrine	Bog
Muskeg	No	Palustrine	Bog
Coastal Fen	Yes	Palustrine	Fen
Northern Fen	Yes	Palustrine	Fen
Patterned Fen	No	Palustrine	Fen
Poor Fen	No	Palustrine	Fen
Prairie Fen	No	Palustrine	Fen
Floodplain Forest	No	Palustrine	Forested Wetland
Hardwood-Conifer Swamp	No	Palustrine	Forested Wetland
Northern Hardwood Swamp	No	Palustrine	Forested Wetland
Poor Conifer Swamp	No	Palustrine	Forested Wetland
Rich Conifer Swamp	No	Palustrine	Forested Wetland
Rich Tamarack Swamp	No	Palustrine	Forested Wetland
Southern Hardwood Swamp	No	Palustrine	Forested Wetland
Wet-mesic Flatwoods	No	Palustrine	Forested Wetland
Coastal Plain Marsh	No	Palustrine	Marsh
Emergent Marsh	Yes	Palustrine	Marsh
Great Lakes Marsh	Yes	Palustrine	Marsh
Interdunal Wetland	No	Palustrine	Marsh
Intermittent Wetland	Yes	Palustrine	Marsh
Northern Wet Meadow	Yes	Palustrine	Marsh
Open Water	No	Palustrine	Marsh
Southern Wet Meadow	Yes	Palustrine	Marsh
Submergent Marsh	Yes	Palustrine	Marsh
Inundated Shrub Swamp	Yes	Palustrine	Shrub Wetland
Northern Shrub Thicket	Yes	Palustrine	Shrub Wetland
Southern Shrub-carr	Yes	Palustrine	Shrub Wetland
Lakeplain Wet Prairie	Yes	Palustrine	Wet Prairie
Lakeplain Wet-mesic Prairie	Yes	Palustrine	Wet Prairie
Wet Prairie	Yes	Palustrine	Wet Prairie
Wooded Dune and Swale Complex	Yes	Palustrine/Terrestrial	Wooded Dune and Swale
Granite Bedrock Glade	No	Primary	Bedrock Glade
Limestone Bedrock Glade	No	Primary	Bedrock Glade
Northern Bald	No	Primary	Bedrock Glade

Volcanic Bedrock Glade	No	Primary	Bedrock Glade
Alvar	Yes	Primary	Bedrock Grassland
Granite Bedrock Lakeshore	Yes	Primary	Bedrock Lakeshore
Limestone Bedrock Lakeshore	Yes	Primary	Bedrock Lakeshore
Sandstone Bedrock Lakeshore	Yes	Primary	Bedrock Lakeshore
Volcanic Bedrock Lakeshore	Yes	Primary	Bedrock Lakeshore
Great Lakes Barrens	Yes	Primary	Dunes
Open Dunes	Yes	Primary	Dunes
Granite Cliff	No	Primary	Inland Cliff
Limestone Cliff	No	Primary	Inland Cliff
Sandstone Cliff	No	Primary	Inland Cliff
Volcanic Cliff	No	Primary	Inland Cliff
Clay Bluff	No	Primary	Lakeshore Cliff/Bluff
Granite Lakeshore Cliff	No	Primary	Lakeshore Cliff/Bluff
Limestone Lakeshore Cliff	No	Primary	Lakeshore Cliff/Bluff
Sandstone Lakeshore Cliff	No	Primary	Lakeshore Cliff/Bluff
Volcanic Lakeshore Cliff	No	Primary	Lakeshore Cliff/Bluff
Limestone Cobble Shore	Yes	Primary	Sand/Cobble Shore
Sand and Gravel Beach	Yes	Primary	Sand/Cobble Shore
Sandstone Cobble Shore	Yes	Primary	Sand/Cobble Shore
Volcanic Cobble Shore	Yes	Primary	Sand/Cobble Shore
Sinkhole	No	Subterranean/Sink	Karst
Boreal Forest	No	Terrestrial	Forest
Dry Northern Forest	No	Terrestrial	Forest
Dry Southern Forest	No	Terrestrial	Forest
Dry-mesic Northern Forest	No	Terrestrial	Forest
Dry-mesic Southern Forest	No	Terrestrial	Forest
Mesic Northern Forest	No	Terrestrial	Forest
Mesic Southern Forest	No	Terrestrial	Forest
Dry Sand Prairie	No	Terrestrial	Prairie
Lakeplain Oak Openings	Yes	Terrestrial	Savanna
Oak Barrens	No	Terrestrial	Savanna
Oak-Pine Barrens	No	Terrestrial	Savanna
Pine Barrens	No	Terrestrial	Savanna

Table A2. Calculation details for area and percent change statistics for individual habitats, habitat classes, species, and regional fishnets. Area differences are based on the total “dry” area for each scenario. The denominator for the percent change varies.

"Percent change" comparison being calculated	Projected scenario is above or below historical average?	Numerator	Denominator
Baseline High vs. CNRM High	Above	Dry area @ Baseline High - Dry area @ CNRM High	Non-missing area of mapped polygon
Baseline High vs. MIROC5 High	Above	Dry area @ Baseline High - Dry area @ MIROC5 High	Non-missing area of mapped polygon
Baseline Low vs. CNRM Low	Below	Dry area @ Baseline Low - Dry area @ CNRM Low	Dry area @ Baseline Low
Baseline Low vs. MIROC5 Low	Below	Dry area @ Baseline Low - Dry area @ MIROC5 Low	Dry area @ Baseline Low
Baseline Average vs. CNRM Average	Above	Dry area @ Baseline Average - Dry area @ CNRM Average	Non-missing area of mapped polygon
Baseline Average vs. MIROC5 Average	Below	Dry area @ Baseline Average - Dry area @ MIROC5 Average	Dry area @ Baseline Average

Table A3. Proportional association of each at-risk species with each natural community. See Table A4 for species codes. Highest values for each species in **bold**.

Natural Community	Count	CHAMEL	CHLNIG	CIRPIT	IRILAC	MIMMIC	PAPBEE
Bog	1	0	0	0	0.19	0	0
Boreal Forest	5	1.09	0.36	1.59	**33.55**	1.02	0
Coastal Fen	3	2.03	0	0.01	1.18	0	0
Dry Northern Forest	4	0.76	0	3.10	0.02	4.10	0
Dry-mesic Northern Forest	3	1.53	0	1.58	1.86	0	0
Dry-mesic Southern Forest	3	0	0	0.02	0.29	0	7.47
Emergent Marsh	3	0	22.38	0	0.35	0	0.51
Floodplain Forest	0	0	0	0	0	0	0
Great Lakes Barrens	3	1.92	0	6.93	0.12	0	0
Great Lakes Marsh	6	6.24	**55.59**	0.09	1.09	5.86	0.01
Hardwood-Conifer Swamp	4	0	3.46	0.01	5.98	1.08	0
Interdunal Wetland	4	10.79	0	4.88	1.03	4.18	0
Intermittent Wetland	1	0	0	0	0.00	0	0
Inundated Shrub Swamp	1	0	0	0	0.00	0	0
Lakeplain Oak Openings	2	0	1.11	0	0	0	0.41
Lakeplain Wet Prairie	2	0	2.09	0	0	0	18.86
Lakeplain Wet-mesic Prairie	1	0	0	0	0	0	**67.87**
Limestone Bedrock Glade	2	0	0	0.02	9.03	0	0
Limestone Bedrock Lakeshore	2	0	0	0.02	6.93	0	0
Limestone Cobble Shore	3	1.55	0	1.53	2.37	0	0
Limestone Lakeshore Cliff	1	0	0	0	0.10	0	0
Mesic Northern Forest	5	0.52	0.10	14.75	5.02	11.78	0
Mesic Southern Forest	1	0	0	0.02	0	0	0
Northern Fen	2	0	0	0.00	2.05	0	0
Northern Hardwood Swamp	3	0	1.20	0.03	0.03	0	0
Northern Shrub Thicket	4	0.06	0.63	0.03	1.71	0	0
Northern Wet Meadow	4	0.02	0.02	0.23	0.50	0	0
Oak-Pine Barrens	0	0	0	0	0	0	0
Open Dunes	3	**54.37**	0	**55.30**	0.65	0	0
Open Water	4	0.88	0.30	0.60	0	1.69	0
Pine Barrens	1	0.05	0	0	0	0	0
Poor Conifer Swamp	2	0.00	0	0	0.29	0	0
Poor Fen	1	0	0	0	0.04	0	0
Rich Conifer Swamp	4	0.02	0	0.03	9.05	**63.79**	0

Rich Tamarack Swamp	1	0	0	0	0.33	0	0
Sand and Gravel Beach	4	5.52	0	1.79	0.13	6.51	0
Southern Hardwood Swamp	1	0	0	0	0	0	2.81
Southern Shrub-carr	1	0	0.31	0	0	0	0
Submergent Marsh	2	0	12.43	0	0.03	0	0
Wet Prairie	1	0	0.02	0	0	0	0
Wet-mesic Flatwoods	1	0	0	0	0	0	2.05
Wooded Dune and Swale	3	12.65	0	7.43	16.07	0	0
Count		18	14	23	30	9	8

Table A3, continued. Proportional association of each at-risk species with each natural community. See Table A4 for species codes. Highest values for each species in **bold**.

Natural Community	PLALEU	RALELE	SISCAT	SOLHOU	SOMHIN	STEHIR	TRIHUR
Bog	0	0	1.04	0	0	0.64	0
Boreal Forest	0	0	14.85	18.14	1.38	15.21	1.52
Coastal Fen	0	0	0.15	6.53	**61.11**	0.20	1.99
Dry Northern Forest	0	0	0.68	0.15	0.61	0	0.71
Dry-mesic Northern Forest	0	0	6.11	0.76	0.17	1.19	3.82
Dry-mesic Southern Forest	0	0	0	0	1.96	0	0.01
Emergent Marsh	0	0	0.18	0.21	0	0.74	0.01
Floodplain Forest	0	0	10.83	0	0	0	0
Great Lakes Barrens	0	0	0	0.54	0	0.17	4.17
Great Lakes Marsh	17.23	**98.43**	**36.46**	12.44	0	**56.23**	4.03
Hardwood-Conifer Swamp	0.71	0	1.95	0.34	0.43	1.29	0.48
Interdunal Wetland	0	0	0	3.68	0	0.01	5.52
Intermittent Wetland	0	0	0	0	0	0	0
Inundated Shrub Swamp	0	0	0	0	0	0	0
Lakeplain Oak Openings	0.76	0	0	0	0	0.64	0
Lakeplain Wet Prairie	**62.99**	0.14	0	0	0	8.48	0
Lakeplain Wet-mesic Prairie	11.16	0	0	0	0	0.84	0
Limestone Bedrock Glade	0	0	2.07	0.17	0	0	0
Limestone Bedrock Lakeshore	0	0	0	1.09	0	0.24	0
Limestone Cobble Shore	0	0	0.84	11.80	5.63	1.71	1.37
Limestone Lakeshore Cliff	0	0	0	0	0	0	0
Mesic Northern Forest	0	0	7.14	1.82	0	1.06	3.18
Mesic Southern Forest	0.03	0	0	0	0	0	0
Northern Fen	0	0	0.50	0.54	2.10	0	0.01
Northern Hardwood Swamp	0	0	0.74	0	0	0.67	0
Northern Shrub Thicket	4.84	0	4.73	0.11	0.46	2.11	2.24
Northern Wet Meadow	0.07	0	2.32	1.25	1.01	2.92	0
Oak-Pine Barrens	0	0	2.47	0	0	0	0
Open Dunes	0	0	0.00	5.31	0.23	0.27	**46.73**
Open Water	0	0	0	0	0	0	0.37
Pine Barrens	0	0	0	0	0	0	0
Poor Conifer Swamp	0	0	0.28	0	0	0	0
Poor Fen	0	0	0.08	0.10	0	0	0
Rich Conifer Swamp	0	0	3.57	4.94	9.66	1.04	0.02
Rich Tamarack Swamp	0	0	0.31	0	0	0	0
Sand and Gravel Beach	0	0	0	0.13	0	0.79	9.96
Southern Hardwood Swamp	0.00	0	0	0	0	0	0
Southern Shrub-carr	0.51	0.04	0	0	0	0.56	0
Submergent Marsh	0	0	0	0	0	0	0
Wet Prairie	0	0	0	0	0	0	0
Wet-mesic Flatwoods	1.69	1.38	0	0	0	0.81	0
Wooded Dune and Swale Complex	0	0	2.72	**29.95**	15.23	2.17	13.86
Count	11	4	23	21	13	24	19

Table A4. Key to species codes used in Table A3.

Code	Common Name	Scientific name
CHAMEL	Piping plover	*Charadrius melodus*
CHLNIG	Black tern	*Chlidonias niger*
CIRPIT	Pitcher’s thistle	*Cirsium pitcheri*
IRILAC	Dwarf lake Iris	*Iris lacustris*
MIMMIC	Michigan monkey flower	*Mimulus michiganensis*
PAPBEE	Blazing star stem borer	*Papaipema beeriana*
PLALEU	Eastern prairie fringed orchid	*Platanthera leucophaea*
RALELE	King rail	*Rallus elegans*
SISCAT	Eastern massasauga	*Sistrurus catenatus*
SOLHOU	Houghton’s goldenrod	*Solidago houghtonii*
SOMHIN	Hine's emerald dragonfly	*Somatochlora hineana*
STEHIR	Common tern	*Sterna hirundo*
TRIHUR	Lake Huron locust	*Trimerotropis huroniana*

Table A5. Impact scores at ranks for natural communities under CNRM scenarios. Mean Weight: mean across species values for each community (Table A3); Comm. Change: percent change in area under each scenario (Table A5); Impact score: Mean Weight X Comm. Change.

		CNRM-Average			CNRM-High			CNRM-Low			
Natural community	Mean Weight	Comm. Change	Impact score	Rank	Comm. Change	Impact score	Rank	Comm. Change	Impact score	Rank	Mean Rank
Great Lakes Marsh	22.59	12.61	284.81	1	14.68	331.59	1	13.85	312.98	1	1.00
Coastal Fen	5.63	18.28	102.92	2	21.95	123.58	4	2.65	14.91	5	3.67
Open Dunes	12.53	2.12	26.58	5	2.63	32.93	6	4.57	57.23	2	4.33
Lakeplain Wet Prairie	7.12	12.27	87.39	3	19.09	135.93	2	0.06	0.45	12	5.67
Limestone Cobble Shore	2.06	31.97	65.93	4	6.82	14.06	12	11.77	24.28	4	6.67
Wooded Dune and Swale	7.70	0.84	6.44	7	3.14	24.21	8	1.62	12.47	6	7.00
Sand and Gravel Beach	1.91	10.60	20.24	6	5.51	10.52	16	16.47	31.46	3	8.33
Emergent Marsh	1.88	2.67	5.00	10	13.68	25.66	7	1.15	2.16	9	8.67
Interdunal Wetland	2.31	2.58	5.98	8	5.64	13.05	13	2.78	6.43	7	9.33
Limestone Bedrock Lakeshore	0.64	7.06	4.50	11	7.60	4.84	20	3.99	2.54	8	13.00
Northern Shrub Thicket	1.30	0.62	0.81	17	10.86	14.12	11	0.91	1.18	11	13.00
Submergent Marsh	0.96	0.82	0.79	18	60.24	57.76	5	0.04	0.04	18	13.67
Boreal Forest	6.82	0.18	1.25	15	1.36	9.27	17	0.02	0.11	15	15.67
Lakeplain Oak Openings	0.23	1.41	0.32	20	48.83	11.01	14	0.23	0.05	16	16.67
Northern Wet Meadow	0.64	5.16	3.31	12	4.50	2.89	25	0.45	0.29	13	16.67
Rich Conifer Swamp	7.09	0.12	0.82	16	2.66	18.88	10	0.00	0.00	25	17.00
Lakeplain Wet-mesic Prairie	6.14	0.97	5.93	9	21.60	132.67	3	0.00	0.00	42	18.00
Hardwood-Conifer Swamp	1.21	1.71	2.07	14	5.83	7.06	18	0.01	0.01	23	18.33
Limestone Bedrock Glade	0.87	3.04	2.64	13	1.65	1.43	26	0.02	0.02	20	19.67
Northern Fen	0.40	0.34	0.14	25	26.93	10.76	15	0.09	0.04	19	19.67
Great Lakes Barrens	1.06	0.27	0.29	21	0.64	0.68	29	1.16	1.23	10	20.00
Mesic Northern Forest	3.49	0.10	0.35	19	0.38	1.32	27	0.01	0.04	17	21.00
Dry-mesic Southern Forest	0.75	0.14	0.11	26	5.79	4.34	22	0.01	0.01	22	23.33
Floodplain Forest	0.83	0.27	0.23	23	27.13	22.60	9	0.00	0.00	40	24.00
Dry-mesic Northern Forest	1.31	0.17	0.22	24	0.95	1.25	28	0.01	0.01	21	24.33
Wet-mesic Flatwoods	0.46	0.17	0.08	27	14.80	6.75	19	0.00	0.00	29	25.00
Dry Northern Forest	0.78	0.31	0.24	22	0.41	0.32	30	0.00	0.00	26	26.00
Southern Hardwood Swamp	0.22	0.28	0.06	29	21.54	4.66	21	0.00	0.00	28	26.00
Open Water	0.30	0.17	0.05	30	0.09	0.03	35	0.47	0.14	14	26.33
Northern Hardwood Swamp	0.20	0.37	0.08	28	14.77	3.02	24	0.00	0.00	39	30.33
Limestone Lakeshore Cliff	0.01	3.53	0.03	32	2.84	0.02	36	0.83	0.01	24	30.67
Poor Fen	0.02	0.46	0.01	34	10.52	0.18	31	0.00	0.00	27	30.67
Southern Shrub-carr	0.11	0.25	0.03	31	29.21	3.19	23	0.00	0.00	38	30.67
Wet Prairie	0.00	0.00	0.00	41	99.28	0.12	32	0.00	0.00	31	34.67
Mesic Southern Forest	0.00	0.36	0.00	35	5.06	0.02	37	0.00	0.00	33	35.00
Poor Conifer Swamp	0.04	0.03	0.00	36	0.79	0.03	34	0.00	0.00	36	35.33
Oak-Pine Barrens	0.19	0.00	0.00	40	0.54	0.10	33	0.00	0.00	37	36.67
Pine Barrens	0.00	0.19	0.00	37	0.09	0.00	40	0.00	0.00	34	37.00
Rich Tamarack Swamp	0.05	0.00	0.00	38	0.34	0.02	38	0.00	0.00	35	37.00
Bog	0.14	0.07	0.01	33	0.10	0.01	39	0.00	0.00	41	37.67
Intermittent Wetland	0.00	0.00	0.00	42	9.13	0.00	41	0.00	0.00	30	37.67
Inundated Shrub Swamp	0.00	0.00	0.00	39	0.79	0.00	42	0.00	0.00	32	37.67

Table A6. Impact scores at ranks for natural communities under MIROC5 scenarios. Mean Weight: mean across species values for each community (Table A3); Comm. Change: percent change in area under each scenario (Table A5); Impact score: Mean Weight X Comm. Change.

		MIROC5-Average			MIROC5-High			MIROC5-Low			
Natural community	Mean Weight	Comm. Change	Impact Score	Rank	Comm. Change	Impact Score	Rank	Comm. Change	Impact Score	Rank	Mean Rank
Great Lakes Marsh	22.59	21.10	476.69	2	7.42	167.69	2	6.76	152.69	1	1.67
Coastal Fen	5.63	156.78	882.77	1	19.53	109.96	4	1.07	6.05	6	3.67
Limestone Cobble Shore	2.06	170.78	352.23	3	6.85	14.13	10	10.44	21.54	3	5.33
Open Dunes	12.53	5.22	65.41	5	1.06	13.26	11	2.56	32.02	2	6.00
Sand and Gravel Beach	1.91	14.34	27.39	7	3.54	6.77	13	10.55	20.14	4	8.00
Wooded Dune and Swale Complex	7.70	2.13	16.42	9	1.34	10.35	12	0.88	6.80	5	8.67
Northern Shrub Thicket	1.30	4.32	5.61	11	17.47	22.70	8	1.80	2.34	8	9.00
Lakeplain Wet Prairie	7.12	14.29	101.78	4	4.21	30.00	7	0.00	0.03	17	9.33
Interdunal Wetland	2.31	9.89	22.88	8	2.64	6.11	14	1.62	3.75	7	9.67
Northern Wet Meadow	0.64	3.43	2.20	12	49.21	31.62	6	0.62	0.40	13	10.33
Limestone Bedrock Lakeshore	0.64	87.92	56.04	6	5.33	3.40	16	1.65	1.05	10	10.67
Emergent Marsh	1.88	4.53	8.50	10	1.74	3.26	17	0.51	0.97	11	12.67
Lakeplain Wet-mesic Prairie	6.14	0.04	0.27	17	5.85	35.95	5	0.00	0.00	26	16.00
Northern Fen	0.40	0.84	0.34	16	2.99	1.20	23	0.15	0.06	15	18.00
Hardwood-Conifer Swamp	1.21	0.32	0.38	15	2.82	3.41	15	0.00	0.00	25	18.33
Submergent Marsh	0.96	0.54	0.52	13	1.24	1.19	24	0.02	0.01	19	18.67
Boreal Forest	6.82	-0.37	-2.51	42	50.19	342.51	1	0.02	0.16	14	19.00
Limestone Bedrock Glade	0.87	0.50	0.43	14	2.51	2.18	20	0.00	0.00	24	19.33
Great Lakes Barrens	1.06	0.23	0.25	18	0.18	0.19	32	0.47	0.50	12	20.67
Mesic Northern Forest	3.49	-0.01	-0.02	39	4.81	16.80	9	0.01	0.03	16	21.33
Lakeplain Oak Openings	0.23	0.30	0.07	20	3.39	0.76	27	0.10	0.02	18	21.67
Dry-mesic Northern Forest	1.31	0.04	0.06	21	0.76	1.00	25	0.00	0.00	21	22.33
Rich Conifer Swamp	7.09	-0.09	-0.67	41	21.02	148.94	3	0.00	0.00	23	22.33
Open Water	0.30	-1.46	-0.43	40	5.62	1.66	21	3.86	1.14	9	23.33
Southern Shrub-carr	0.11	0.09	0.01	24	20.39	2.22	19	0.00	0.00	28	23.67
Dry-mesic Southern Forest	0.75	0.02	0.02	23	0.70	0.53	31	0.01	0.01	20	24.67
Limestone Lakeshore Cliff	0.01	5.63	0.04	22	1.37	0.01	35	0.43	0.00	22	26.33
Dry Northern Forest	0.78	0.12	0.09	19	0.10	0.08	34	0.00	0.00	27	26.67
Northern Hardwood Swamp	0.20	0.02	0.00	27	3.93	0.80	26	0.00	0.00	31	28.00
Floodplain Forest	0.83	0.01	0.01	25	0.68	0.56	30	0.00	0.00	30	28.33
Wet-mesic Flatwoods	0.46	0.00	0.00	29	5.11	2.33	18	0.00	0.00	41	29.33
Bog	0.14	0.02	0.00	28	0.03	0.00	36	0.00	0.00	29	31.00
Rich Tamarack Swamp	0.05	-0.05	0.00	37	31.30	1.53	22	0.00	0.00	34	31.00
Southern Hardwood Swamp	0.22	0.02	0.01	26	3.24	0.70	29	0.00	0.00	42	32.33
Poor Conifer Swamp	0.04	-0.10	0.00	38	17.34	0.76	28	0.00	0.00	33	33.00
Poor Fen	0.02	0.01	0.00	31	10.57	0.18	33	0.00	0.00	36	33.33
Mesic Southern Forest	0.00	0.23	0.00	30	0.97	0.00	37	0.00	0.00	37	34.67
Oak-Pine Barrens	0.19	0.00	0.00	33	0.00	0.00	40	0.00	0.00	32	35.00
Pine Barrens	0.00	0.00	0.00	32	0.03	0.00	38	0.00	0.00	35	35.00
Inundated Shrub Swamp	0.00	0.00	0.00	34	0.37	0.00	39	0.00	0.00	38	37.00
Wet Prairie	0.00	0.00	0.00	35	0.00	0.00	42	0.00	0.00	39	38.67
Intermittent Wetland	0.00	0.00	0.00	36	0.00	0.00	41	0.00	0.00	40	39.00

Table A7. Predicted inundation (positive values) and expansion (negative values) of MNFI natural communities (Cohen et al. 2025) under six scenarios. Impacts greater than 10% and the greatest impacts for a scenario when none exceeds 10% are in **bold**, as are classes and groups for which at least one scenario satisfies this condition.

Natural community	MIROC5 Average	MIROC5 High	MIROC5 Low	CNRM Average	CNRM High	CNRM Low	Group	Class
Exposed Unclassed	175.54	0.00	9.38	0.00	**0.00**	-10.52	N/A	N/A
N/A	8.46	5.22	2.36	-4.84	**-14.34**	-7.39	N/A	N/A
Not Mapped	0.57	6.89	0.26	-1.57	-3.45	-0.34	N/A	N/A
Plantation	0.02	0.07	0.05	-0.08	-0.11	-0.07	N/A	N/A
Bog	0.02	0.03	0.00	-0.07	-0.10	0.00	Bog	Palustrine
Muskeg	0.00	0.00	0.00	0.00	0.00	0.00	Bog	Palustrine
Coastal Fen	**156.78**	**19.53**	1.07	**-18.28**	**-21.95**	-2.65	Fen	Palustrine
Northern Fen	0.84	2.99	0.15	-0.34	-26.93	-0.09	Fen	Palustrine
Patterned Fen	0.00	0.00	0.00	0.00	0.00	0.00	Fen	Palustrine
Poor Fen	0.01	**10.57**	0.00	-0.46	**-10.52**	0.00	Fen	Palustrine
Prairie Fen	0.00	0.01	0.00	-0.35	**-15.05**	0.00	Fen	Palustrine
Floodplain Forest	0.01	0.68	0.00	-0.27	**-27.13**	0.00	Forested Wetland	Palustrine
Hardwood-Conifer Swamp	0.32	2.82	0.00	-1.71	-5.83	-0.01	Forested Wetland	Palustrine
Northern Hardwood Swamp	0.02	3.93	0.00	-0.37	**-14.77**	0.00	Forested Wetland	Palustrine
Poor Conifer Swamp	-0.10	**17.34**	0.00	-0.03	-0.79	0.00	Forested Wetland	Palustrine
Rich Conifer Swamp	-0.09	**21.02**	0.00	-0.12	-2.66	0.00	Forested Wetland	Palustrine
Rich Tamarack Swamp	-0.05	**31.30**	0.00	0.00	-0.34	0.00	Forested Wetland	Palustrine
Southern Hardwood Swamp	0.02	3.24	0.00	-0.28	**-21.54**	0.00	Forested Wetland	Palustrine
Wet-mesic Flatwoods	0.00	5.11	0.00	-0.17	**-14.80**	0.00	Forested Wetland	Palustrine
Coastal Plain Marsh	0.00	0.00	0.00	0.00	0.00	0.00	Marsh	Palustrine
Emergent Marsh	4.53	1.74	0.51	-2.67	**-13.68**	-1.15	Marsh	Palustrine
Great Lakes Marsh	**21.10**	7.42	6.76	**-12.61**	**-14.68**	**-13.85**	Marsh	Palustrine
Interdunal Wetland	9.89	2.64	1.62	-2.58	-5.64	-2.78	Marsh	Palustrine
Intermittent Wetland	0.00	0.00	0.00	0.00	-9.13	0.00	Marsh	Palustrine
Northern Wet Meadow	3.43	**49.21**	0.62	-5.16	-4.50	-0.45	Marsh	Palustrine
Open Water	-1.46	5.62	3.86	-0.17	-0.09	-0.47	Marsh	Palustrine
Southern Wet Meadow	0.00	2.08	0.00	-0.33	-3.83	0.00	Marsh	Palustrine
Submergent Marsh	0.54	1.24	0.02	-0.82	**-60.24**	-0.04	Marsh	Palustrine
Inundated Shrub Swamp	0.00	0.37	0.00	0.00	-0.79	0.00	Shrub Wetland	Palustrine
Northern Shrub Thicket	4.32	**17.47**	1.80	-0.62	**-10.86**	-0.91	Shrub Wetland	Palustrine
Southern Shrub-carr	0.09	**20.39**	0.00	-0.25	**-29.21**	0.00	Shrub Wetland	Palustrine

Lakeplain Wet Prairie	**14.29**	4.21	0.00	**-12.27**	**-19.09**	-0.06	Wet Prairie	Palustrine
Lakeplain Wet-mesic Prairie	0.04	5.85	0.00	-0.97	**-21.60**	0.00	Wet Prairie	Palustrine
Wet Prairie	0.00	0.00	0.00	0.00	**-99.28**	0.00	Wet Prairie	Palustrine
Wooded Dune and Swale Complex	2.13	1.34	0.88	-0.84	-3.14	-1.62	Wooded Dune and Swale	Palustrine/Terrestrial
Granite Bedrock Glade	0.00	0.01	0.00	-0.08	-0.01	0.00	Bedrock Glade	Primary
Limestone Bedrock Glade	0.50	2.51	0.00	-3.04	-1.65	-0.02	Bedrock Glade	Primary
Northern Bald	0.00	**83.39**	0.00	0.00	0.00	0.00	Bedrock Glade	Primary
Volcanic Bedrock Glade	-0.18	**75.51**	0.07	-0.04	-0.06	-0.07	Bedrock Glade	Primary
Alvar	0.68	0.37	0.83	-0.53	-2.99	-1.26	Bedrock Grassland	Primary
Granite Bedrock Lakeshore	4.22	0.66	1.04	-0.74	-0.80	-1.41	Bedrock Lakeshore	Primary
Limestone Bedrock Lakeshore	**87.92**	5.33	1.65	-7.06	-7.60	-3.99	Bedrock Lakeshore	Primary
Sandstone Bedrock Lakeshore	3.90	1.00	4.98	-2.48	-1.15	-5.82	Bedrock Lakeshore	Primary
Volcanic Bedrock Lakeshore	1.45	**10.00**	2.82	-1.05	-0.84	-2.25	Bedrock Lakeshore	Primary
Great Lakes Barrens	0.23	0.18	0.47	-0.27	-0.64	-1.16	Dunes	Primary
Open Dunes	5.22	1.06	2.56	-2.12	-2.63	-4.57	Dunes	Primary
Granite Cliff	0.00	0.00	0.00	0.00	0.00	0.00	Inland Cliff	Primary
Limestone Cliff	7.40	0.62	1.17	-0.82	-1.20	-3.02	Inland Cliff	Primary
Sandstone Cliff	0.54	0.12	0.13	-0.03	-0.08	0.02	Inland Cliff	Primary
Volcanic Cliff	-0.23	**86.64**	0.01	-0.02	-0.02	-0.01	Inland Cliff	Primary
Clay Bluff	7.45	2.09	7.00	-5.20	-4.52	**-12.22**	Lakeshore Cliff/Bluff	Primary
Granite Lakeshore Cliff	**14.00**	0.17	0.02	-0.32	-0.38	-0.01	Lakeshore Cliff/Bluff	Primary
Limestone Lakeshore Cliff	5.63	1.37	0.43	-3.53	-2.84	-0.83	Lakeshore Cliff/Bluff	Primary
Sandstone Lakeshore Cliff	1.54	0.32	3.89	-0.78	-0.39	-3.04	Lakeshore Cliff/Bluff	Primary
Volcanic Lakeshore Cliff	1.49	0.13	3.20	-0.30	-0.23	-0.80	Lakeshore Cliff/Bluff	Primary
Limestone Cobble Shore	**170.78**	6.85	**10.44**	**-31.97**	-6.82	**-11.77**	Sand/Cobble Shore	Primary
Sand and Gravel Beach	**14.34**	3.54	**10.55**	**-10.60**	-5.51	**-16.47**	Sand/Cobble Shore	Primary
Sandstone Cobble Shore	1.97	0.67	3.71	-1.53	-0.78	-4.59	Sand/Cobble Shore	Primary
Volcanic Cobble Shore	1.67	**46.70**	4.77	-2.91	-5.26	-5.16	Sand/Cobble Shore	Primary
Sinkhole	0.07	0.00	0.07	0.00	0.00	0.07	Karst	Subterranean/Sink
Boreal Forest	-0.37	**50.19**	0.02	-0.18	-1.36	0.02	Forest	Terrestrial
Dry Northern Forest	0.12	0.10	0.00	-0.31	-0.41	0.00	Forest	Terrestrial

Dry Southern Forest	0.13	1.98	0.00	-0.09	**-32.69**	0.00	Forest	Terrestrial
Dry-mesic Northern Forest	0.04	0.76	0.00	-0.17	-0.95	-0.01	Forest	Terrestrial
Dry-mesic Southern Forest	0.02	0.70	0.01	-0.14	-5.79	-0.01	Forest	Terrestrial
Mesic Northern Forest	-0.01	4.81	0.01	-0.10	-0.38	-0.01	Forest	Terrestrial
Mesic Southern Forest	0.23	0.97	0.00	-0.36	-5.06	0.00	Forest	Terrestrial
Dry Sand Prairie	0.00	0.00	0.00	0.00	0.00	0.00	Prairie	Terrestrial
Lakeplain Oak Openings	0.30	3.39	0.10	-1.41	**-48.83**	-0.23	Savanna	Terrestrial
Oak Barrens	3.29	2.02	1.87	-2.06	-1.00	-3.73	Savanna	Terrestrial
Oak-Pine Barrens	0.00	0.00	0.00	0.00	-0.54	0.00	Savanna	Terrestrial
Pine Barrens	0.00	0.03	0.00	-0.19	-0.09	0.00	Savanna	Terrestrial
	2.13	1.34	0.88	-0.84	-3.14	-1.62		
>10%	8	13	2	5	19	5		
Maximum	175.54	86.64	10.55	-31.97	-99.28	-16.47		

Table A8. Distribution of natural communities across focal areas by acreage and percent.

	Drummond Island		Wilderness State Park		Wildfowl Bay	
Natural Community	Acres		Acres		Acres	
Alvar	2,420,053	4.06%	0.00	0.00%	0	0.00%
Boreal Forest	31,909,064	53.48%	4,492,135.63	18.36%	0	0.00%
Coastal Fen	0	0.00%	2,722,633.15	11.13%	0	0.00%
Dry Northern Forest	67,608	0.11%	0.00	0.00%	0	0.00%
Dry-mesic Northern Forest	697,996	1.17%	0.00	0.00%	0	0.00%
Dry-mesic Southern Forest	0	0.00%	0.00	0.00%	390,750	0.51%
Emergent Marsh	943,919	1.58%	174,351.92	0.71%	3,715,672	4.84%
Great Lakes Barrens	0	0.00%	268,212.40	1.10%	0	0.00%
Great Lakes Marsh	2,286,243	3.83%	5,709,827.03	23.34%	62,877,634	81.97%
Hardwood-Conifer Swamp	5,314,373	8.91%	777,701.30	3.18%	52,002	0.07%
Interdunal Wetland	0	0.00%	265,080.08	1.08%	0	0.00%
Lakeplain Oak Openings	0	0.00%	0.00	0.00%	2,629,089	3.43%
Lakeplain Wet Prairie	0	0.00%	0.00	0.00%	2,147,914	2.80%
Lakeplain Wet-mesic Prairie	0	0.00%	0.00	0.00%	840,441	1.10%
Limestone Bedrock Glade	1,468,540	2.46%	0.00	0.00%	0	0.00%
Limestone Bedrock Lakeshore	3,604,045	6.04%	0.00	0.00%	0	0.00%
Limestone Cliff	1,222,439	2.05%	0.00	0.00%	0	0.00%
Limestone Cobble Shore	1,612,443	2.70%	3,630,278.97	14.84%	0	0.00%
Mesic Northern Forest	2,707,300	4.54%	186,178.73	0.76%	172,773	0.23%
Mesic Southern Forest	0	0.00%	0.00	0.00%	347,688	0.45%
Northern Fen	72,595	0.12%	441,949.23	1.81%	0	0.00%
Northern Hardwood Swamp	165,967	0.28%	0.00	0.00%	0	0.00%
Northern Shrub Thicket	1,146,610	1.92%	328,486.07	1.34%	586,523	0.76%
Northern Wet Meadow	1,919,516	3.22%	40,350.80	0.16%	62,844	0.08%
Open Dunes	0	0.00%	1,207,618.29	4.94%	0	0.00%
Poor Conifer Swamp	226,002	0.38%	0.00	0.00%	0	0.00%
Poor Fen	43,583	0.07%	20,125.03	0.08%	0	0.00%
Rich Conifer Swamp	1,816,777	3.05%	1,564,702.38	6.39%	0	0.00%
Rich Tamarack Swamp	939	0.00%	79,904.17	0.33%	0	0.00%
Sand and Gravel Beach	18,269	0.03%	75,688.04	0.31%	0	0.00%
Southern Hardwood Swamp	0	0.00%	0.00	0.00%	694,475	0.91%
Southern Shrub-carr	0	0.00%	0.00	0.00%	645,034	0.84%
Submergent Marsh	0	0.00%	35,533	0.15%	0	0.00%
Wet Prairie	0	0.00%	0.00	0.00%	152,296	0.20%
Wet-mesic Flatwoods	0	0.00%	0.00	0.00%	1,395,422	1.82%
Wooded Dune/Swale	0	0.00%	2,447,445	10.00%	0	0.00%
		100.00%		100.00%		100.00%
sum:	59,664,281		24,468,200.90		76,710,557	

Table A9. Predicted percent change in species occurrence polygons for 13 at-risk species for six climate scenarios, relative to baseline lake levels. Positive values represent habitat expansion and negative values indicate habitat inundation. Impacts greater than 10% and the greatest impacts for a scenario when none exceeds 10% are in **bold**.

		MIROC5				CNRM			
Scientific Name	**Common Name**	**Average**	**High**	**Low**	**Mean**	**Average**	**High**	**Low**	**Mean**
Charadrius melodus	Piping plover	4.26	3.39	0.51	2.72	-7.19	-6.64	-2.07	-5.30
Chlidonias niger	Black tern	**17.30**	8.13	1.72	9.05	**-19.65**	**-18.35**	**-6.37**	-14.79
Cirsium pitcheri	Pitcher's thistle	1.04	1.43	0.09	0.85	-2.78	-4.30	-0.65	-2.58
Iris lacustris	Dwarf lake iris	4.53	0.94	0.02	1.83	-1.23	-3.09	-0.11	-1.48
Mimulus michiganensis	Michigan monkey flower	2.93	3.48	0.08	2.16	-6.79	-7.55	-0.88	-5.07
Papaipema beeriana	Blazing star borer	0.00	2.54	0.00	0.85	-0.38	-13.61	0.00	-4.66
Platanthera leucophaea	Eastern prairie fringed orchid	0.30	**14.60**	0.00	4.96	-4.82	**-54.12**	0.00	-19.65
Rallus elegans	King rail	0.00	1.73	0.00	0.58	0.00	**-51.19**	0.00	-17.06
Sistrurus catenatus	Eastern massasauga	0.18	0.14	0.01	0.11	-0.23	-20.92	-0.02	-7.06
Solidago houghtonii	Houghton's goldenrod	2.20	6.76	0.36	3.11	-7.64	**-13.25**	-0.96	-7.28
Somatochlora hineana	Hine's emerald dragonfly	0.07	3.15	0.00	1.07	-2.53	**-28.12**	0.00	-10.22
Sterna hirundo	Common tern	**15.90**	3.94	4.80	8.21	**-14.63**	-7.62	-1.61	-7.96
Trimerotropis huroniana	Lake Huron locust	2.17	3.45	0.55	2.06	-5.98	-7.05	-1.84	-4.96

Table A10. Predicted percent change in habitat for 13 at-risk species under six climate scenarios at three focal areas, relative to baseline lake levels: *Wildfowl* Bay in the Saginaw Bay in Lake Huron, Waugoshance Point in *Wilderness* State Park in Lake Michigan, and the *Drummond* Island region at the outlet of the St. Mary's River at Lake Huron. Positive values represent habitat expansion and negative values indicate habitat inundation. Impacts greater than 10% and the greatest impacts for a scenario when none exceeds 10% are in **bold**. See Figures 21-23.

Scientific Name	Common Name	MIROC5 (mean)			CNRM (mean)		
		Wildfowl	Wilderness	Drummond	Wildfowl	Wilderness	Drummond
Charadrius melodus	Piping plover	1.06	**14.07**	**21.33**	-1.23	**-13.98**	0.21
Chlidonias niger	Black tern	9.73	**23.66**	**10.26**	**-19.26**	**-13.31**	-6.75
Cirsium pitcheri	Pitcher's thistle	0.03	**10.38**	6.94	-0.04	**-10.68**	0.20
Iris lacustris	Dwarf lake iris	0.39	1.78	2.52	-2.40	-2.77	-1.49
Mimulus michiganensis	Michigan monkey flower	1.02	3.96	**24.23**	-1.43	-6.68	0.30
Papaipema beeriana	Blazing star borer	6.48	0.01	0.00	**-16.56**	-0.10	0.00
Platanthera leucophaea	Eastern prairie fringed orchid	8.14	7.22	3.18	**-18.89**	-2.72	-2.10
Rallus elegans	King rail	**16.74**	**41.23**	**18.16**	**-19.33**	**-15.54**	**-11.93**
Sistrurus catenatus	Eastern massasauga	6.51	**15.66**	7.29	-8.92	-6.61	-4.82
Solidago houghtonii	Houghton's goldenrod	2.20	**10.54**	7.31	-2.63	-7.44	-2.49
Somatochlora hineana	Hine's emerald dragonfly	0.09	8.02	2.39	-0.39	-10.74	-0.68
Sterna hirundo	Common tern	**10.49**	**24.34**	**13.96**	**-14.15**	**-10.08**	-7.00
Trimerotropis huroniana	Lake Huron locust	0.76	**11.95**	**36.65**	-1.49	**-12.29**	1.33

APPENDIX B: RESULTS OF FISHNET ANALYSIS

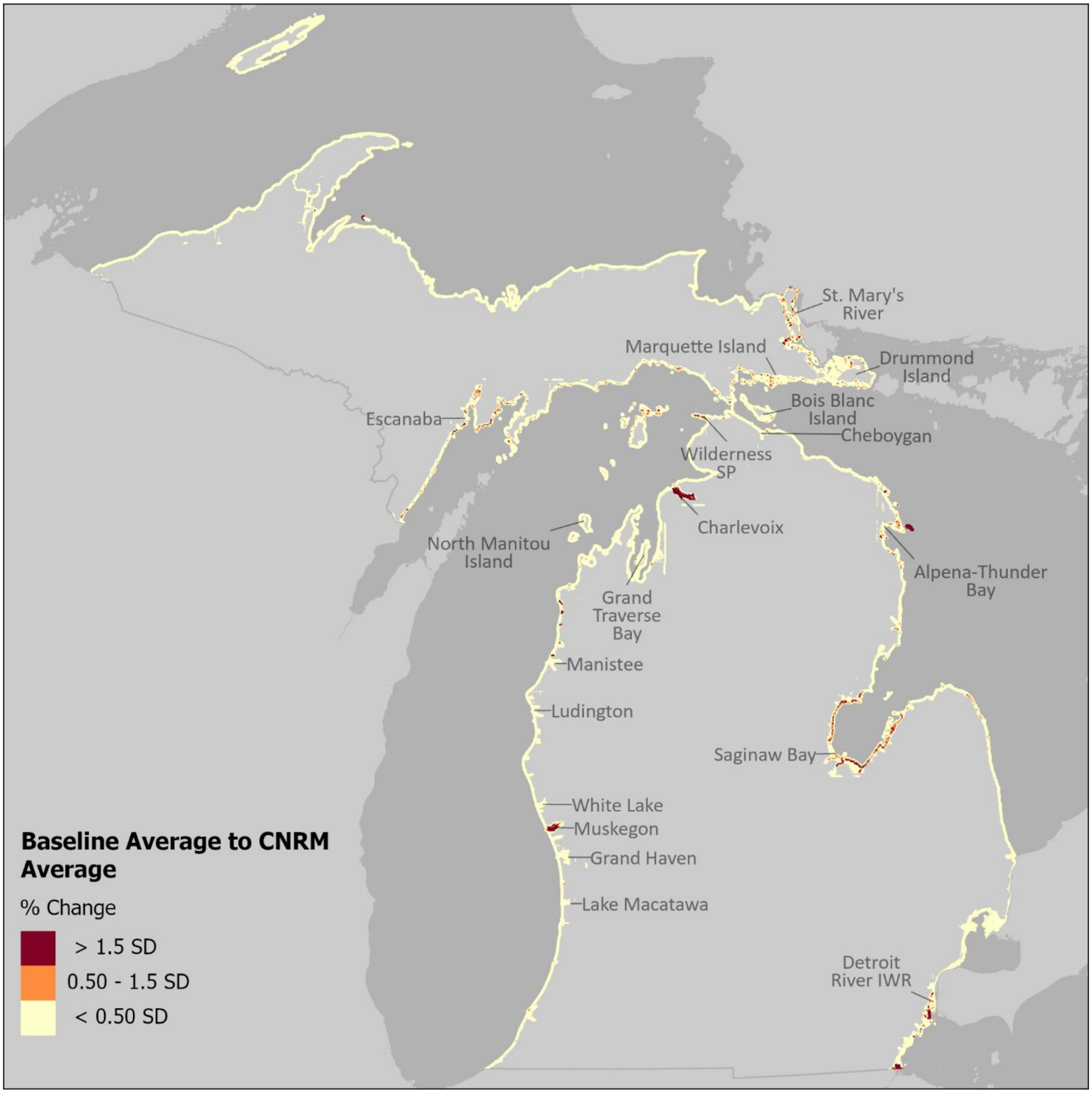

Figure B1. Regional variation of inundation and expansion according CNRM-average scenario.

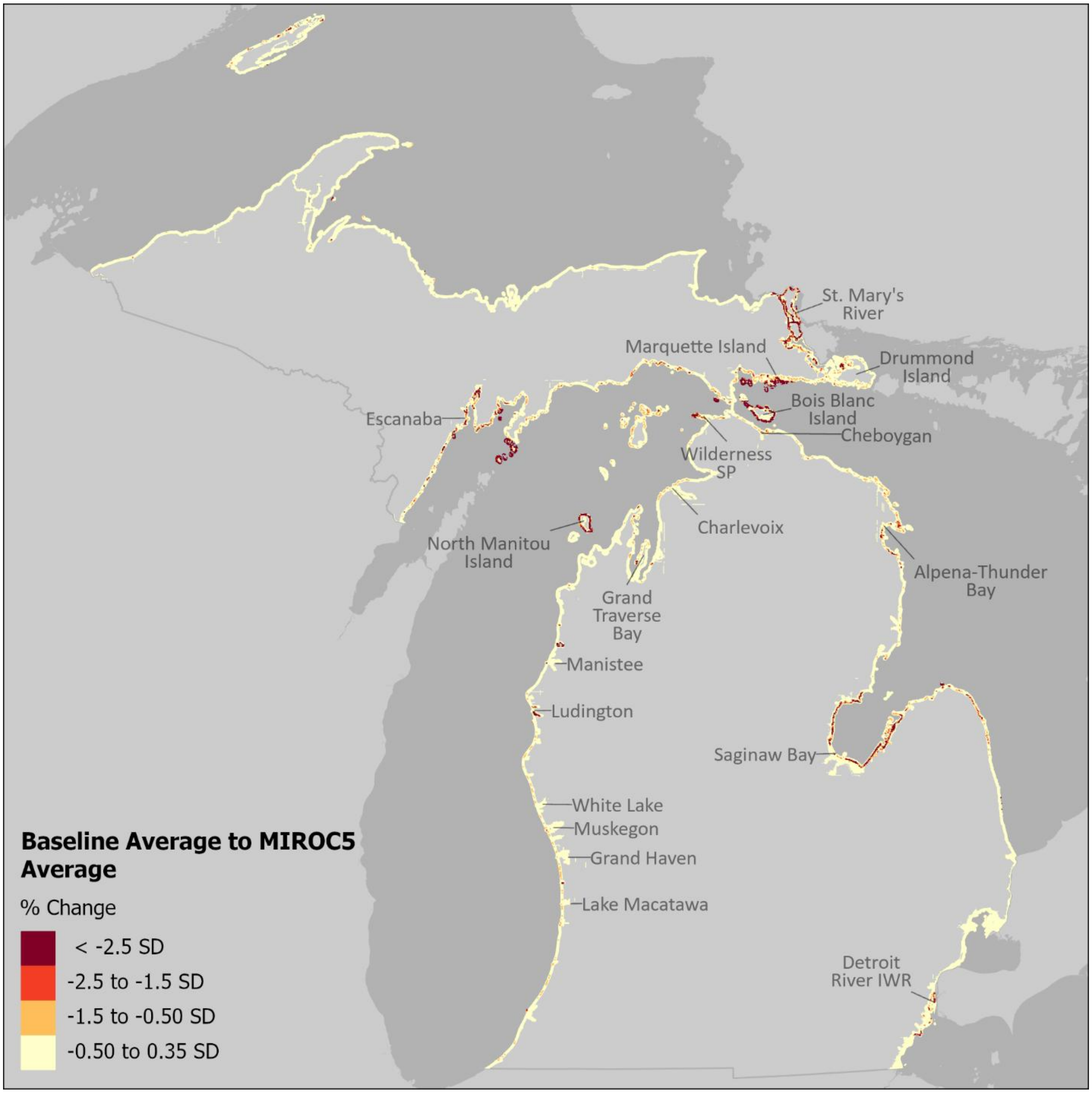

Figure B2. Regional variation of inundation and expansion according MIROC5-average scenario.

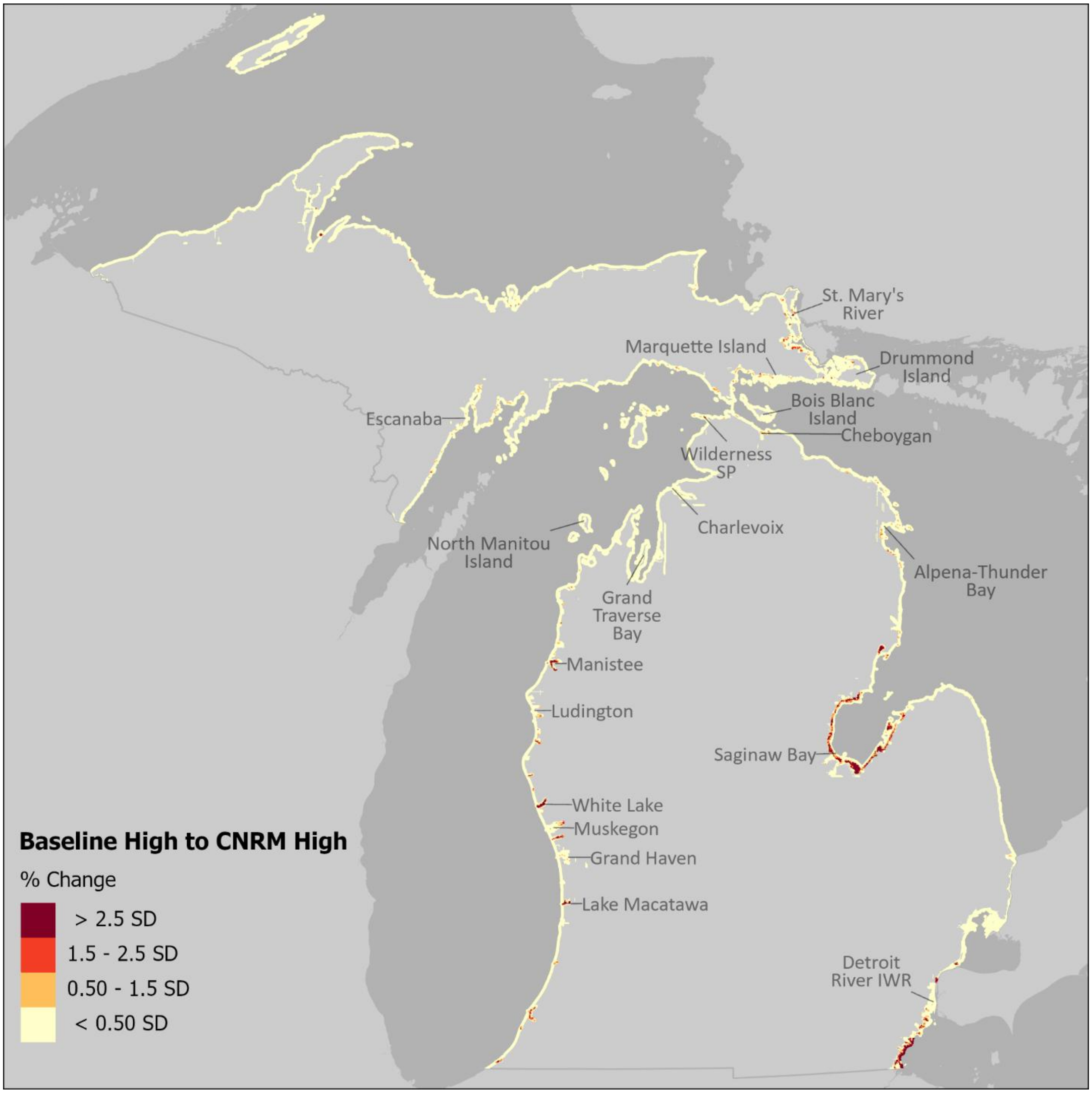

Figure B3. Regional variation of inundation and expansion according CNRM-high scenario.

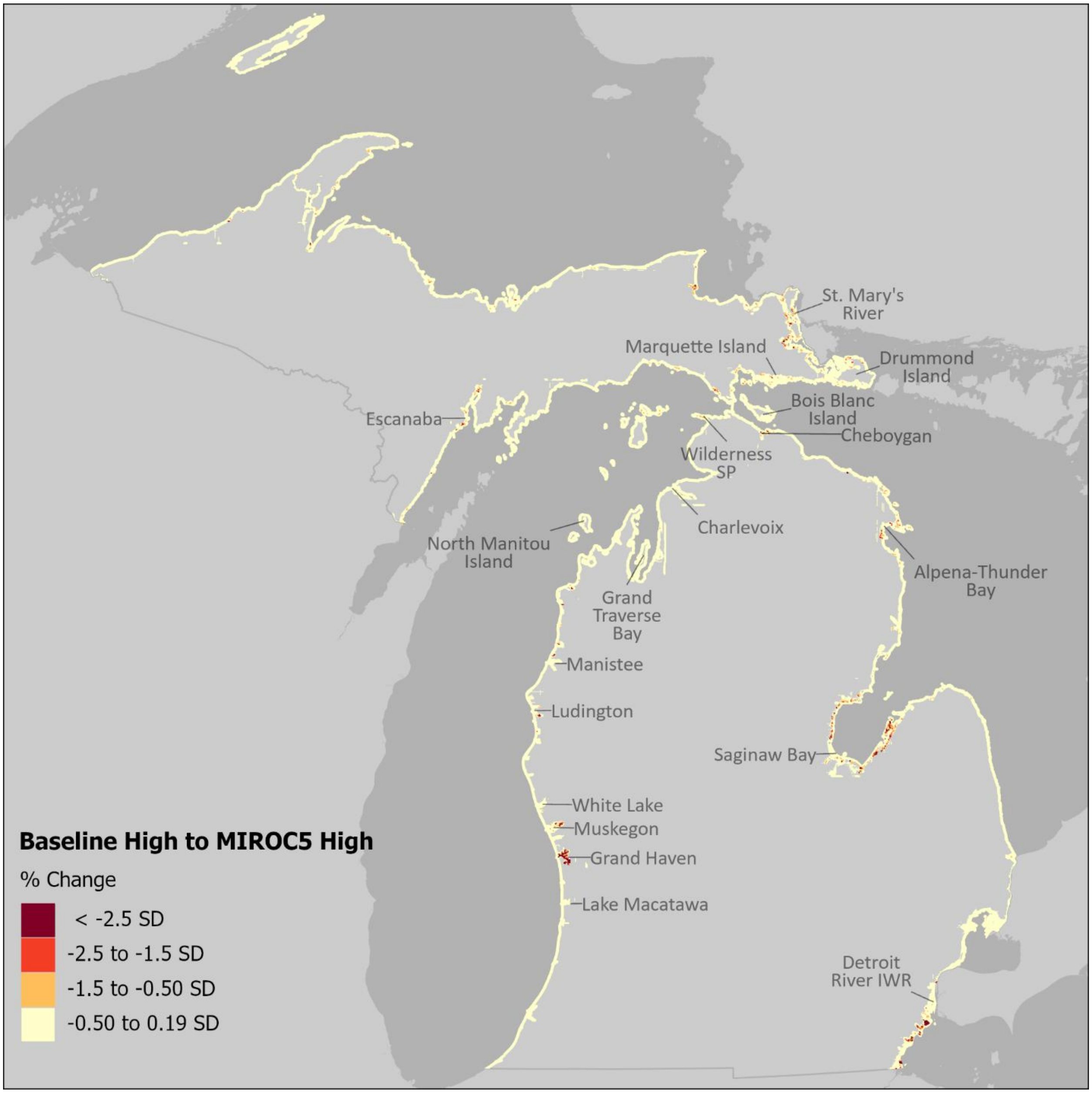

Figure B4. Regional variation of inundation and expansion according MIROC5-High scenario.

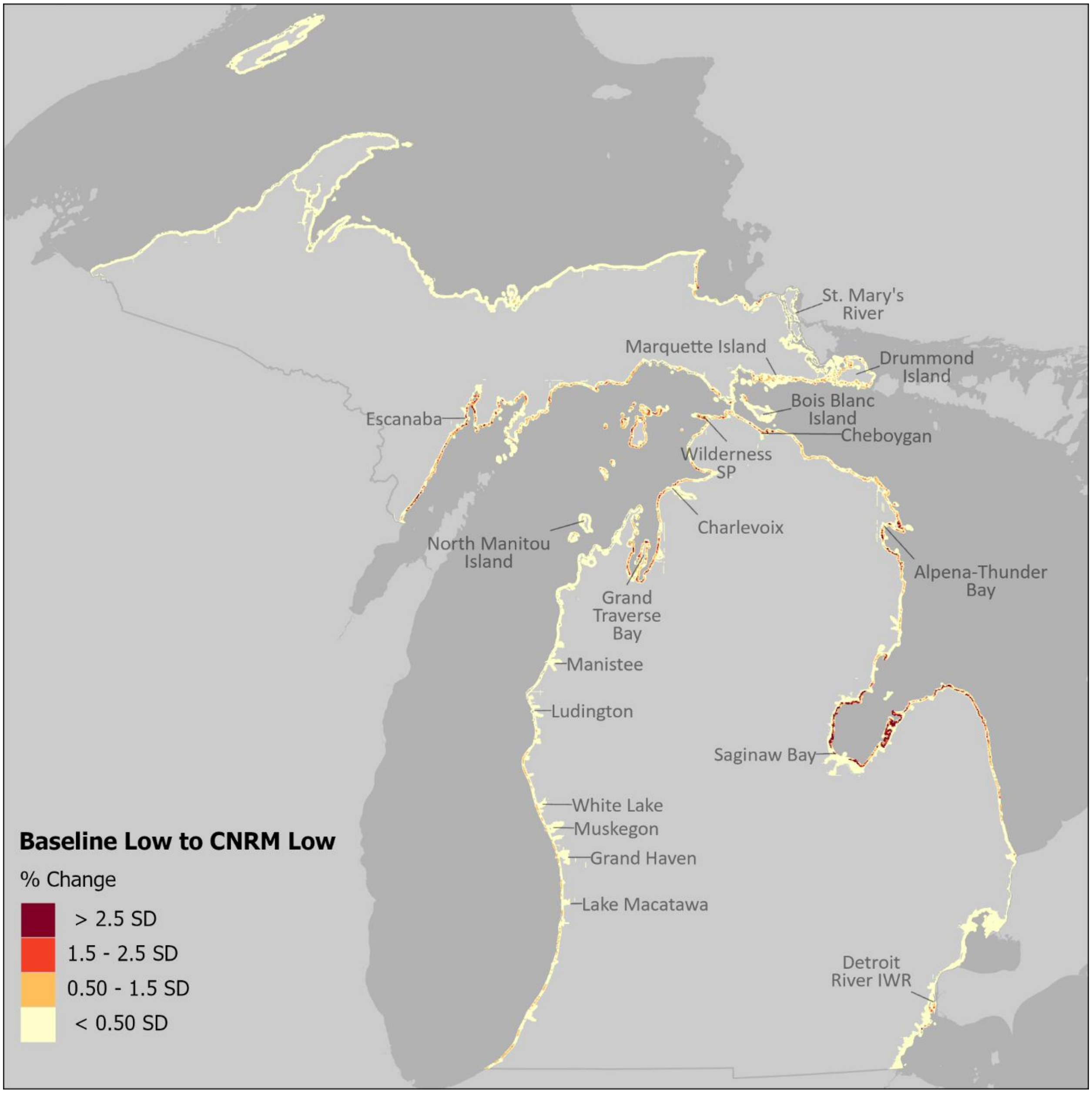

Figure B5. Regional variation of inundation and expansion according CNRM-Low scenario.

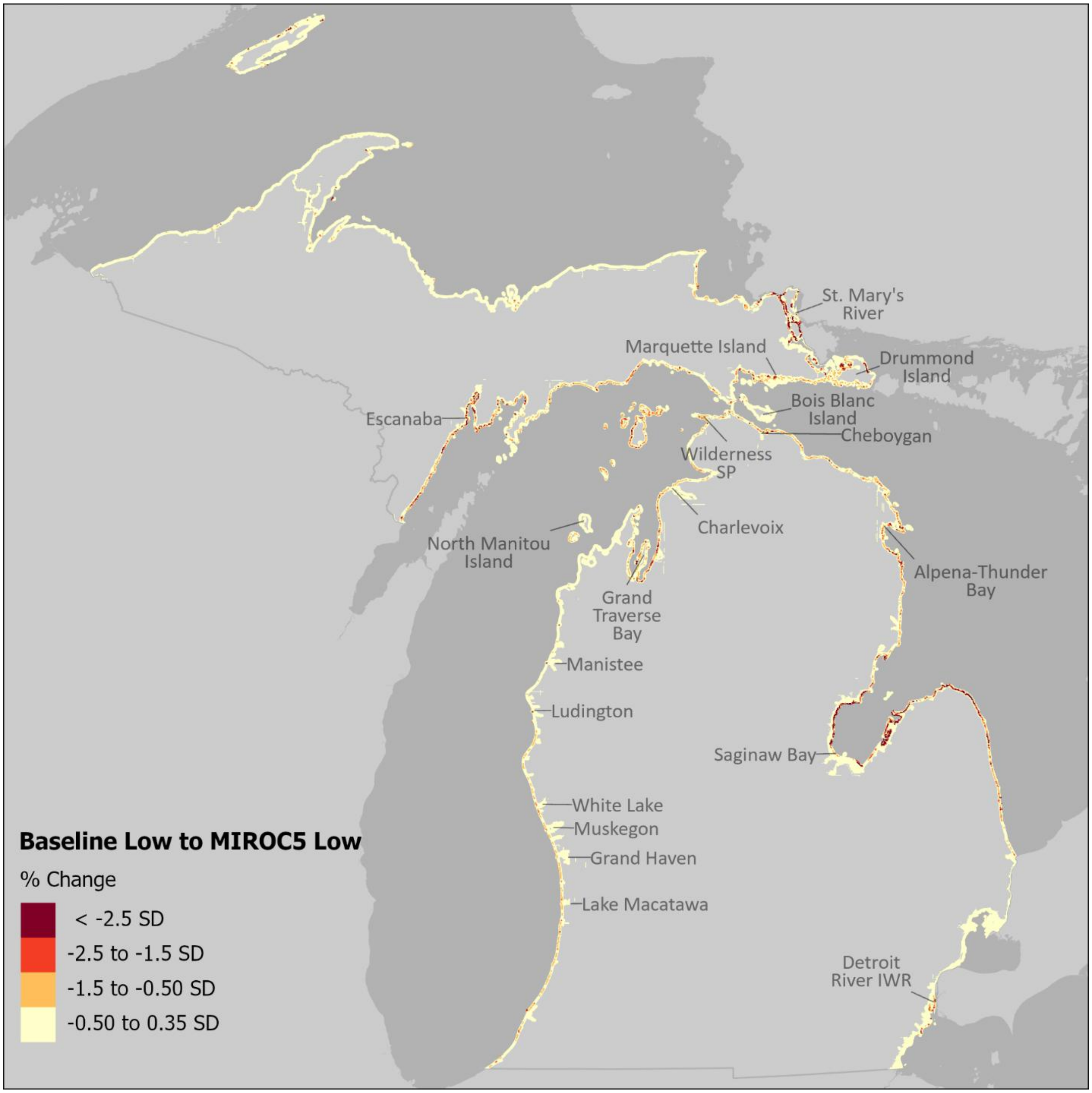

Figure B6. Regional variation of inundation and expansion according MIROC5-Low scenario.

APPENDIX C: CONSERVATION RANKS ACCORDING TO NATURAL HERITAGE METHODOLOGY

Table C1. Global rank element definitions.

Global Rank		DEFINITION
G1	Critically Imperiled	At very high risk of extinction or elimination due to extreme rarity (often 5 or fewer occurrences), very restricted range, very few populations or occurrences, very steep declines, very severe threats, or other factors.
G2	Imperiled	At high risk of extinction or elimination due to restricted range, few populations or occurrences (often 20 or fewer), steep declines, severe threats, or other factors.
G3	Vulnerable	At moderate risk of extinction or elimination due to a fairly restricted range, relatively few populations or occurrences (often 80 or fewer), recent and widespread declines, threats, or other factors.
G4	Apparently Secure	At fairly low risk of extinction or elimination due to an extensive range and/or many populations or occurrences, but with possible cause for some concern as a result of local recent declines, threats, or other factors.
G5	Secure	At very low risk or extinction or elimination due to a very extensive range, abundant populations or occurrences, and little to no concern from declines or threats.
GH	Possibly Extinct (species) or Eliminated (communities)	Known from only historical occurrences but still some hope of rediscovery. Examples of evidence include (1) that a species has not been documented in approximately 20-40 years despite some searching and/or some evidence of significant habitat loss or degradation; (2) that a species or ecosystem has been searched for unsuccessfully, but not thoroughly enough to presume that it is extinct or eliminated throughout its range.
GX	Presumed Extinct (species) or Eliminated (natural communities)	Not located despite intensive searches and virtually no likelihood of rediscovery (species); Eliminated throughout its range, due to loss of key dominant and characteristic taxa and/or elimination of the sites and ecological processes on which the type depends (natural communities).
GU	Unrankable	Currently unrankable due to lack of information or due to substantially conflicting information about status or trends.
G?	Inexact	Incomplete data

Table C2. Subnational (state) rank element definitions.

Subnational (State) Rank		DEFINITION
S1	Critically Imperiled	At very high risk of extirpation in the state because of extreme rarity (often 5 or fewer occurrences) or other factors making it especially vulnerable to extirpation, including: very restricted range, very few populations or occurrences, very steep declines, or severe threats.
S2	Imperiled	At high risk of extirpation in the state due to restricted range, few populations or occurrences (often 20 or fewer), steep declines, severe threats, or other factors.
S3	Vulnerable	At moderate risk of extirpation in the state due to a fairly restricted range, relatively few populations or occurrences (often 80 or fewer), recent and widespread declines, threats, or other factors.
S4	Apparently Secure	At a fairly low risk of extirpation in the state due to an extensive range and/or many populations or occurrences, but with possible cause for some concern as a result of local recent declines, threats, or other factors.
S5	Secure	At very low or no risk of extirpation in the state due to a very extensive range, abundant populations or occurrences, with little to no concern from declines or threats.
SH	Possibly Extirpated	Known from only historical records but still some hope of rediscovery. There is evidence that the species or ecosystem may no longer be present in the jurisdiction, but not enough to state this with certainty. Examples of such evidence include (1) that a species has not been documented in approximately 20-40 years despite some searching and/or some evidence of significant habitat loss or degradation; (2) that a species or natural community has been searched for unsuccessfully, but not thoroughly enough to presume that it is no longer present in the jurisdiction.
SX	Presumed Extirpated	Species or ecosystem is believed to be extirpated from the state. Not located despite intensive searches of historical sites and other appropriate habitat, and virtually no likelihood that it will be rediscovered. [equivalent to “Regionally Extinct” in IUCN Red List terminology]
SNR	Unranked	National or subnational conservation status not yet assessed.
S?	Inexact	Incomplete data