National Park Service
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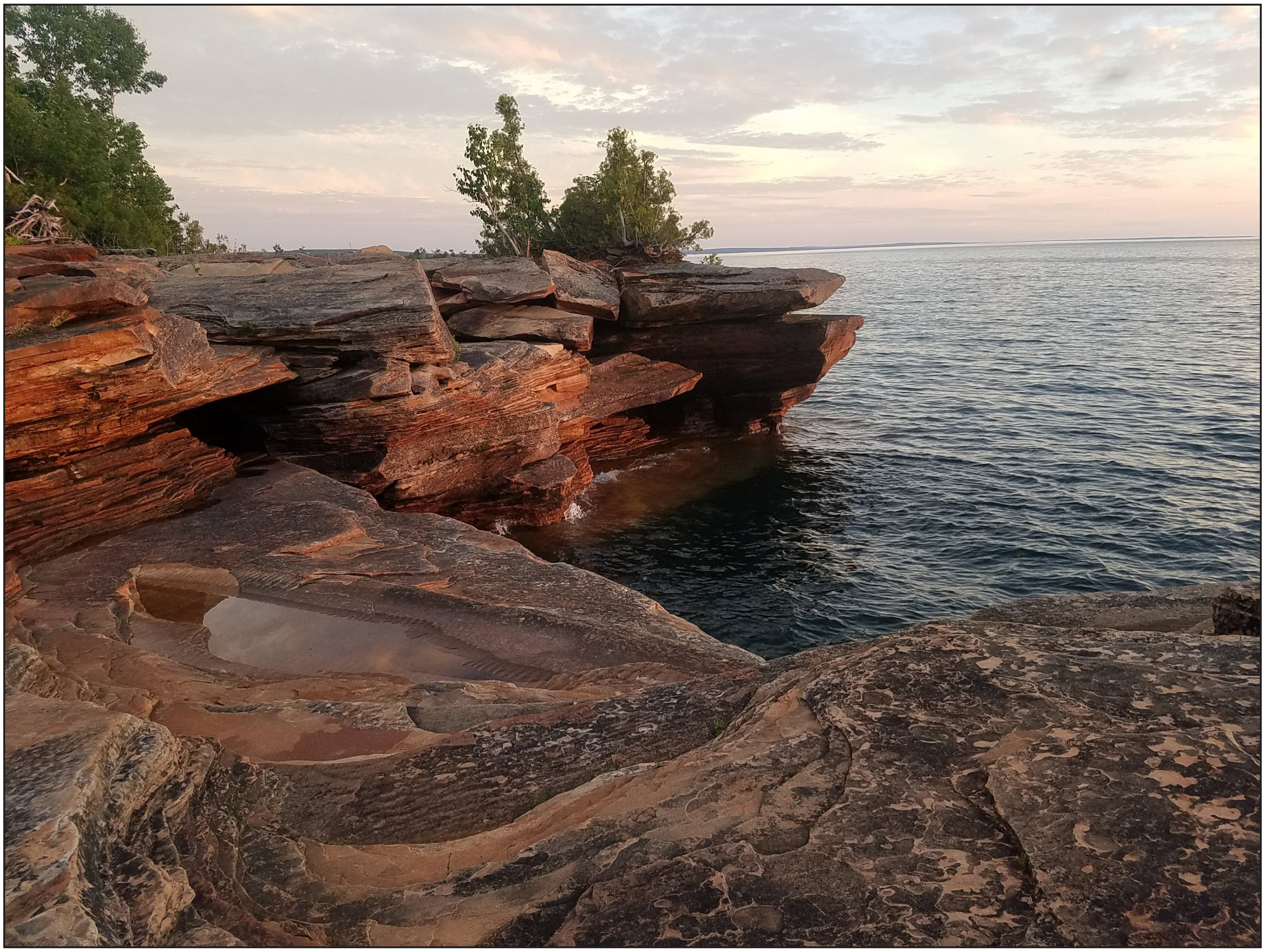
Natural Resource Stewardship and Science

Climate Change Vulnerability Assessment for Terrestrial Ecosystems at Apostle Islands National Lakeshore

Natural Resource Report NPS/APIS/NRR—2020/2121



ON THIS PAGE
Western shoreline of Devils Island
Photo by: Sarah Johnson, Northland College.

ON THE COVER
Apostle Islands bedrock cliff with adjacent forest.
Photo by: Maria Janowiak, USDA Forest Service.

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This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

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Executive Summary

As our climate continues to change, it is increasingly clear that natural landscapes are being affected in a variety of ways. Managers of the Apostle Islands National Lakeshore have observed notable changes in their own backyard, and they are rightfully concerned that continued change will challenge their mission to preserve and enhance the ecological and cultural legacy of this remarkable place. Therefore, the National Park Service has undertaken this vulnerability assessment to gather the best available information on how climate change may affect the park's terrestrial ecosystems. This assessment, created by a team of local experts representing diverse institutions and disciplines, is designed to provide information about what ecosystems are vulnerable, how vulnerable they are, and why they are vulnerable. It is not designed to give management recommendations to managers of Apostle Islands National Lakeshore. Our intent is to improve the understanding of local vulnerabilities to climate change and to draw conclusions about potential ecosystem vulnerability and change across a range of plausible future climate scenarios by the end of the 21st century.

This vulnerability assessment summarizes the physical environment, ecological character, and cultural history of the Apostle Islands in Chapter 1. The park's island setting and location within Lake Superior fundamentally shapes its ecology, for example by creating a more maritime climate, limiting deer abundance, and exposing the park's vegetation to persistent winds and waves. The cultural history of the Apostle Islands has also shaped the landscape that we see today, from several eras of indigenous inhabitation to the intense period of extraction and disruption following European settlement, and finally to the most recent 50 years as a part of the National Park System.

Chapter 2 presents information about the observed climate trends in the local area over the past several decades, as well as a range of plausible climate projections by the end of the century. Chapter 3 ties this information together by providing a synthesis of how these climate trends may shape the ecology of the Apostle Islands. For example, Lake Superior has experienced dramatic warming over the past half-century, which has led to a substantial decline in ice coverage across the lake and in the immediate vicinity of the Apostle Islands. Concurrently, prevailing wind speed over Lake Superior has increased and the prevailing wind direction has tended to shift clockwise, so that winds are more often coming from north or north-east of the Apostle Islands across a longer stretch of Lake Superior. Each of these trends might not have much effect in isolation, but acting in concert they have resulted in substantial increases in wave height and erosion along Apostle Islands and mainland coastlines, particularly in winter months. This is just one of many storylines that are examined in Chapters 2 and 3.

Chapter 4 provides detailed vulnerability and confidence determinations for the eleven ecosystems considered in the assessment. For each ecosystem, authors discussed how climate change might affect important ecosystem drivers, key species, and stressors, as well as the inherent ability of each ecosystem to naturally adapt and cope with change. A detailed rationale is presented for each ecosystem, along with a rating of the authors' overall confidence in the assessment.

Overall, most of the terrestrial ecosystems in the Apostle Islands are expected to have low or moderate vulnerability to climate change over the next century (see table below). This does not directly translate to the overall degree of impact that the park will experience, because many of these ecosystems occupy a relatively small land area but may feature iconic vegetation or be culturally important (e.g. Great Lakes Pine Forests and Barrens, or Coastal Wetlands). Ecosystems that are adapted to a narrow range of conditions or that exist near their

range limits may be more vulnerable to changing conditions. Boreal Forests, Coastal Wetlands, and Rock Cliffs and Ledges are rated as the most vulnerable ecosystems in the park, largely for these reasons. Communities with higher plant diversity or that are adapted to tolerate disturbances are expected to be better able to persist under a range of plausible climates. For example, Beaches and Dunes, Deep Ravine Forests, Erodible Maritime Bluffs, Great Lakes Pine Forests and Barrens, Interior Alder Thickets, and Upland Hardwood Forests were all rated low or low-moderate vulnerability. These vulnerability determinations only represent general expectations, and it is essential to consider local characteristics such as past management history, soils, topographic features, species composition, deer levels, visitation patterns, and recent disturbances when applying these general vulnerabilities to local scales. Therefore, local knowledge and management experience will be critical for identifying particular sites in the Apostle Islands that may have higher or lower vulnerability to climate change.

A final chapter highlights major findings of the assessment and a discussion of monitoring, other important resources within the park, and the potential for managers in the Apostle Islands to manage for climate change adaptation.

Determinations of climate change vulnerability and confidence for the 11 terrestrial Apostle Islands ecosystems. Potential impacts are rated on a scale from Disruptive to Supportive, and adaptive capacity is rated on a scale from Low to High. Potential impacts and adaptive capacity are combined to reach a vulnerability determination (Low to High). Evidence is rated on a scale from Limited to Robust, and agreement is rated on a scale from Low to High. Evidence and agreement are combined to reach a confidence determination. See Appendix 5 for more detail.

Ecosystem	Potential Impacts	Adaptive Capacity	Vulnerability[1]	Evidence	Agreement	Confidence[2]
Beaches and Dunes	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate	Moderate
Boreal Forests	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low-Moderate
Coastal Wetlands	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low
Deep Ravine Forests	Moderate	High	Low-Moderate	Moderate	Moderate	Moderate
Erodible Maritime Bluffs	Moderate-Supportive	High	Low	Moderate	Moderate-High	High
Great Lakes Pine Forests and Barrens	Moderate-Supportive	Moderate-High	Low	Limited-Moderate	Moderate	Moderate
Interior Alder Thickets	Moderate-Supportive	High	Low	Moderate-Robust	High	High
Interior Peat Swamps and Bogs	Disruptive-Moderate	High	Moderate	Moderate	Moderate	Moderate
Mixed Conifer Hardwoods	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Rock Cliffs and Ledges	Disruptive-Moderate	Moderate	Moderate-High	Moderate	Moderate	Moderate
Upland Hardwood Forests	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate-High	High

[1] Potential impacts and adaptive capacity are combined to reach a vulnerability determination (Low to High), following Figure 15.

[2] Evidence and agreement are combined to reach a confidence determination, following Figure 16.

Stockton Island. USDA Forest Service/M. Janowiak

Old yellow birch on North Twin Island.

Acknowledgements

This project was supported in part by funding from the National Park Service Climate Change Response Program. E. Judziewicz (University of Wisconsin-Stevens Point) provided valuable input to the ecosystem classifications used in this assessment, and his book *Flora of the Apostle Islands* was an invaluable reference. Several people contributed their expertise on the dynamics of Lake Superior and shoreline processes: G. Meadows (Michigan Technological University); C. Wu (University of Wisconsin-Madison); and E. Pendleton, E. Lentz, and R. Theiler (U.S. Geological Survey). R. Clark (Inter-Tribal Council of Michigan) provided a glossary of Ojibwe species names. A. Staffen (Wisconsin Department of Natural Resources), S. Sanders (National Park Service), and S. Perles (National Park Service) provided technical reviews that improved this assessment. T. Gostomski completed the formatting and design of the final publication. S. Handler wishes to especially thank P. Burkman. This project would not have been possible without her foresight and persistence.

BOX 1: Relationship to Other Assessments

This assessment bears some similarity to other regional vulnerability assessments and synthesis documents about climate change science and ecosystem impacts. Where appropriate, we refer to these larger-scale documents. This assessment differs from these reports because of the specific focus on the Apostle Islands landscape and different vulnerability assessment processes. Readers may want to refer to these vulnerability assessments and synthesis documents to get a more complete picture of climate change effects in the region.

Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and Western Upper Michigan
This assessment focuses on a much larger region and specifically addresses forest ecosystems and native tree species. Produced by the Northern Institute of Applied Climate Science and the USDA Forest Service. www.nrs.fs.fed.us/pubs/46393

Climate Change Vulnerability Assessments for Wisconsin Natural Communities
This series of assessments addresses ten broad Community Groups and 52 more specific Natural Communities across the state, focusing on non-forested ecosystems and southern forested ecosystems. Produced by the Wisconsin Initiative on Climate Change Impacts and the Wisconsin Dept. of Natural Resources Natural Heritage Program. www.wicci.wisc.edu/plants-and-natural-communities-working-group.php

Great Lakes Indian Fish and Wildlife Commission Climate Change Vulnerability Assessment: Integrating Scientific and Traditional Ecological Knowledge
This report assesses the vulnerability of over 60 beings/species of interest to Ojibwe tribes across the Ceded Territories in northern Minnesota, Wisconsin, and Michigan. This assessment relies on a standardized vulnerability assessment process, as well as numerous interviews to gather traditional ecological knowledge. Produced by the Great Lakes Indian Fish and Wildlife Commission. www.glifwc.org/ClimateChange/VulnerabilityAssessment.html

Bad River Reservation Seventh Generation Climate Change Monitoring Plan
This document provides an overview of the Bad River reservation, including several natural habitat types and their cultural importance. It provides a priority list of resource concerns related to climate change, as well as an implementation plan for monitoring effects on those resources. Produced by the Bad River Band of Lake Superior Chippewa, and available on the Northeast Indigenous Climate Resilience Network website: www.nicrn.org/uploads/7/2/8/1/72815671/bad_river_seventhgenclimatemonitoringplan.pdf

4th National Climate Assessment
This national-scale report includes a chapter on the Midwest, with separate sections on the region's forests, biodiversity, and ecosystems. Produced by the US Global Change Research Program. https://nca2018.globalchange.gov/

Introduction

Managers of the Apostle Islands National Lakeshore are tasked with preserving and enhancing the ecological and cultural legacy of this remarkable place for the benefit of the public and for future generations. As stewards of this landscape, the National Park Service has undertaken this vulnerability assessment to gather a more complete picture of how climate change may affect the park's ecology for decades to come.

As the effects of climate change become clearer year after year, natural resources managers are grappling with the fact that the future will undoubtedly look much different than what we have come to expect as current conditions. Additionally, current conditions in the Apostle Islands are much different from historical conditions, due to a complex history of indigenous and European settlement. Therefore, historical conditions and the historical range of variability are no longer reliable as stand-alone benchmarks for ecosystem management and conservation. Climate change vulnerability assessments attempt to gauge future risks and changes given the best information available today. Ecosystem vulnerability assessments such as this one are not designed to provide recommendations about how managers should respond and adapt to potential changes. Rather, a vulnerability assessment should provide an even-handed appraisal of potential climate change impacts, along with a transparent account of uncertainty and information gaps.

The Apostle Islands National Lakeshore commissioned this ecosystem vulnerability assessment to specifically address the major terrestrial ecosystems found within the park boundary. This effort is part of a multi-pronged campaign that will inform park managers about stewarding the ecological and cultural resources of the Apostle Islands for the future. A complementary effort is underway to assess the aquatic ecosystems within the park. Additionally, the park plans to consult traditional ecological knowledge (TEK) holders in order to more completely understand the relationships and connections between local Ojibwe communities and the Apostle Islands. Therefore, although this ecosystem vulnerability assessment addresses a limited set of topics and information sources, it can be viewed in concert with related projects to provide a more holistic understanding of how climate change may affect the ecology, visitor experience, and cultural relationships within the Apostle Islands.

Apostle Islands National Lakeshore Headquarters and Visitor Center in Bayfield. NPS PHOTO.

Purpose and Scope

This assessment describes the climate change vulnerability of terrestrial ecosystems in Apostle Islands National Lakeshore. It is designed to provide detailed information that will be useful to resource managers and interpretive staff at the park. Other partners with an interest in learning specifically about this landscape may also benefit from this assessment, including tribes, natural resource agencies, and the general public. Some particular features of this assessment include:

Purpose

Vulnerability assessments provide information about what resources are vulnerable, how vulnerable they are,

and why they are vulnerable, but they do not tell a manager how to respond. This assessment, therefore, does not give advice or recommendations to managers of Apostle Islands National Lakeshore. Instead, this report is designed to improve the understanding of local vulnerabilities to climate change and to draw conclusions about potential ecosystem vulnerability and change across a range of plausible future climate scenarios. Although it was written to be a resource for land managers and interpretive staff, it is first and foremost a scientific document that represents the findings and interpretations of the authors.

Geography

The lands contained within the Apostle Islands National Lakeshore boundary, including the 21 islands and a mainland unit that is a 12-mile strip of land along the shore of Lake Superior.

Scope

Terrestrial and wetland ecosystems within the park. See Chapter 1 for a complete description of the different ecosystems considered in this assessment. For the purposes of this assessment, we are using the term "ecosystem" to describe a particular natural community, including many factors such as disturbance processes, soils and landform, characteristic plant species, and interactions between living organisms and the physical environment. We are deliberately not addressing wildlife habitat or aquatic ecosystems in this assessment.

Timeframe

Vulnerability determinations in this assessment are for the end of the century (i.e., the year 2100). This long-term timeframe is appropriate due to the often gradual nature of climate change and ecosystem response. Additionally, this assessment focuses on assessing the vulnerability of the park's ecosystems in their current existing condition, rather than measuring them against a historical baseline or particular successional stage. The Apostle Islands have a long and dynamic history of indigenous and European settlement and ecosystem manipulation, which is summarized in Chapter 1 and in other resources.

Vulnerability Determination

For the purposes of this assessment, an ecosystem is determined to be vulnerable to climate change if it is expected to experience one or more of the following impacts by the end of the century:

- A decline in health
- A decline in extent
- A substantial change in identity
- A decline in crucial ecosystem functions

See Chapter 4 for a more complete description of ecosystem vulnerability.

Assessment Process

This assessment relied on a structured process, completed at an expert panel workshop in March 2018. See Appendix 5 for more information about the assessment process.

Supplemental Questions

In addition to the primary objective of determining the climate change vulnerability of the terrestrial ecosystems within the Apostle Islands, this assessment was also intended to address a set of related questions that are of interest to National Park Service managers. These questions include:

1. How vulnerable to climate change are rare and character-defining terrestrial features and natural communities of the park, specifically sandscapes and boreal, krummholz, and old-growth forests? How vulnerable are iconic species, including eastern hemlock (gagaagi wanzh, *Tsuga canadensis*)[1], yellow birch (wiinizik, *Betula alleghaniensis*), northern white-cedar (giizhikaatig, *Thuja occidentalis*), and Canada yew (niibaayaandag,

[1] Species names are accompanied by Ojibwe language names (where available) and Latin names upon first use. Ojibwe names were compiled from sources based in the western Lake Superior region where possible, including resources from the Great Lakes Fish and Indian Wildlife Commission and the Ojibwe People's Dictionary (ojibwe.lib.umn.edu/). A glossary of Ojibwe names from the Inter-Tribal Council of Michigan was used as a supplement, recognizing that Ojibwe dialects sometimes differ between Wisconsin and Michigan. See Appendix 2 for a complete list of species names mentioned in this assessment.

Taxus canadensis)? And how does the park's island setting influence these vulnerabilities?

2. Could the park serve as an important refugium for some terrestrial plant species or community types?
3. Will Lake Superior function as a barrier to northward migration of species, and what are the implications?
4. How will increasing lake temperatures and wind speeds alter the natural disturbance regimes in the park? What are the implications for both wind and fire processes?

Partners

This vulnerability assessment would not have been possible without the combined efforts of several partners and dedicated individuals. The authors of this assessment represent a diverse range of organizations, including the National Park Service, U.S. Department of Agriculture Forest Service, Wisconsin Department of Natural Resources, Bad River Band of Lake Superior Chippewa, Northland College, National Oceanographic and Atmospheric Administration, Great Lakes Integrated Sciences and Assessments (GLISA), Northern Institute of Applied Climate Science, and the Great Lakes Indian Fish and Wildlife Commission (GLIFWC). The authors also represent a variety of backgrounds and discipline areas including native plant ecology, fire ecology, cultural resources, indigenous knowledge, wetland ecology, soils, climate science, and Lake Superior dynamics. Participants were also selected for their familiarity with the Apostle Islands and the local area. This product is truly a collaborative effort and draws on each contributor's expertise. Partners and other organizations in the region will ideally be able to use this assessment in their own land management and conservation programs. This assessment may also supplement other climate change vulnerability assessments that have been produced in the region (see Box 1).

Assessment Chapters

This assessment contains the following chapters and appendices:

Chapter 1 provides a brief overview of the physical environment, ecological character, and cultural history of the Apostle Islands. This chapter also describes the eleven ecosystems considered for the purposes of this assessment.

Chapter 2 summarizes the observed climate trends in the local area. This chapter also presents information about a range of plausible climate projections for the Apostle Islands.

Chapter 3 includes information on projected climate change impacts for tree species in the local area, as well as a synthesis of existing literature on several climate-related effects that are important to consider in the Apostle Islands.

Chapter 4 provides detailed vulnerability and confidence determinations for the eleven ecosystems considered in the assessment.

Chapter 5 highlights major findings of the assessment and potential implications.

Appendix 1 provides definitions of select technical terms used throughout the assessment.

Appendix 2 lists common names, Latin names, and Ojibwe names (Anishinaabemowin) of all species mentioned in the assessment.

Appendix 3 gives a technical summary of general circulation models, downscaling methods, and ways to account for uncertainty in future climate projections.

Appendix 4 explains the model results provided in Chapter 3 in more detail, including expanded outputs for each species.

Appendix 5 describes how conclusions for this assessment were reached at an expert panel workshop.

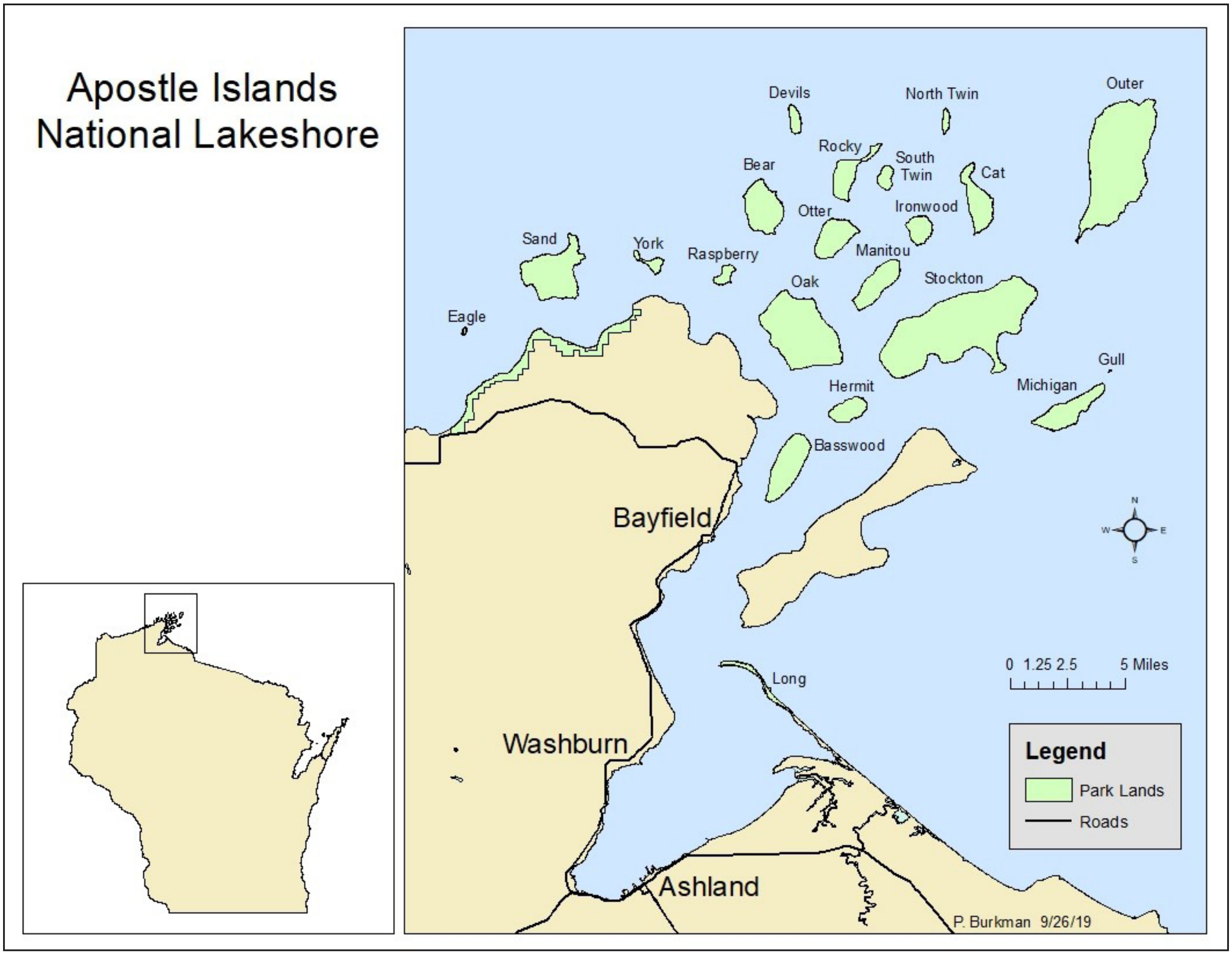

Figure 1. Map of the Apostle Islands National Lakeshore and surrounding area.

Chapter 1: Apostle Islands Context and Ecosystems

The Apostle Islands are a remarkable landscape. This archipelago of islands in Lake Superior contains a wide variety of forests, wetlands, and ever-changing coastlines of beaches, dunes, and cliffs (Figure 1). The smallest island is barely 2 acres, while the largest island (excluding Madeline Island, which is not included in the park) is nearly 10,000 acres. The islands are clustered relatively close to the mainland, with the most distant island being about 15 miles offshore. For a relatively small land area (approximately 42,000 acres), it seems that the full array of nature's earth-shaping forces are on display in the Apostle Islands National Lakeshore.

Visitors to the park will see ecosystems shaped by geology; soils; and the forces of wind, ice, waves, mist, sun, fire, elevation, and more. Visitors may also learn that the Apostle Islands are a landscape that has been intimately shaped by humans for thousands of years, through activities as diverse as subsistence hunting and gathering and indigenous habitat management to commercial logging, mining, and fishing. Each island has a unique ecological and cultural history.

This chapter provides a brief overview of the physical and cultural context of the Apostle Islands. Much has been written about this landscape through the years, and this chapter will not attempt to replicate that vast body of knowledge. This report will strive to succinctly cover important contextual information about the Apostle Islands and provide readers with recommendations for further references on particular topics. This chapter also describes the eleven terrestrial ecosystems that will be the focus of later chapters.

Cultural History

The Apostle Islands has a long and dynamic cultural history (Cronon 2003, Busch 2008). Lake Superior Ojibwe (Chippewa) and their ancestors have resided among and used the islands for several hundred years, and earlier occupation by native peoples stretches back thousands of years. The Apostle Islands, and specifically Madeline Island (Moningwunakauning or Mooningwanekaaning in Ojibwe, "the place of the golden-breasted woodpecker"), are of particular importance to indigenous people in the area. See Box 2 for more information about this relationship.

European history in the Apostle Islands dates to the 17th century, with outposts established for trade as well as military defense. The area was a regional commercial center through the 1800s, with fur trading, commercial fishing, mining, quarrying, logging, and tourism. Along with developments to support these enterprises, the 1800s also saw the start of limited homesteading and farming in the Apostle Islands. Farming declined in the first half of the 20th century, and most of the valuable timber had been harvested from the islands by 1930, with the exception of a handful of protected areas around lighthouses. Commercial fishing declined in the 1950s for a variety of reasons, as did year-round inhabitation on the islands.

Conservation interests began to have a stronger voice in the Apostle Islands in the 1950s, and the state of Wisconsin purchased Stockton, Oak, and Basswood Islands to form the Apostle Islands State Forest in 1959. U.S. Senator and former Wisconsin governor Gaylord Nelson spearheaded the establishment of the Apostle Islands National Lakeshore in 1970. Long Island, which is geologically distinct from the other Apostle Islands, was added to the National Lakeshore in 1986. In 2004, Congress designated most of the land in the park as the Gaylord Nelson Wilderness, with the exception of the mainland unit, Sand Island, Basswood Island, Long Island, the Stockton tombolo, and small inclusions on several islands. Today, approximately 80% of the land area in the park is federally designated wilderness.

BOX 2: Home of the Ojibwe

The relationship of the Ojibwe people to the Apostle Islands stretches back for hundreds of years and continues through today. As of the time of this assessment, the Apostle Islands National Lakeshore has launched a project with the Red Cliff and Bad River Bands of Lake Superior Chippewa to better describe the traditional knowledge associated with the place. This summary draws from other resources, including Busch (2008) and National Park Service (2015), and readers should explore those resources for a deeper understanding.

Evidence of people occupying the Apostle Islands region dates back to "Paleo-Indian" people who lived in the area around Chequamegon Bay roughly 11,000 years ago, followed by later populations from the Archaic and Woodland eras. Several bands likely occupied and traveled through the region to hunt and trade. Ojibwe ancestors arrived in the region in a westward migration from the east coast, following the Great Lakes until reaching Mooningwanekaaning (Madeline Island). The Ojibwe lived and thrived in the area around Lake Superior and Lake Huron for hundreds of years, and Mooningwanekaaning became a regional hub of economic and cultural activity.

As European traders and missionaries came to the region in the 17th century, native culture continued to adapt and evolve, and fragments of tribes from elsewhere also migrated to the Chequamegon Bay region. Dynamic political and economic relationships with Europeans and other tribes fueled trade and conflict, though the Ojibwe still primarily followed a traditional seasonal pattern of hunting, fishing, and gathering. The principles of respect and reciprocity underpin the Ojibwe worldview, which means that all plants and animals have something important to teach us as humans and that nothing should be taken without giving something in return.

The U.S. Government began to establish treaties with the Ojibwe and other tribes in the region beginning with the 1825 treaty, and these treaties generally served to divide alliances between tribes and claim access to lands for natural resource extraction. Treaties of 1842 and 1854 directly addressed the rights and lands of Ojibwe living in and around the Apostle Islands, formalizing the Bad River Reservation and Red Cliff Reservation. The Bad River Reservation included a small portion of land on Mooningwanekaaning, and the Red Cliff Reservation was placed on the northern tip of the Bayfield Peninsula. In the midst of this period of intense pressure and displacement, Ojibwe people managed to avert a forced relocation attempt to Minnesota but suffered the tragedy at Sandy Lake, when over 400 people died waiting for promised food and supplies during a forced wintertime journey. Ojibwe people faced further attempts at cultural assimilation over the subsequent years, including land allotment; religious conversion; boarding schools; and pressure to adopt farming, lumbering, and other industries. Regardless of these pressures, Ojibwe people continued to travel to the Apostle Islands for subsistence and cultural purposes. Their relationship with this place, and the beings and spirits that reside there, continues to the present day.

The relationship between the Bad River and Red Cliff Bands and the Apostle Islands National Lakeshore has evolved through time. The tribes essentially initiated the movement to form the park with a tribal council resolution in 1962, but opposition to the park's formation grew as the proposal was formalized by the US government. Negotiations eventually gained support from the tribes in 1970, and the Apostle Islands National Lakeshore was formed. The tribes also opposed the subsequent addition of

BOX 2 (continued): Home of the Ojibwe

Long Island to the park in the 1980s, until they were able to win additional concessions to protect the island's cultural and natural resources. Tribal members continue to hunt, fish, and gather within the park as allowed by established treaties and subsequent agency agreements. In recent years, the Apostle Islands National Lakeshore has acknowledged and supported the Ojibwe relationship with the area. This includes a formal Memorandum of Understanding with both bands, as well as a recent prescribed burn on Stockton Island that was carried out in cooperation with the tribes according to cultural traditions. As climate change affects the Apostle Islands landscape and the beings that reside in the place, the Ojibwe culture and relationship with the place may continue to evolve.

A symbolic petition from several Lake Superior bands of Ojibwe to the U.S. government for adjustments to the 1842 LaPointe Treaty. The connecting lines to the hearts and eyes of the figures represent the unified views of the separate bands, and the last line, going out from the Crane's eye, indicates that the entire group had authorized Chief Buffalo (Crane Clan) to speak to President Fillmore on their behalf. This image was copied by Seth Eastman in 1849 from an original birch bark version. Photo from Wisconsin Historical Society, image number 1871.

The waters throughout the Apostle Islands are still accessed for commercial fishing, particularly by tribal members, but the majority of visitors now come for recreation in the National Lakeshore. Visitors to the Apostle Islands typically come during the peak season of mid-June to early September, with occasional spikes in the winter when conditions create spectacular ice caves. In 2016, the park recorded 203,421 visitors through the entire year (Thomas et al. 2018). For comparison, in a 2-month span during the winter of 2014 it was estimated that 138,000 people came to visit the ice caves, and in the winter of 2015 more than 38,000 people visited to see this phenomenon that lasted only nine days (Kaeding 2017). Ice caves did not form in the winters of 2016–2018.

Formation of the ice caves — and safe walking conditions on lake ice — draw thousands of visitors to the Apostle Islands. NPS PHOTO.

Neighboring Land Ownership

The Apostle Islands National Lakeshore includes land in both Ashland and Bayfield Counties in Wisconsin. Nearly half of the land in Bayfield County is publicly owned, and approximately 85% is forested (Kraft et al. 2007). The county owns a majority of the land in the northern Bayfield Peninsula, including most of the watershed upstream from the park's mainland unit. The Red Cliff Band of Lake Superior Chippewa Indian Reservation lies on the northern edge of the Bayfield Peninsula, including Frog Bay Tribal National Park. The Bad River Band of Lake Superior Chippewa Indian Reservation occupies the northern portion of Ashland County, directly to the south of the Apostle Islands and contiguous with Long Island. Other major landowners in the Bayfield Peninsula include the Wisconsin Department of Natural Resources and the USDA Chequamegon-Nicolet National Forest.

Physical Setting

A complete discussion of the geology of the Apostle Islands can be found in *A Guidebook to the Geology of Lake Superior's Apostle Islands National Lakeshore and Nearby Areas of the Bayfield Peninsula of Wisconsin* (Nuhfer and Dalles 2004). The Apostle Islands are primarily underlain by 600-million-year-old Precambrian sandstone of the Bayfield Group of the Keweenawan Supergroup (Kraft et al. 2007, Judziewicz and Koch 1993). The Bayfield Group includes sub-categories of sandstone named the Chequamegon, Devils Island, and Orienta Formations, which range from less than 100 meters to over 500 meters in thickness and occur in different combinations throughout the park. These sandstone formations differ in color and durability and give the park's islands their distinct appearance. Long Island is geologically distinct from the rest of the archipelago, being an extension of the sand spit off Chequamegon Point.

The topography of the Apostle Islands reflects the complicated history of glaciation and subsequent lake action. The most recent glaciation ended about 12,000 years ago (Kraft et al. 2007), and the islands were mostly submerged until about 10,600 years ago (Breckenridge 2013). During this long period of fluctuating lake levels, thick clay deposits were laid down as well as sand and cobble. More recent lake levels have further influenced the intricate shorelines of the islands through erosion and deposition.

This history is evidenced in the shorelines present today. Sandstone cliffs and ledges are on large portions of Bear, Devils, Eagle,

Hermit, Ironwood, Manitou, North Twin, Sand, and York shorelines. Sandstone with boulders ring Cat and York Islands. Clay banks with boulders ring the edges of Basswood, Michigan, Oak, Otter, Raspberry, Stockton, and South Twin. Rocky followed by Stockton Island have the longest beach shorelines and several other islands have extensive beaches (Bear, Cat, Manitou, Michigan, Oak, Outer, Raspberry, Sand, South Twin, and York).

Soils are commonly coarse till and glacial outwash sands in higher landscape positions in the Apostle Islands, with clayey soils in lower positions and closer to the Lake Superior shoreline (Kirschbaum et al. 2012). Poorly-drained clays are common across the entire park (Judziewicz and Koch 1993). Island soils tend to have a thicker humus and organic matter layer than mainland soils (Kraft et al. 2007). Sand and clay deposits can be 30 or more meters thick on the larger islands (e.g., Stockton, Madeline, Sand, Oak, and Outer Islands) and the mainland unit. The smaller, more distant islands have very thin till over bedrock (e.g., Devils, Eagle, North Twin). The mainland unit of the park is part of the larger Bayfield Lake-Modified Till Plain, featuring hilly topography with deep ravines and sandstone cliffs.

Apostle Islands National Lakeshore is surrounded by Lake Superior, the largest freshwater lake in the world. There are over 160 miles of coastline within the park. The Apostle Islands are relatively sheltered by the Bayfield Peninsula and Minnesota's north shore to the west, but the islands are very exposed to the northeast and east. Wind and storms coming from the northeast in particular travel across nearly 200 miles of open lake before reaching the Apostle Islands, which can result in considerable wave action. The lake has a powerful influence on the climate, weather, and natural processes of the park, as described below and in subsequent sections of this assessment.

Climate

The Apostle Islands have a climate with four distinct seasons, featuring long, cold winters and short, moderately warm summers. The mean temperature is approximately 66°F in July and 12°F in January (Kirschbaum et al. 2012). The local climate of the Apostle Islands is more maritime than nearby areas in Bayfield and Ashland Counties because of the proximity of Lake Superior (Judziewicz and Koch 1993, Kraft et al. 2007). Winters tend to be milder than areas just a few miles inland, with warmer average winter temperatures and less extreme cold temperatures. Spring arrives later, and fall extends later into the year. Summers are cooler in the Apostle Islands, with more prevalent fog and mist. The park also tends to get slightly more rain and snow than areas on the mainland (Judziewicz and Koch 1993). According to weather station data on Madeline Island from 1993–2019, the park receives an average of about 31 inches of precipitation each year and 71 inches of snow (Midwestern Regional Climate Center 2020).

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These climate gradients can even be observed within the archipelago, with more distant islands (e.g., Devils and Outer) exhibiting a more maritime climate than inner islands. Similar trends occur within a single island as well, with upland interior locations being noticeably warmer during the spring than areas next to the lake (Judziewicz and Koch 1993). On average, the growing season is about 120–130 days across the park.

Prevailing winds tend to be from the west during the fall, winter, and early spring, and from the east during late spring and summer (Kraft et al. 2007). Winter storms tend to come from the northeast, north, and northwest (Judziewicz and Koch 1993).

Apostle Islands Ecosystems

Several resources offer extensive descriptions of Apostle Islands ecosystems, including *Flora of the Apostle Islands* (Judziewicz and Koch 1993), *The Ecological Landscapes of Wisconsin* (Wisconsin Department of Natural Resources 2015), and recent National Park Service reports on vegetation inventory and landscape dynamics (Hop et al. 2010, Kirschbaum et al. 2012, Sanders and Grochowski 2012).

Prior to commercial logging in the late 1800s and early 1900s, almost 90% of the archipelago was covered with upland mixed conifer and hardwood forest dominated by eastern hemlock, eastern white pine (biisaandago-zhingwaak, *Pinus strobus*), sugar maple (ziinzibaakwadwaatig, *Acer saccharum*), yellow birch, and paper birch (wiigwaasaatig, *Betula papyrifera*) (Judziewicz and Koch 1993, Paulson et al. 2016). Canada yew, now a species of special concern in Wisconsin, is assumed to have been the dominant understory shrub on many of the islands. A period of intense timber extraction resulted in widespread ecosystem change, although the heterogeneity of the islands influences how harvesting occurred. Logging first selectively removed large white pine, followed by successive waves of removal targeting large eastern hemlock, yellow birch, and sugar maple. These operations resulted in or were followed by severe slash fires, as well as damage to ravines and waterways used as log transport routes. As mentioned above, mining, quarrying, commercial fishing, and small-scale farming also occurred on the islands in the 1800s and early 1900s.

In all, over 96% of the Apostle Islands landscape is still classified as forest habitat (Kraft et al. 2007), but the identity of these forests has changed considerably. Forest cover in the park is now composed mainly of second-growth northern hardwood forest consisting of sugar maple, red maple (zhiishiigimiiwanzh, *Acer rubrum*), aspen (azaadi, *Populus* spp), birch (*Betula* spp.), American basswood (wiigobaatig, *Tilia americana*), and northern red oak (wiisagi-mitigomizh, *Quercus rubra*) (Figure 2) (Hop et al. 2010, Sanders and Grochowski 2012).

Lack of seed sources and white-tailed deer (waawaashkeshi, *Odocoileus virginianus*) browse pressure, particularly on islands closer to the mainland, has contributed to the continued lack of white pine and the success of maple species. Suppression of wildfires and human-origin fires since the 1930s is also limiting the recovery of white and red pine (bapakwanagemag, *Pinus resinosa*) (Paulson et al. 2016). It is estimated that roughly 1,350 acres, or about 3% of the total land area, still exists in true "old-growth" condition today. North Twin, Devils, and Raspberry Islands are almost entirely old growth, and small inclusions of old growth remain on Sand, Bear, Oak, and Outer Islands. Canada yew remains a primary understory shrub on several islands that went without local irruptions of deer or severe slash fires associated with logging (Johnson et al. 2015).

Aside from forest ecosystems, the Apostle Islands also contain iconic sandscapes, some of the best examples in the Great Lakes region. These various features include sand spits (narrow land formations extending from mainland into the water), cuspate forelands (triangular land formations formed by longshore drift), tombolos (islands connected to the mainland by a narrow

Canada yew. © S. Johnson/Northland College

strip of land), and numerous beaches. Other noteworthy ecosystems in the park include sandstone cliffs and ledges, coastal wetlands, and interior bogs and peatlands. The Apostle Islands harbor the only known, or most intact, occurrence of some of these ecosystems in the Great Lakes region, such as Great Lakes Barrens and some types of coastal wetlands.

Species richness across the islands reflects some of the basic principles of island biogeography (Judziewicz and Koch 1993). Larger islands (Stockton, Outer, Oak) tend to have more total species than smaller islands (York, Gull, Eagle). Islands that are closer to the mainland (Basswood, Sand, Hermit) tend to have more total vegetation species than distant islands (Cat, Ironwood). Devils, North Twin, and Raspberry Islands stand out from the rest as very small islands that host relatively diverse floras. This is likely because those islands do not have a history of high deer populations and contain diverse sandscapes, rock ledges, and wetland habitats. Devils and Raspberry Islands also have lighthouse reservations, which contain gardens and introduced species.

Ecosystem Disturbance Processes

Ecosystems in the Apostle Islands evolved to contend with a regular battery of disturbances. Violent storms that sweep across Lake Superior are perhaps the most dramatic example. These storms, and the wind and waves that accompany them, can completely reshape shorelines and bluffs, and even wear away uplands. Little Steamboat Island, which existed to the southwest of Sand Island in the late 1800s, was completely washed away by a powerful storm in 1901. Gull Island wore away nearly to the level of the lake between 1850 and 1915. A 2014 storm created a 280-foot breach in a sand bar that had previously protected an inland lagoon on Outer Island, and the new connection to Lake Superior has irreversibly changed the water conditions and lagoon ecosystem.

Action from Lake Superior can alter ecosystems in less dramatic fashion as well. Rock cliffs and clay bluffs are common features across the Apostle Islands, and both of these systems are affected by regular erosion driven by waves, wind, freeze-thaw events, and abrasion from lake ice. Sandscapes are subjected to continual

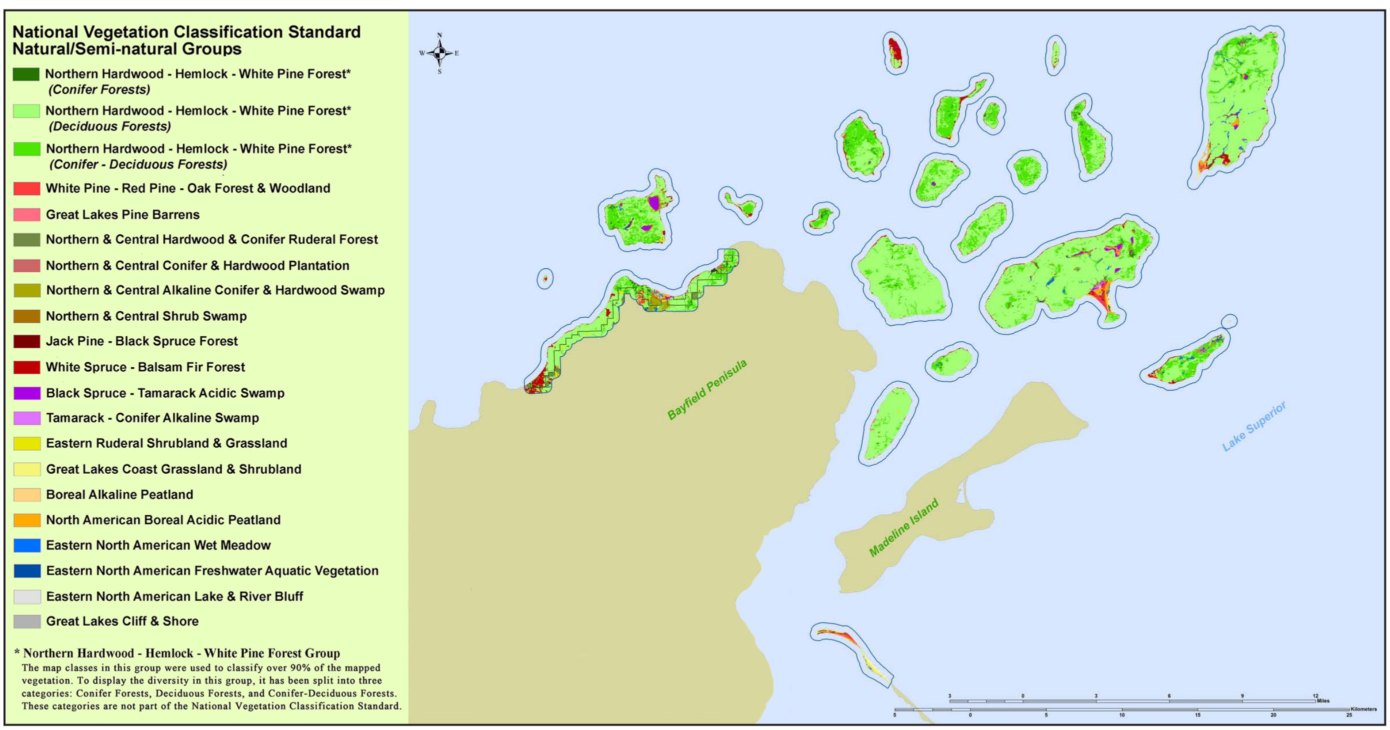


Figure 2. Vegetation of Apostle Islands National Lakeshore, presented at the natural/semi-natural group and the cultural class levels of the National Vegetation Classification Standard (Version 2). From Hop et al. (2010).

erosion and deposition of sediment, and storms can remove or add several feet of sand at a time. Similarly, low-intensity windstorms that occur every decade or two can create small gaps in the forest canopy by knocking down individual trees or small groups of trees. These small forest disturbances help maintain a multi-aged, late-successional forest. Additionally, chronic exposure to winds can result in stunted and deformed forest structure. This characteristic "krummholz" forest can be observed on the exposed windward coastlines of several islands in the park (Judziewicz and Koch 1993).

Fire has been a recurring event in some Apostle Islands ecosystems, both through natural and human-caused ignitions. It is estimated that Ojibwe people started more than half of the fires in Great Lakes coastal pine forests before the early 1900s (Loope and Anderton 1998), because fire was intentionally used to promote blueberries (miinagaawanzh, *Vaccinium angustifolium* and *V. myrtilloides*) and other valued plants. Human-origin fires likely occurred in wetlands and other ecosystems as well. Today, wildfires on the Apostle Islands tend to peak in July and August, which is later in the season than fires across the larger region (Martin and Johnson, in preparation).

Roughly 90% of the park is categorized as having a fire return interval of 350–1,000 years, due to wet and mesic conditions (Dickmann and Cleland 2002), and this relative lack of fire is what allowed mature hemlock-hardwood forests to develop. The remaining 10% of the park is more prone to fire due to drier conditions. The fire return interval has been as often as 5–15 years in locations with sandy, well-drained soils, such as the Stockton Island tombolo (Dickmann and Cleland 2002). Fires also occurred roughly every 30–75 years in pine forests and 75–350 years in oak-dominated systems (Dickmann and Cleland 2002). Recent research has shown that Canada yew is slow to recover from even small ground fires (Martin and Johnson, in preparation). Yews growing adjacent to burned areas continue to experience mortality for a year or longer after a fire.

Forest pests are another regular source of disturbance in the Apostle Islands. From 2004–2009, a study of land disturbance in the park revealed that a defoliation outbreak of the gypsy moth (*Lymantria erebidae*) affected about 7.5% of the land area in the park (Kirschbaum et al. 2012). This single non-lethal event was responsible for the overwhelming majority of disturbance detected in the park during these six years. Minor flooding attributed to beavers (amik, *Castor canadensis*) was the other principal land-based natural disturbance detected during this period. By contrast, neighboring lands in Bayfield and Ashland Counties experienced lower levels of disturbance related to forest pests during this timeframe, and the primary disturbance on the mainland was forest harvest.

Ecosystem Stressors

Recent vegetation surveys in the Apostle Islands have found that less than 1% of the flora is not native to the park, so non-native plants are currently a localized feature (Sanders and Grochowski 2014). Nevertheless, non-native and invasive plants are a small but important risk to native ecosystems within the Apostle Islands. Some of these species were likely introduced decades ago by early European settlers, and some are more recent arrivals transported by visitors on foot or by boat. Non-native species can become invasive and disrupt the functioning of an ecosystem due to high reproduction rates; widespread dispersal; and lack of pressure from their natural predators, competitors, or diseases. Some notable invasive plants in the Apostle Islands include tansy (oshkiniikwebagoons, *Tanacetum vulgare*), purple loosestrife (*Lythrum salicaria*), valerian (*Valeriana officinalis*), reed canary grass (*Phalaris arundinacea*), hybrid cattail (*Typha* × *glauca*) and spotted knapweed (*Centaurea stoebe* ssp. *micranthos*) (Judziewicz and Koch 1993, Miles and Burkman 2018) (personal communication with Sarah Johnson, 16 September 2019).

Exotic insects are currently not a major

impact in the Apostle Islands, although transport by park visitors is a continual threat. Gypsy moths were first detected in the park in 1997, and there was a severe defoliation in 2006 (Thayn 2013). These insects are mostly limited to the mainland unit, as well as Basswood and Stockton Islands (in addition to Madeline Island) (Tobin et al. 2010). Oaks and aspen are particularly threatened by gypsy moth larvae, although this insect can feed on over 300 tree species. The emerald ash borer (*Agrilus planipennis*) has not yet been detected in the park, but it does occur nearby in upper Michigan and in Superior, Wisconsin. The pale juniper webworm (*Aethes rutilana*) has been documented in high densities on juniper plants (gaagaagiwaandag, *Juniperus communis*) on Outer Island, but the effects are unclear (Johnson et al. 2017).

As mentioned above, white-tailed deer have had a considerable influence on the vegetation of the Apostle Islands. Deer became more common on several islands in the 1940s and peaked in the 1950s, and deer numbers were subsequently reduced through a combination of aging forests, increased hunting, and a stretch of severe winters. On the five islands that have maintained moderate deer densities over the past 50 years, grasses and sedges are becoming more abundant while perennial forbs such as wild sarsaparilla (waaboozojiibik, *Aralia nudicaulis*) are declining (Mudrak et al. 2009). Canada yew in particular is dramatically reduced on islands with continued deer presence, as are eastern hemlock, northern white-cedar, yellow birch, bluebead lily (odotaagaans, *Clintonia borealis*), white mandarin (*Streptopus amplexifolius*), and most orchids. Studies elsewhere in the region have confirmed the dramatic influence of persistent deer herbivory on plant communities (Frerker et al. 2014, Waller 2007, White 2012, Salk et al. 2011). In 2009, park management initiated a project to reduce recent deer migration to two islands to protect yew populations and recovery has been successful. Research from the Apostle Islands and the mainland suggests that deer browse pressure reduces Canada yew in most landscapes (Johnson et al. 2015, Frerker et al. 2014).

Currently, the park maintains two deer hunting zones to control deer populations on the islands (Figure 3) (Apostle Islands National Lakeshore 2014). Zone 1 is composed of 11 islands that historically had few or no deer: Cat, Devils, Eagle, Gull, Ironwood, North Twin, Otter, Outer, Raspberry, Sand, and York. In this Zone, the park intends to keep the deer population as low as possible or to eradicate deer. Management Zone 2 includes the nine islands that historically had notable deer population levels: Basswood, Bear, Hermit, Manitou, Michigan, Oak, Rocky, South Twin, and Stockton. The management goal of Zone 2, by contrast, is to keep deer populations at or below the estimated historical level of 10 deer per square mile. Long Island and the mainland unit are managed as part of larger management units established by the state. Red Cliff tribal members hunt deer in the mainland portion of the park that lies within the reservation, but these areas have not historically held many deer due to topography and browse availability (personal communication with Mark Duffy, 13 August 2019).

Rare Plants and Animals

The Apostle Islands support over 800 recorded plant species (Judziewicz and Koch 1993). This is due to a variety of factors, including the tremendous landscape variety, their protected status, and the maritime climate, which has allowed several “arctic disjunct” species to persist. A recent study identified the Apostle Islands as the most diverse bioregion in northern Wisconsin, with a high proportion of species with very narrow distributions (Spalink et al. 2018). The park contains 17 species listed as threatened or endangered in Wisconsin, including coast sedge (*Carex exilis*), lenticular sedge (*Carex lenticularis*), Michaux’s sedge (*Carex michauxiana*), drooping sedge (*Carex prasina*), broad-leaved twayblade (*Listera convallarioides*), flat-leaved willow (oziisigobiminzh, *Salix planifolia*), and narrow false oats (*Trisetum spicatum*) (Kraft et al. 2007). The park is also

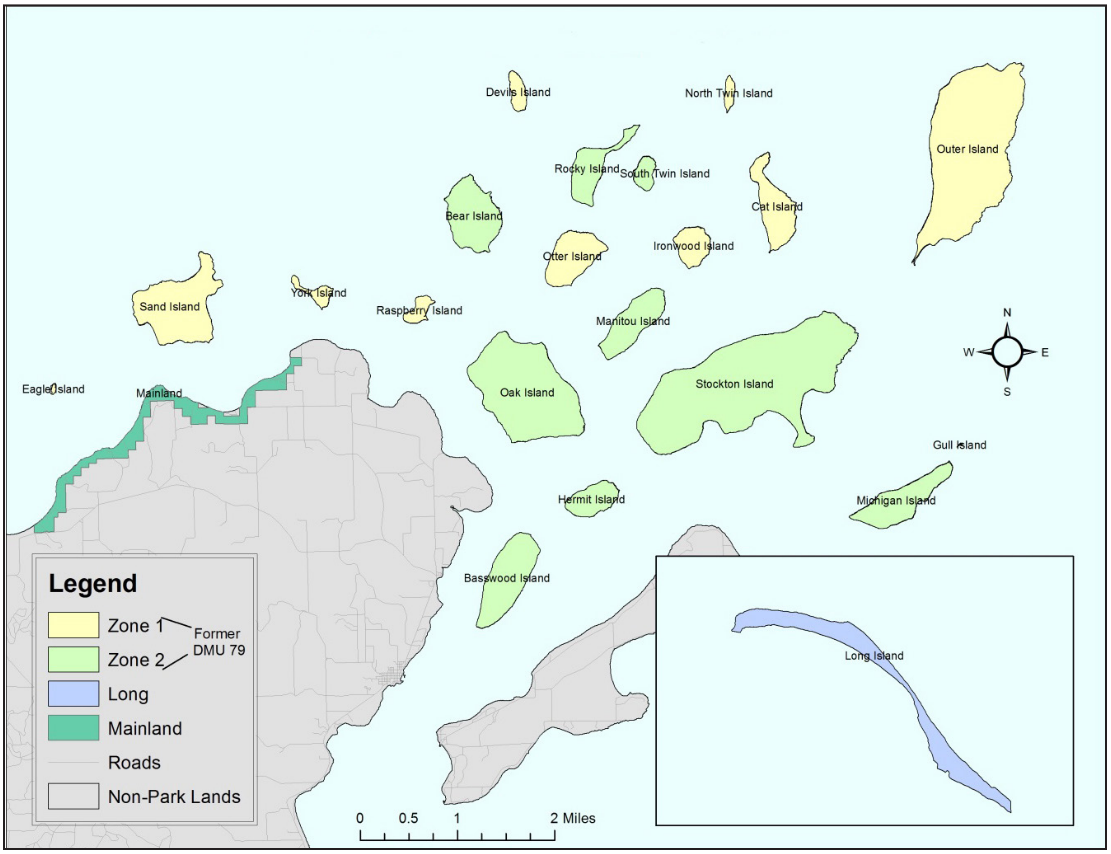


Figure 3. Deer management zones in the Apostle Islands National Lakeshore. From Apostle Islands National Lakeshore (2014).

home to 23 plant species of special concern.

In terms of wildlife, the Apostle Islands provide habitat for a variety of birds, mammals, amphibians, and aquatic species. Although wildlife are generally outside the scope of this assessment, it is worth noting that the Apostle Islands are home to the federally endangered piping plover (*Charadrius melodus*), along with 11 bird species of special concern in Wisconsin. Other species of special concern include four-toed salamanders (*Hemidactylium scutatum*), several types of aquatic and terrestrial insects, and American marten (waabizheshi, *Martes americana*), which were recently rediscovered on the islands. Migrating birds pass through the archipelago twice a year and the undeveloped shorelines and forests of the Apostle Islands provide critical stopover habitat.

Ecosystem Classifications Used in this Assessment

The vegetation resources mentioned above (Judziewicz and Koch 1993, Wisconsin Department of Natural Resources 2015, Hop et al. 2010, Kirschbaum et al. 2012, Sanders and Grochowski 2012) each use different classification systems to categorize and describe distinct ecosystems within the park. For the purposes of this assessment, the authors developed a hybrid approach to classifying different ecosystems based on accurately representing important ecological distinctions and yet reducing the number of categories to a manageable number. Table 1 presents a quick summary of the eleven ecosystems that ultimately emerged after several rounds of discussion and input. Ecosystems are defined according to their current existing condition, not in reference to a historical baseline or particular successional stage.

The following sections of this chapter contain more detail about the ecosystem drivers, current stressors, and characteristic plant species for each of the eleven ecosystems considered in this assessment.

Species lists are not meant to be exhaustive, but to give a basic impression of the common vegetation in each ecosystem.

Table 1. Apostle Islands ecosystems considered in this assessment, with a summary of major drivers and related natural communities for each ecosystem.

Ecosystem	Characteristics and Major Drivers[1]	Related Natural Communities[2]
Beaches and Dunes	• Active, unconsolidated dunes • Disturbed by frequent wind and wave action • Depend on sources of sediment and sediment transport • Occur on a wide variety of formations—cuspate forelands, barrier beaches, tombolos, barrier spits, and sand spits • Common on southern ends of islands or in protected embayments where lake currents deposit sediment	Great Lakes Beach Great Lakes Dune
Boreal Forests (including krummholz)	• Cool summers & short growing seasons • Periodic catastrophic disturbances: windthrow, ice storms, fire, pest outbreaks • Boreal forests are restricted to northern two-thirds of Devils Island • Shallow, acidic, nutrient-poor soils • High and constant moisture throughout the year from fog, snow, and wave spray • Krummholz occurs on exposed windy coasts and bluff tops, with shallow depth to bedrock	Boreal Forest
Coastal Wetlands	• Filled-in or partially filled-in embayments that occur inland from dune ridges • Cool conditions and low oxygen levels slow decomposition • Groundwater, streams, and lake connection influence water pH and nutrients • Sand or peat substrates • Partially protected from wind, wave, and ice action by sand spits	Great Lakes Shore Fen Poor Fen Interdunal Wetland Submergent Marsh Emergent Marsh Northern Sedge Meadow
Deep Ravine Forests	• Occur in deep, sheltered ravines (Oak Island, mainland unit) • Naturally buffered from fire, wind, and deer browse • Ground is shaded by dense canopy, especially northern white-cedar and hemlock. • Consistent moisture from groundwater seeps • Seasonal flooding and a redistribution of sediment in ravine bottoms is an occasional disturbance	Northern Mesic Forest Hemlock-Hardwood Forest
Erodible Maritime Bluffs	• Clay or loamy sand bluffs with steep slopes • Constantly eroding or slumping from wind, wave action, rain events, and ice scour • Vegetation depends on erosion rate, slope, and aspect • Common on approx. 50% of the coastline of all islands, mostly on east, west, and south shores	Clay Seepage Bluff

Table 1 (continued). Apostle Islands ecosystems considered in this assessment, with a summary of major drivers and related natural communities for each ecosystem.

Ecosystem	Characteristics and Major Drivers[1]	Related Natural Communities[2]
Great Lakes Pine Forests and Barrens	• Sandy, droughty, nutrient-poor soils • Strong winds and sandy soils have maintained xeric forest or barrens vegetation • Periodic, variable wildfire from natural and human origins • Heavy accumulation of snow and ice • Forests occur on stabilized beach ridges • Gradation from stabilized dunes to pine savanna to closed-canopy forest, based on landforms, soils, and disturbance frequency	Northern Dry Forest Great Lakes Barrens
Interior Alder Thickets	• Laterally moving water (not stagnant) • Seasonal water table fluctuation—inundated in the spring but can be saturated or dry late in the growing season • Oxygenated nutrient-enhanced water with neutral pH • Can be an intermediate stage between open and forested wetlands, or a persistent community • Found in beaver flowages, old roads, and the margins of other wetland communities	Alder Thicket
Interior Peat Swamps and Bogs	• Water input mostly from precipitation—limited or no groundwater connection • Very acidic water conditions, and a range of nutrient conditions • Cool conditions and low oxygen levels slow decomposition • Peat substrates • Occur on poorly drained summit plateaus	Black Spruce Swamp Northern Tamarack Swamp Muskeg Open Bog Boreal Rich Fen
Mixed Conifer Hardwoods	• Clay till soils with gentle to moderate slopes • Regular patterns of seasonal water and nutrient availability • Thick forest canopy of shade-tolerant species • Gap-sized disturbance from mortality, wind, and pests • Naturally buffered from fire and other catastrophic disturbances • High amounts of coarse woody debris • Include scattered vernal pools • This is the dominant forest type that covers approx. 85% of the park	Northern Mesic Forest Northern Wet-Mesic Forest
Rock Cliffs and Ledges	• Sandstone ledges and bluffs • Exposed to fog, wave spray, and splash pools • Heavy snow and ice cover • Erosion from wind, ice, waves, and freeze-thaw expansion • Vegetation depends on height, slope, aspect, and seepage • Occur on approx. 33% of the coastline of all islands	Bedrock Shore Moist Cliff
Upland Hardwood Forests	• Well-drained loamy sand soils—drier than the majority of the matrix forest • Naturally buffered from fire and other large disturbances • Gap-sized disturbance from mortality, wind, and pests • Canada yew is less prevalent than in Mixed Conifer Hardwoods, but herbaceous layer is more diverse • Occur in higher elevations in the park	Northern Mesic Forest

[1] Drivers are defining features or processes that determine the identity of an ecosystem.

[2] Natural Community descriptions can be found in Chapter 7 of ***The Ecological Landscapes of Wisconsin*** (Wisconsin Department of Natural Resources 2015).

Beaches and Dunes

Characteristic Species

<u>Shrubs</u>

- Heart-leaved, sandbar, and slender willows (*Salix* spp.)
- Dwarf juniper
- Sand cherry (*Prunus pumila*)
- Bearberry or kinnikinnick (apaakozigan, *Arctostaphylos uva-ursi*)
- Beach wormwood (*Artemisia stelleriana*)

<u>Herbaceous species</u>

- Beach grass (*Ammophila breviligulata*)
- Evening primrose (*Oenothera biennis*)
- Hairgrass (*Avenella flexuosa*)
- Beach pea (*Lathyrus japonicus*)
- Lichens such as reindeer moss (aasaakamig, *Cladina subtenuis*)

Ecosystem Drivers

- Active, unconsolidated dunes.
- Disturbed by frequent wind and wave action.
- Depend on sources of sediment and sediment transport.
- Occur on a wide variety of formations—cuspate forelands, barrier beaches, tombolos, barrier spits, and sand spits.
- Common on southern ends of islands or in protected embayments where lake currents deposit sediment.

Current Stressors

- Trampling from foot traffic, kayaks, and boats.
- Invasive species such as spotted knapweed, ox-eye daisy (*Leucanthemum vulgare*), quack grass (*Elymus repens*), beach rose (*Rosa rugosa*) and tansy.
- Pale juniper webworm causes partial defoliation on juniper species, but long-term effects are unclear.

Lichen and hairgrass on a Rocky Island dune.
© S. Johnson/Northland College

Quarry Bay beach, Stockton Island.
© S. Johnson/Northland College

Outer Island.
NPS photo

Boreal Forests (including krummholz)

Characteristic Species

<u>Trees</u>

- White spruce (gaawaandag, *Picea glauca*)
- Balsam fir (zhingob, *Abies balsamea*)
- Balsam poplar (maanazaadi, *Populus balsamifera*)
- Northern white-cedar
- Paper birch
- Quaking aspen (azaadi, *Populus tremuloides*)
- Showy mountain ash (makominagaawanzh, *Sorbus decora*)

<u>Shrubs</u>

- Mountain maple (*Acer spicatum*)
- Canada yew
- Herbaceous species
- Lichens (*Usnea* spp.)
- Mosses, including sphagnum moss (mashkiigwakamig, *Sphagnum* spp.)
- Sedges (*Carex* spp.)

Ecosystem Drivers

- Cool summers and short growing seasons.
- Periodic catastrophic disturbances: windthrow, ice storms, fire, pest outbreaks.
- Boreal forests are mostly restricted to northern two-thirds of Devils Island (although boreal “elements” are embedded within other forest types in the park).
- Shallow, acidic, nutrient-poor soils.
- High and constant moisture throughout the year from fog, snow, and wave spray.
- Krummholz occurs on exposed windy coasts and bluff tops, with shallow depth to bedrock.

Current Stressors

- Spruce budworm (*Choristoneura fumiferana*) and other insect pests.

True boreal forest of spruce, fir, paper birch, and showy mountain ash occurs in limited locations in the Apostle Islands, such as Devils Island. NPS PHOTO/P. BURKMAN

Krummholz is a stunted, wind-shaped forest found on exposed, windy coasts and bluff tops. NPS PHOTO/P. BURKMAN

Coastal Wetlands

Characteristic Species

Coastal wetlands in the Apostle Islands are repositories of many rare species, including a number of specialists and culturally important medicinal species.

<u>Trees</u>

- Tamarack (mashkiigwaatig, *Larix laricina*)
- Black spruce (zesegaandag, *Picea mariana*)
- Northern white-cedar

<u>Shrubs</u>

- Sweet gale (wa'sawasni'mike, *Myrica gale*)
- Leatherleaf (*Chamaedaphne calyculata*)
- Cranberry (mashkiigimin, *Vaccinium macrocarpon* and *V. oxycoccos*)
- Speckled alder (wadoop, *Alnus incana*)

<u>Herbaceous species</u>

- Sedges, including mat-forming woolyfruit sedge (*Carex lasiocarpa*), fewseed sedge (*C. oligosperma*), and white beak-rush (*Rhynchospora alba*)
- Rushes
- Sphagnum mosses
- Marsh cinquefoil (*Comarum palustre*)
- Water horsetail (*Equisetum fluviatile*)
- Bladderworts (*Utricularia* spp.)
- Sundews (*Drosera* spp.)
- Pitcher plant (*Sarracenia purpurea*)

A coastal wetland in the Apostle Islands.
© S. Johnson/Northland College

Coastal wetland in a dune swale, Stockton Island.
© S. Johnson/Northland College

Ecosystem Drivers

- Filled-in or partially filled embayments that occur inland from dune ridges or on the margins of lagoons inland from the dunes.
- Cool conditions and low oxygen levels slow decomposition.
- Groundwater, streams, and lake connection influence water pH and nutrients.
- Sand or peat substrates.
- Partially protected from wind, wave, and ice action by sand spits or dunes.

Current Stressors

- Nutrient loading due to sedimentation from uplands.
- Sedimentation
- Non-native species, such as non-native cattails (apakweshk, *Typha* spp.) and purple loosestrife and invasive native species such as common reed (aaboojigan, *Phragmites australis*) that did not historically occupy these wetlands.
- Human disturbance on adjacent uplands (road construction, ditching, development) leading to hydrologic disruption (more of an issue on the mainland compared to islands).

Deep Ravine Forests

Characteristic Species

Trees
- Eastern hemlock
- Yellow birch
- Northern white-cedar
- Eastern white pine
- Mountain maple

Herbaceous species
- Bryophytes
- Drooping sedge
- Broad-lipped twayblade
- Rattlesnake plantain (*Goodyera oblongifolia*)
- Chilean sweet cicely (*Osmorhiza berteroi*)
- White mandarin
- Dwarf scouring rush (anaakanashk, *Equisetum scirpoides*)
- Bulblet fern (*Cystopteris bulbifera*)

Ecosystem Drivers

- Occur in deep, sheltered ravines (Oak Island, mainland unit).
- Naturally buffered from fire, wind, and deer browse (although mainland unit has higher deer density).
- Ground is shaded by dense canopy, especially northern white-cedar and hemlock.
- Consistent moisture from groundwater seeps.
- Seasonal flooding and a redistribution of sediment in ravine bottoms is an occasional disturbance.

Current Stressors

- Past logging and hauling have affected some locations through compaction, rutting, erosion, and introduction of weeds.
- Mainland ravines are vulnerable to deer herbivory.
- Invasive species introduction through timber harvests at the head of the ravines on the mainland and a campground at the mouth of one of the ravines.
- Excessive erosion and sediment deposition due to severe rainstorms in recent years.

Ravine forest. © S. Johnson/Northland College

A ravine forest with eastern hemlock regeneration. © S. Johnson/Northland College

Erodible Maritime Bluffs

Characteristic Species

Trees
- Eastern white pine
- Quaking aspen
- Red pine
- Balsam poplar
- Paper birch
- Red maple
- Mountain ash
- Northern white-cedar
- Balsam fir

Shrubs
- Speckled alder
- Green alder (*Alnus viridis*)
- Willows
- Raspberry (miskomin, *Rubus idaeus*)
- Serviceberry (gozigwaakomin, *Amelanchier* spp.)
- Red-osier dogwood (miskwaabiimizh, *Cornus sericea*)

Herbaceous species
- Canada wild rye (*Elymus canadensis*)
- Canada blue grass (*Poa compressa*)
- Clover spp. (*Trifolium* spp.)
- Fireweed (*Chamerion angustifolium*)
- Thistle spp. (mazaanaatig, *Cirsium* spp.)
- Aster spp.
- Grass-of-Parnassus (*Parnassia palustris*) (Outer Island)
- Elegant groundsel (*Packera indecora*) (Rocky Island)
- green bog orchid (*Platanthera huronensis*)
- Variegated horsetail (*Equisetum variegatum*) (one site on Rocky Island)

Ecosystem Drivers
- Clay or loamy sand bluffs with steep slopes.
- Constantly eroding and slumping from wind, wave action, rain events, and ice scour.
- Vegetation depends on erosion rate, slope, and aspect.
- Common on approximately 50% of the coastline of all islands, mostly on east, west, and south shores.

Steep, eroding bluffs are found on roughly half of Apostle Islands coastlines. NPS PHOTO/P. BURKMAN

Eroding bluffs near Little Sand Bay. NPS PHOTO

Current Stressors
- Invasive species, such as clover, sow thistle (*Sonchus arvensis*), ox-eye daisy, and dandelion (doodooshaaboojiibik, *Taraxacum officinale*).

Great Lakes Pine Forests and Barrens

Characteristic Species

Trees
- Red pine
- White pine
- Jack pine (akikaandag, *Pinus banksiana*) (occasional, mostly on Long Island)
- Northern pin oak (mitigomizh, *Quercus ellipsoidalis*) (mostly on Long Island)
- Balsam fir
- Paper birch
- Black spruce (mostly on Stockton Island)

Shrubs
- Blueberry
- Huckleberry (miinan, *Gaylussacia baccata*)
- Sand cherry
- Common juniper
- Fire cherry (*Prunus pensylvanicum*)

Herbaceous species
- Shaved sedge (*Carex tonsa*)
- Lichen spp.
- Mosses such as Schreber's big red stem moss (*Pleurozium schreberi*)
- Hair grass (*Avenella flexuosa*)
- Wintergreen (*Gaultheria procumbens*)
- Roughleaf ricegrass (*Oryzopsis asperifolia*)
- Pink lady's slipper (*Cypripedium acaule*)
- Narrowleaf cow-wheat (*Melampyrum lineare*)
- Bracken fern (waagaan, *Pteridium aquilinum*)

Ecosystem Drivers
- Sandy, droughty, nutrient-poor soils.
- Strong winds, moving sands, and minimal soil development have maintained semi-open barrens communities in some locations.
- Xeric forests occur on stabilized beach ridges.
- Periodic, variable wildfire from natural and human origins.
- Gradation from open, active dunes to more stabilized sand ridges supporting pine savanna to closed-canopy pine forest, based on landform, soils, and disturbance frequency and intensity.

Pines and lichens established on an old dune.
© S. Johnson/Northland College

Pink lady's slipper (*Cypripedium acaule*).
NPS photo/T. Gostomski

Current Stressors
- Insect pests.
- Lack of recent fire (pine forests in particular).
- Invasive plants.
- Trampling from foot traffic and associated erosion.

Interior Alder Thickets

Characteristic Species

Trees
- Willow spp.
- Mountain ash
- Black ash (baapaagimaak, *Fraxinus nigra*)
- American elm (aniib, *Ulmus americana*)

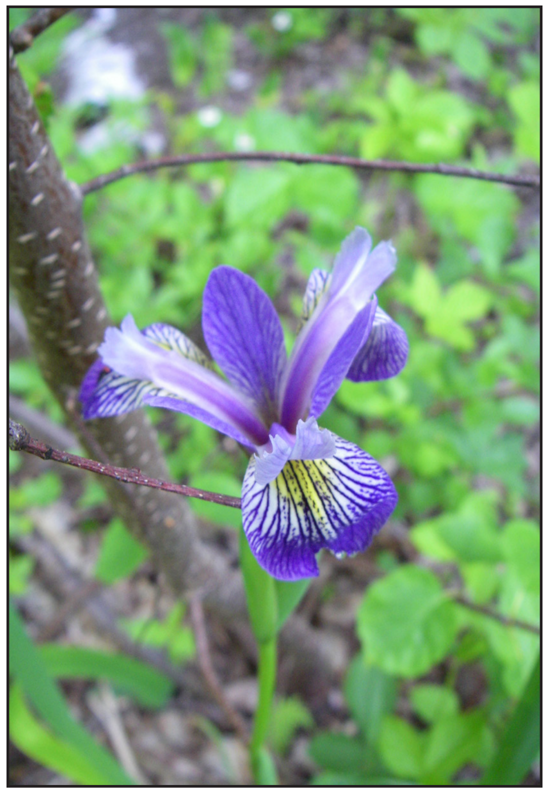
Shrubs
- Speckled alder
- Ninebark (*Physocarpus opulifolius*)
- Skunk currant (*Ribes glandulosum*) and red currant (*Ribes triste*)
- Red osier dogwood

Herbaceous species
- Touch-me-not (omakakiibag, *Impatiens capensis*)
- Norwegian cinquefoil
- Lake sedge (*Carex lacustris*)
- Harlequin blueflag (*Iris versicolor*)
- Bluejoint grass (*Calamagrostis canadensis*)

Ecosystem Drivers
- Laterally moving groundwater (not stagnant).
- Seasonal water table fluctuation-inundated in the spring, saturated or dry late in the growing season.
- Oxygenated nutrient-enhanced water with neutral pH.
- Can be an intermediate stage between open and forested wetlands, or a persistent, stable community.
- Found in beaver flowages, old roads, and in the zones between forests and open wetlands.

Current Stressors
- Invasive/non-native species, such as reed canary grass, thistles, and purple loosestrife.
- Prolonged inundation and other hydrologic disruption.

Alder thickets can be stable communities that last for years.
E. Epstein/Wisconsin Department of Natural Resources



Harlequin blueflag (*Iris versicolor*).
NPS photo/T. Gostomski

Interior Peat Swamps and Bogs

Characteristic Species

<u>Trees</u>
- Tamarack
- Black spruce
- Eastern white pine
- Paper birch
- Jack pine

<u>Shrubs</u>
- Leatherleaf
- Bog rosemary (binemiiki, *Andromeda polifolia* var. *glaucophylla*)
- Bog laurel (*Kalmia polifolia*)
- Labrador tea (mashkiigobag, *Ledum groenlandicum*)
- Cranberry (*Vaccinium oxycoccos*)

<u>Herbaceous species</u>
- Sphagnum moss
- Sedges
- Pod-grass (*Scheuchzeria palustris*)

Ecosystem Drivers
- Water input mostly from precipitation—limited or no groundwater connection.
- Very acidic water conditions, and a range of nutrient conditions.
- Cool conditions and low oxygen levels slow decomposition.
- Peat substrates.
- Occur on poorly drained summit plateaus.

Current Stressors
- Forest pests, such as eastern larch beetle (*Dendroctonus simplex*), tamarack sawfly (*Pristiphora erichsonii*), spruce budworm.
- Non-native species, such as reed canary grass.
- Legacy roads in some areas that disrupt hydrology (e.g., Devils Island).
- Atmospheric deposition of nitrogen.

Inland raised bog on Devils Island.
© S. Johnson/Northland College

Bog laurel (*Kalmia polifolia*).
NPS photo/T. Gostomski

Mixed Conifer Hardwoods

Characteristic Species

Trees
- Sugar maple
- Red maple
- Yellow birch
- American basswood
- Paper birch
- Balsam fir
- American basswood
- Northern red oak
- Northern white-cedar
- Eastern white pine
- Eastern hemlock
- Mountain maple

Shrubs
- Canada yew
- Hazelnut (bagaanimizh, *Corylus cornuta*)
- Skunk currant
- Honeysuckle (*Lonicera* spp.)
- Juneberries

Herbaceous species
- Wood ferns (*Dryopteris* spp.)
- Bluebead lily
- Wild sarsaparilla
- Nodding trillium (ininiwin dibige'gun, *Trillium cernuum*)
- Dwarf ginseng (*Panax trifolius*)

Ecosystem Drivers
- Clay till soils with gentle to moderate slopes.
- Mesic to wet-mesic soil moisture conditions.
- Regular patterns of seasonal water and nutrient availability.
- Continuous forest canopy of shade-tolerant species.
- Gap-sized disturbance from mortality, wind, and pests.
- Naturally buffered from fire and other catastrophic disturbances.
- High amounts of coarse woody debris.
- Include scattered ephemeral ponds and vernal pools.
- This is the dominant forest type that covers approximately 85% of the park.

Approximately 1,350 acres of old growth mixed conifer hardwoods remain in the park, mostly on North Twin, Devils, and Raspberry Islands. NPS photo/J. Van Stappen

Current Stressors
- Deer herbivory on some islands and on the mainland.
- Forest insect pests such as forest tent caterpillar (*Malacosoma disstria*) and gypsy moth.

Rock Cliffs and Ledges

Characteristic Species

Trees
- Northern white-cedar
- Balsam fir
- Paper birch
- Heart-leaved birch (*Betula cordiformis*)
- Willow spp.
- Eastern white pine

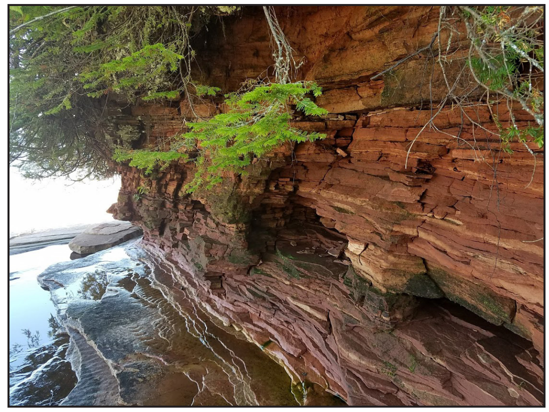
Herbaceous species
- Rare subarctic species on north-facing cliffs, such as butterwort (*Pinguicula vulgaris*), spike trisetum (*Trisetum spicatum*), hair-like sedge (*Carex capillaris*), and bird's-eye primrose (*Primula mistassinica*)
- Calciphic species, such as harebell (*Campanula rotundifolia*) and ninebark
- Elegant groundsel in rock crevices
- Mosses and lichens
- Fireweed
- Strawberry (ode'iminijiibik, *Fragaria virginiana*)
- Yarrow (nookwezigan, *Achillea millefolium*)
- Pearly everlasting (waabigwan, *Anaphalis margaritacea*)

Ecosystem Drivers

- Sandstone ledges, bluffs, and splash pools.
- Exposed to fog and wave spray.
- Heavy snow and ice cover.
- Erosion from wind, ice, waves, and freeze-thaw expansion.
- Vegetation is often sparse and depends on height, slope, aspect, and seepage.
- Occur on approximately 33% of the coastline of all islands.

Current Stressors

- Weedy species, such as bluegrass (ozhaawashkwa-mashkosiwan, *Poa* spp.), yarrow, and dandelion.
- Trampling on rock ledges near popular recreation sites.



Sheltered rock cliff with a splash pool.
© S. Johnson/Northland College

Upland Hardwood Forests

Characteristic Species

Trees
- Northern red oak
- Sugar maple
- Red maple
- Yellow birch
- Paper birch
- Balsam fir
- American basswood
- Eastern white pine

Shrubs
- Canada yew (less prevalent than in Mixed Conifer Hardwoods)
- Hazelnut
- Skunk currant
- Honeysuckle
- Juneberries

Herbaceous species
- Canada mayflower (agongosminaan, *Maianthemum canadense*)
- Starflower (*Trientalis borealis*)
- Bigleaf aster (migizibag, *Eurybia macrophylla*)
- Bluebead lily

Ecosystem Drivers
- Well-drained sandy or loamy soils—drier than the majority of the forest.
- Naturally buffered from fire and other large disturbances.
- Gap-sized disturbance of single trees or small groups from mortality, wind, and pests.

Upland hardwoods in the Apostle Islands tend to have slightly drier soils and a more open understory. NPS PHOTO/P. BURKMAN

- Canada yew is less prevalent than in the more moist Mixed Conifer Hardwoods, but the herbaceous layer is more diverse.
- Occur in higher elevations in the park.

Current Stressors
- Forest insect pests, such as forest tent caterpillar, gypsy moth, and two-lined chestnut borer (*Agrilus bilineatus*).
- Invasive earthworms (*Dendrobaena octaedra*, *Lumbricus rubellus* and *L. terrestris*).

Conclusion
This chapter has provided the fundamental ecological and cultural contexts of the Apostle Islands National Lakeshore. The brief synopsis of the eleven terrestrial ecosystems considered for this assessment will be a helpful reference. Readers may wish to refer back to this information, as following chapters describe how climate change may affect important ecosystem drivers, characteristic species, and current stressors to these ecosystems.

Chapter 2: Observed and Projected Changes in Climate and Physical Processes in the Apostle Islands

This chapter describes observed climate trends and a range of plausible climate change projections for the Apostle Islands National Lakeshore and the nearby region. Information is organized by topic, with summary information about observed and projected trends for each item. Topics include direct climate variables such as temperature and precipitation, as well as indirect effects on relevant physical processes such as lake ice formation. Projections focus on conditions at the end of the 21st century. This information was considered by the panel of authors at a vulnerability assessment workshop and was a key source of information for the ecosystem vulnerability conclusions, described in Chapter 4. Box 3 includes a brief description of the climate data used in this assessment.

Climate Data Used in this Assessment

For this ecosystem vulnerability assessment, a panel of experts used multiple sources of climate change data. For observed temperature and precipitation trends, participants considered summary data from the Northwestern Wisconsin Climate Division, as summarized by Great Lakes Integrated Sciences and Assessments, the Midwest Regional Climate Center, and the Office of the Michigan State Climatologist (GLISA 2019a). The Northwestern Wisconsin Climate Division includes the entire Bayfield Peninsula and a portion of the Apostle Islands, but also stretches west to the Minnesota border and south to Chippewa Falls, WI. The majority of this region is not directly influenced by Lake Superior and has a more continental climate, so some of the detailed features of the local Apostle Islands climate may not be represented. Observed change is calculated from the linear best fit over the period from 1950 to 2017. Percent change is reported relative to the 1951 to 1980 historical baseline period. For other topics, information on observed or historical trends was drawn from different sources which are referenced throughout the chapter, including several sources that directly address the Apostle Islands.

To present future climate projections for the region surrounding the Apostle Islands, participants considered information from a nationwide statistically downscaled dataset and a set of dynamically downscaled climate models that were designed specifically for the Great Lakes Region. Appendix 3 contains a comparison of statistical and dynamical downscaling approaches. The Multivariate Adaptive Constructed Analogs (MACA, www.climatologylab.org/maca.html) statistically downscaled dataset from the University of Idaho Climatology Lab includes 20 General Circulation Models (GCMs) that have been downscaled and run under two representative concentration pathways (RCPs), RCP 4.5 and RCP 8.5 (Abatzoglou and Brown 2012). RCPs are sometimes referred to in the text as “scenarios” for the sake of brevity, although technically they are greenhouse gas concentration pathways. See Appendix 3 for an explanation of GCMs and RCPs. Participants considered the ensemble average of 20 GCMs, using both RCP 4.5 and RCP 8.5 to represent a range of futures. This dataset was used to describe the broad trends in temperature, precipitation, growing season length, and other variables.

The MACA data are supplemented where possible with information from a dynamically downscaled dataset (RegCM4) from the University of Wisconsin-Madison Center for Climatic Research and provided by Dr. Michael Notaro (https://nelson.wisc.edu/ccr/resources/dynamical-downscaling/index.php). This dataset, henceforth referred to as the Notaro dataset, was designed to represent local climate processes in the Great Lakes region, but consists of six GCMs that have been run only at RCP 8.5 (Notaro et al. 2015a, Notaro et al. 2015b). These datasets were supplemented with other sources when it was necessary to find information about particular climate variables. Other sources of downscaled

climate data are available for the Great Lakes Region (Byun and Hamlet 2018) but they also tend to support and confirm the overall picture presented by the MACA and Notaro datasets.

Temperature

Across the Northwestern Wisconsin Climate Division, the average annual temperature has increased 3.2°F from 1950 to 2017 (GLISA 2019a). Northwestern Wisconsin is one of the most rapidly warming areas within the state and nation. Seasonally, the greatest warming has occurred during winter (5.4°F) and spring (3.3°F) (Table 2). This pattern mirrors the trend across the entire state and the larger region, as winter has experienced the most rapid warming in recent decades (Janowiak et al. 2014).

For the Apostle Islands, both the MACA and Notaro datasets project warming in all seasons by the end of the century. Under RCP 4.5, the MACA data projects an average annual temperature increase of 6.4°F compared to the 1971–2000 baseline (Table 2), with the largest amount of warming occurring in winter (7.7°F). Spring, summer, and fall are projected to warm by about 6°F under RCP 4.5. Under RCP 8.5, the MACA data projects an average annual temperature increase of 11.2°F, also with the largest temperature change occurring in winter (13.3°F).

The Notaro dataset (RCP 8.5) provides a similar range of projected temperature increases by the end of the century. For example, the range of future summer warming in the Notaro dataset is 7°F to 13°F, while for winter, it is 6°F to 11°F.

Precipitation

The Apostle Islands receives about 29 inches of precipitation each year. Across the Northwestern Wisconsin Climate Division, the average annual precipitation has increased 1.1 inches from 1950 to 2017 (GLISA 2019a). This represents an increase of about 3.4% compared to the historical baseline of 1951 to 1980. Seasonally, the greatest precipitation increase has occurred during fall (1.5 inches, 20.4% increase) and winter (0.4 inches, 12.2% increase) (Table 3). Summer precipitation has decreased by 1.2 inches (8.9% decrease) over the same period.

Future projections of seasonal precipitation are controlled by many factors, such as how convection is resolved in the model, future projections on global circulation, changes in storm tracks, and natural variability. These factors make it difficult to predict the magnitude of future precipitation change. Additionally, although regional averages provide an overall estimation of future conditions, local changes in precipitation may be much larger. For the Apostle Islands, the MACA data projects an annual increase in precipitation of 2.8 inches under RCP 4.5 and an increase of 4.2 inches under RCP 8.5 (Table 3). Under RCP 4.5, there is either no change or an increase in precipitation in each season. By contrast, under RCP 8.5 there is a 0.8-inch decrease in precipitation in summer, and increases of more than an inch in winter, spring, and fall. Both concentration pathways project spring to have the largest increase in precipitation. Other statistically downscaled datasets offer similar projections for regional precipitation under RCP 4.5 and RCP 8.5 by the end of the century (Byun and Hamlet 2018).

The Notaro dataset provides similar projections of precipitation increases for the Apostle Islands in winter, spring, and fall by the end of the century. The largest uncertainty occurs with summer precipitation, where the projections span a decrease of 3 inches up to an increase of 3 inches. The largest-magnitude projected change occurs during the winter, with as much as 6 inches more precipitation in some models. As discussed above, the Notaro dataset is based on a regional climate model that attempts to represent local weather processes such as the effect of the Great Lakes. So the projected increase in winter precipitation in this dataset is at least partially reflecting the expected increase in lake-effect snow and rain as ice cover continues to decline (Notaro et al. 2015b).

Table 2. Observed and projected increases in temperature for the Apostle Islands region. Observed change is calculated from the linear best-fit change over the period 1950 to 2017 (GLISA 2019a). RCP = Representative Concentration Pathways. RCP 4.5 and RCP 8.5 indicate the projected temperature increase by the end of the century according to the ensemble average of 20 GCMs in the statistically downscaled MACA dataset (Abatzoglou and Brown 2012). Values in parentheses indicate the lowest and highest value among the 20 GCMs. "Notaro" values under Projected Change 8.5 indicate the range of results from six GCMs that were dynamically downscaled by Michael Notaro at the University of Wisconsin-Madison.

Season	Observed Change (°F)	Projected Change: RCP 4.5 (°F)	Projected Change: RCP 8.5 (°F)
Annual	3.2	6.4 (3.1 to 10.4)	11.2 (6.8 to 16.5)
Winter	5.4	7.7 (4.3 to 13.4)	13.3 (7.7 to 20.8) Notaro: 6 to 11
Spring	3.3	6.0 (3.0 to 13.2)	10.1 (6.3 to 19.0) Notaro: 4 to 11
Summer	1.5	5.8 (2.2 to 9.2)	10.8 (5.3 to 15.9) Notaro: 7 to 13
Fall	2.5	6.0 (2.3 to 10.0)	10.7 (6.5 to 16.1) Notaro: 5 to 12

Table 3. Observed and projected changes in precipitation for the Apostle Islands region. Observed change is calculated from the linear best-fit change over the period 1950 to 2017 (a). RCP = Representative Concentration Pathways. RCP 4.5 and RCP 8.5 indicate the projected precipitation change by the end of the century according to the ensemble average of 20 GCMs in the statistically downscaled MACA dataset (Abatzoglou and Brown 2012). Values in parentheses indicate the lowest and highest value among the 20 GCMs. "Notaro" values under Projected Change 8.5 indicate the range of results from six GCMs that were dynamically downscaled by Michael Notaro at the University of Wisconsin-Madison.

Season	Observed Change (inches)	Projected Change: RCP 4.5 (inches)	Projected Change: RCP 8.5 (inches)
Annual	1.1	2.8 (–0.1 to 4.7)	4.2 (0.3 to 8.8)
Winter	0.4	0.7 (0.2 to 1.6)	1.3 (0 to 2.6) Notaro: 1 to 6
Spring	0.4	1.3 (0.2 to 2.4)	2.3 (0.3 to 5.0) Notaro: –0.5 to 2
Summer	–1.2	0 (–1.7 to 1.8)	–0.8 (–2.3 to 2.0) Notaro: –3 to 3
Fall	1.5	0.8 (–0.5 to 2.0)	1.4 (–0.4 to 2.7) Notaro: 0.5 to 3

Growing Season Length

The growing season is the time during which conditions allow plant growth to occur. In many cases, growing season length is defined as the frost-free season (last spring frost to first fall frost). The frost-free growing season has already lengthened by 8–12 days in the Bayfield Peninsula from 1950 to 2006 (WICCI 2011). The historical growing season in the Apostle Islands is about 120 days.

By the end of the century, the frost-free season is projected to increase by an average of 28 days under RCP 4.5 and an average of 56 days under RCP8.5 according to the MACA dataset. Under these projections, the last spring frost is projected to advance earlier in the year much more rapidly than the fall frost is projected to retreat later into the year. Under the dynamically downscaled Notaro dataset (RCP 8.5), the total frost-free season is projected to increase by 33 to 48 days by the end of the century. These projections are in line with other downscaled climate change projections (Zobel et al. 2017).

Extreme Precipitation

The physical mechanisms that control extreme precipitation are different than those that control normal precipitation. For each degree Fahrenheit that temperature increases, precipitation intensity has the potential to increase, for a given event, by about 4% due to air's increased ability to hold water vapor (USGCRP 2017). This increase in water vapor increases the likelihood of extreme precipitation events, both in terms of frequency and intensity. The Midwest has experienced 25%–35% increases in the frequency of extreme precipitation events (defined as events that would have historically been among the top 1% of all daily rain events) over the past several decades, compared to the 1900–1960 average (Walsh et al. 2014, Pryor and Scavia 2014). The frequency of rainstorms of three inches or more increased by over 200% in Wisconsin between 1961 and 2011 (Saunders et al. 2012).

As temperatures are projected to increase throughout the year under all climate change scenarios, it follows that extreme precipitation will also increase. The dynamically downscaled Notaro dataset (RCP 8.5) projects that the Apostle Islands region will experience 9–31 more one-inch rainfall events per decade by the end of the century. This represents a substantial increase compared with the current average of 40–60 events per decade according to the 1981–2010 historical average (Dan Vimont, personal communication, 18 June 2019). The area may also experience 3–5 more events per decade that drop more than 3 inches of rain. The Apostle Islands region currently experiences about one event of that magnitude per decade (Dan Vimont, personal communication, 18 June 2019).

Other research points to a similar conclusion of more heavy and extreme precipitation. Across the Midwest, daily precipitation that currently has a 20-year return period is projected to occur 11% more often in RCP4.5 and 20% more often in RCP8.5 at the end of the century (USGCRP 2017). In other words, extreme events are projected to increase in frequency.

Extreme Heat

As discussed in Chapter 1, the Apostle Islands generally have a climate regime that is moderated by Lake Superior. Locations in the Apostle Islands have historically experienced fewer than 10 days each year with maximum temperatures above 90°F (Dan Vimont, personal communication, 18 June 2019). Extreme heat is projected to increase in both frequency and magnitude by the end of the century, however. The MACA dataset indicates that the hottest daytime temperature recorded over the year in the Apostle Islands is projected to increase by an average of 6.9°F under RCP 4.5, and by 11.9°F under RCP 8.5.

Similarly, the Bayfield Peninsula is projected to experience 20 to 30 days per year with a maximum temperature greater than 95°F by the end of the century, compared with nearly zero of these days during the 1971 to 2000 baseline period (Byun and Hamlet 2018).

Hot spells, defined as 4-day periods whose mean temperatures exceed a threshold for a 1-in-5-yr reoccurrence, are projected to increase in magnitude by between 6° and 7° in the Midwest by the end of the century (Wuebbles et al. 2014). Additionally, rare temperature extremes, defined as 1-in-20 year events in the historical reference period of 1971 to 2000, are projected to become nearly annual events under RCP 8.5 (Wuebbles et al. 2014).

Extreme Cold

Extreme cold winter conditions can limit suitable habitat conditions for plant and animal species and create a competitive advantage for cold-tolerant, boreal species. Lake Superior also buffers the Apostle Islands and the nearby shoreline from extreme cold temperatures, compared to areas further inland from the lake. According to the MACA dataset, the coldest nighttime temperature recorded over the year in the Apostle Islands is projected to increase by an average of 11.8°F under RCP 4.5, and by 20.5°F under RCP 8.5. This is compared to a baseline average of −15.3°F from 1971–2000. Compared to the trend for hottest daytime temperature (see 'Extreme Heat' above), this means that the rate of warming is nearly twice as fast for the coldest conditions in the Apostle Islands compared to the hottest conditions.

Often the coldest temperatures during winter are only reached for short periods of time, so they can be described as "cold air outbreaks." Cold air outbreaks are defined as two or more continuous days where the average daily temperature is within the coldest 2.5% of the measured temperatures within an area (Gao et al. 2015). As winters are projected to warm, these cold air outbreaks are expected to become far less common in the Great Lakes region. Cold air outbreaks are projected to occur roughly 60% less frequently under RCP4.5 by mid-century (2026 to 2045), and 80%–90% less frequently under RCP8.5 by the end of the century (2081 to 2100) (Gao et al. 2015). While cold air outbreaks will continue to occur in the future, they may be even more closely tied to times of snow coverage than they are currently (Gao et al. 2015). That is to say, snow cover will become a necessary factor for cold air outbreaks to occur. Similarly, Byun and Hamlet (2018) project that the Bayfield Peninsula may experience fewer than 20 days each winter where the temperature drops below 5°F by the end of the century.

Another metric of measuring extreme cold is "cold spells" (4-day periods whose mean temperatures meet a threshold for a 1-in-5-yr reoccurrence), which are projected to be more than 10°F warmer by the end of the century in the Midwest (Wuebbles et al. 2014).

Snowfall (includes Lake-effect Snow)

The Apostle Islands receive an average of about 71 inches of snow each winter (Midwestern Regional Climate Center 2020), while the larger region of northwest Wisconsin has on average 55 inches (+/- 20 inches) of snowfall per year (a). Lake-effect snowfall accounts for the difference between snowfall in the park and in the neighboring Bayfield Peninsula (Figure 4). During the 1950 to 2010 period, snowfall tended to increase through time in northwest Wisconsin (GLISA 2019a).

Lake Superior has a large effect on local snowfall, and therefore it is preferable to rely on dynamical downscaling methods as opposed to statistical downscaling methods to project future changes in snowfall. This is because dynamical downscaling attempts to simulate how local weather processes influence snow formation. As winters are projected to warm under climate change, most dynamical downscaling models project a long-term decrease in snowfall for the Great Lakes region. For the region around the Bayfield Peninsula and the Apostle Islands, models project an annual snowfall decline of 22 to 51 inches by the end of the century depending on the RCP and climate model (Notaro et al. 2015b, Notaro et al. 2014). By the end of the century, northern Wisconsin is expected to have 15 to 45 fewer days each winter with at least 0.4 inches of snowfall, and the mean snow depth

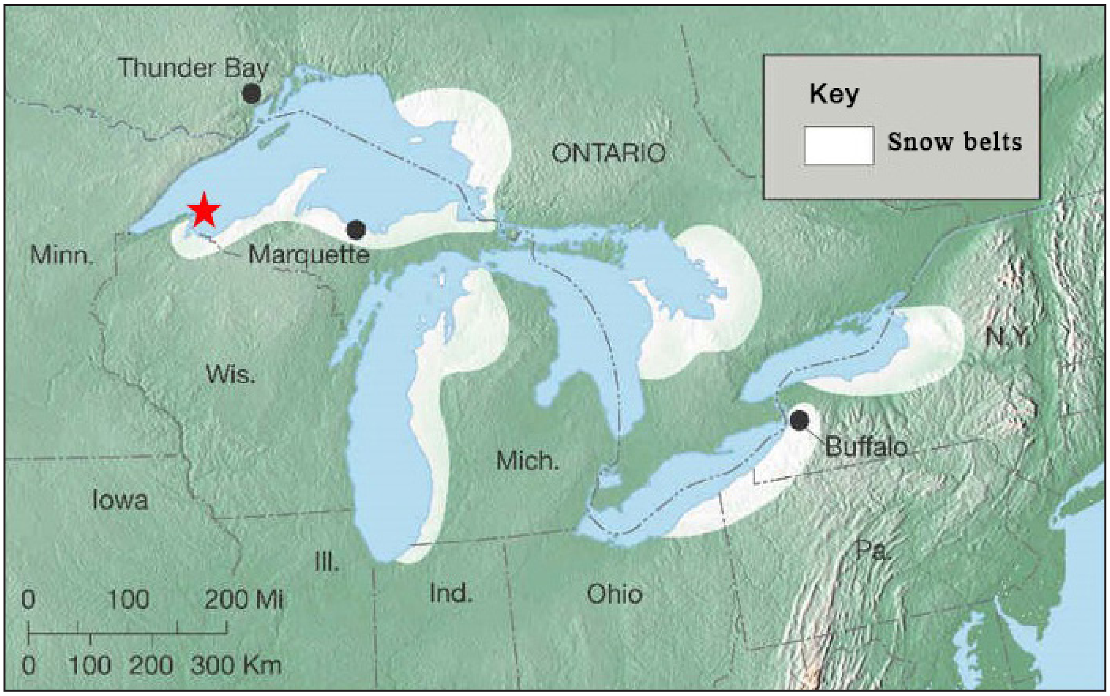


Figure 4. Approximate location of "snow belts" in the Great Lakes region that receive substantial lake-effect snow. The star indicates the location of Apostle Islands National Lakeshore. Modified from GLISA (2019b).

across the November to April snow season is expected to decline by 16 to 32 inches (Notaro et al. 2015b, Notaro et al. 2014). Most of the snowfall decline is projected to occur in December, so the snow season will begin later in the winter (Notaro et al. 2015b).

Lake-effect snowfall has been increasing in downwind zones around Lake Superior for the past several decades, as ice cover has declined but air temperatures have remained cold enough to generate snowfall. Future projections indicate that ice cover on Lake Superior will continue to decline, leaving more exposed lake surface, but cold air outbreaks will also become less common (Gao et al. 2015, Notaro et al. 2015b). Projections indicate that lake-effect snowfall could increase in February and March by mid-century around Lake Superior, but that lake effect snow is expected to decline in other months (Notaro et al. 2015b). By the end of the century, lake-effect snow is expected to become confined to January–March (Notaro et al. 2015b). Areas that traditionally experience lake-effect snow will be more likely to receive winter precipitation in the form of rain by the end of the 21st century.

Drought

There are many factors contributing to drought frequency, including meteorological "blocking" (i.e., how often an atmospheric pattern stays stagnant) and the ratio of evaporation to precipitation. Climate change projections for basic physical processes suggest that drought will become more likely for the Apostle Islands by the end of the century. For example, higher temperatures will likely lead to increased frequency and magnitude of drought, as projected increases in evaporation are larger than projected increases in precipitation (Collins et al. 2013). Annual evapotranspiration is projected to increase by the end of the century for the land around the Apostle Islands. The MACA dataset indicates that potential evapotranspiration (PET, the amount of evapotranspiration that would occur if sufficient water were available) may increase 6.1 inches across the year under RCP 4.5, and by 10.7 inches under RCP 8.5. The dynamically downscaled Notaro dataset indicates that evapotranspiration (ET, the actual amount of evapotranspiration that occurs based on water availability) may increase 1.4 inches across the year under RCP 8.5. Both datasets project that most of these increases will occur in the spring

and summer, with little to no change in the winter.

Furthermore, large-scale projections of near surface soil moisture indicate a 1% to 3% decrease in northern Wisconsin under RCP8.5 in spring, summer, and fall, with little to no soil moisture change in winter (USGCRP 2017). These general projections do not account for differences in soil types or layers of organic material.

Lake Temperature

As mentioned in Chapter 1, conditions in the Apostle Islands are strongly influenced by Lake Superior. From 1979 to 2006, July–September surface water temperature on Lake Superior increased roughly 4.5°F (Austin and Colman 2007). The long-term temperature increase from 1906 to 2005 was even greater, at 6.3 °F (Austin and Colman 2008). This means that Lake Superior is warming more rapidly than the regional air temperature (Austin and Colman 2007). Most of the observed warming has occurred in the eastern portion of Lake Superior, with slighter warming trends around the coastlines such as in the Apostle Islands region (Figure 5) (Mason et al. 2016). It appears that deeper areas of the lake are warming faster than shallow areas (Sugiyama et al. 2018). Cooler water upwelling in the southwestern portion of the lake near the Apostle Islands is caused by prevailing summertime winds from the southwest, which could be buffering the temperature increases of surface water (Mason et al. 2016).

There is also a positive feedback loop between lake ice and lake temperature, as reduced lake ice on Lake Superior has contributed to warmer summer water temperatures (see 'Lake Ice' section below). This is likely because the summer stratified season has started earlier as ice cover has declined, so the upper warm layer of water can absorb heat over a longer period of time. Additionally, the decline in lake ice allows the dark lake surface to absorb more energy, which further enhances warming (Sugiyama et al. 2018).

Projections of temperature and ice cover on Lake Superior are another instance where it is preferable to rely on dynamical downscaling methods as opposed to statistical downscaling methods. This is because there are numerous feedbacks

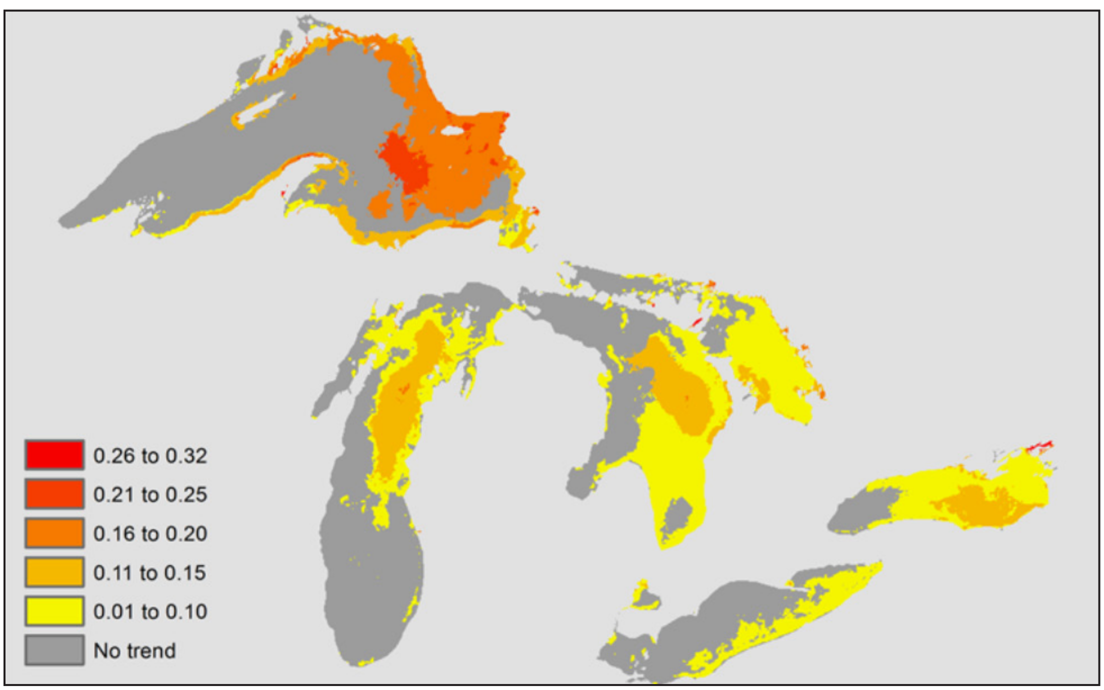


Figure 5. Summer surface water temperature trend across the Great Lakes in degrees-Celsius/year. Trend is calculated as the linear regression trend model from 1994 to 2013. Modified from Mason et al. (2016).

between water temperature, wind speed and direction, water depth, and ice formation. To incorporate these localized effects into future climate projections, Dr. Michael Notaro's research group integrates a separate model to simulate energy transfer throughout Lake Superior (Notaro et al. 2015b).

Under a high greenhouse gas (GHG) concentration scenario (RCP 8.5), Lake Superior summer lake temperature is projected to continue warming faster than the air temperature through the end of the century (Notaro et al. 2015b). Lake Superior surface water temperatures may rise 12°F–18°F in the spring and early summer. Winter surface water temperatures are projected to increase only slightly. The models used to simulate Lake Superior are biased towards an earlier spring stratification season, so although they suggest Lake Superior's surface water is projected to warm the most during spring, this is earlier than historical observations of rapid mid-to-late summer warming. So the seasonal timing of this warm-up may be later than what is suggested by the models, and the trend of summer warming may continue.

Lake Ice

Ice cover on Lake Superior has been shown to be very sensitive to winter air temperatures, so a change in winter temperature of a few degrees from one year to the next can make the difference between a moderate or high-ice year and a low-ice year (Titze 2016). Given the observed increase in winter air temperature over the past several decades, it is unsurprising that average Lake Superior ice cover has declined as well. Despite the long-term trend, winters with high ice cover have still occurred in recent years, as mentioned in Chapter 1.

Lake ice declines are not a simple linear response to increasing air temperatures. Recent research suggests that ice cover on the Great Lakes has undergone a sudden shift to less ice, as opposed to a slow gradual decline, with the shift coinciding with the strong El Niño Southern Oscillation (ENSO) event in 1998 (Mason et al. 2016). Prior to 1998, ice cover duration was just under 60 days/season, while after the shift, ice cover duration decreased to under 30 days/season. The rate of decline has been more rapid around the Apostle Islands (Mason et al. 2016). From 1857 to 2007, the duration of ice cover at Bayfield, Wisconsin, declined about 45 days, with an accelerated rate of decline in the most recent 40 years (Howk 2009). The change in ice onset date has been about the same as the change in ice-out date.

Similarly, a study that estimated ice cover around the Apostle Islands from 1979 to 2013 reported a decline in ice cover duration from 1 to 2.5 days per year throughout the archipelago (Anderson et al. 2015). The fastest declines in lake ice have occurred in the northeastern, outermost portions of the park (Figure 6).

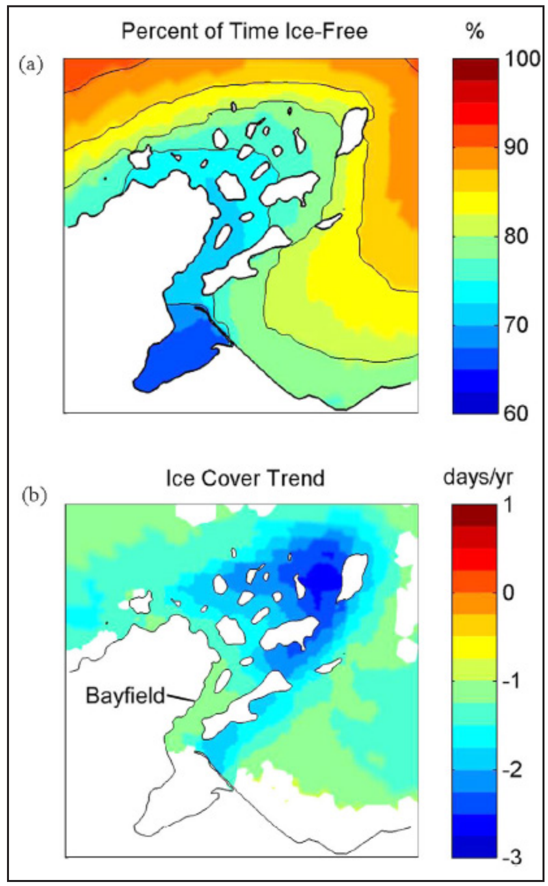


Figure 6. Panel A is the contour plot of the percent of time that locations were ice-free from 1979 to 2013. Panel B is the trend in ice cover duration over the same time period, where ice cover is defined as a mean ice concentration of greater than 30%. Only significant trends (95% confidence) are shaded. From Anderson et al. (2015).

Dynamical downscaled projections indicate that ice cover on Lake Superior is projected to continue to decline through the end of the century, with substantial reductions in February and March in particular (Notaro et al. 2015b). Ice cover around the Apostle Islands and Chequamegon Bay is projected to be on the order of 15%–45% in February and March by the end of the century, compared to greater than 60% in the baseline period at the end of the 20th century. Despite these long-term trends, it is likely there will continue to be occasional cold winters with extensive ice cover.

Lake Levels

Detailed lake level measurements are available for Lake Superior from about 1917 through the present day (Gronewold et al. 2013a). Over the past century, Lake Superior has fluctuated by about 4 feet from the highest to lowest recorded levels. As of July 2019, Lake Superior was about 10 inches below the historical high, and the lake has been at or above the long-term average level for about the past 6 years (Figure 7). Prior to this recent period of high water, Lake Superior experienced about 15 years of average or below average water levels. The changes from periods of high water to low water have been very abrupt in some cases, and very gradual in others. Lake levels also vary seasonally, with lows tending to occur in March and April and high levels tending to occur from August through October.

Researchers have been investigating climate change effects on Great Lakes water levels for over 30 years. The ability of monitoring networks and climate change models to capture the complexities involved with this question have improved over time, including estimates of basin runoff, over-lake precipitation, evaporation, lake ice coverage, and more (Box 3). Researchers continue to refine their approaches to projecting future lake levels, but the best current understanding is that both increases and decreases are possible for Lake Superior by the end of the century. A

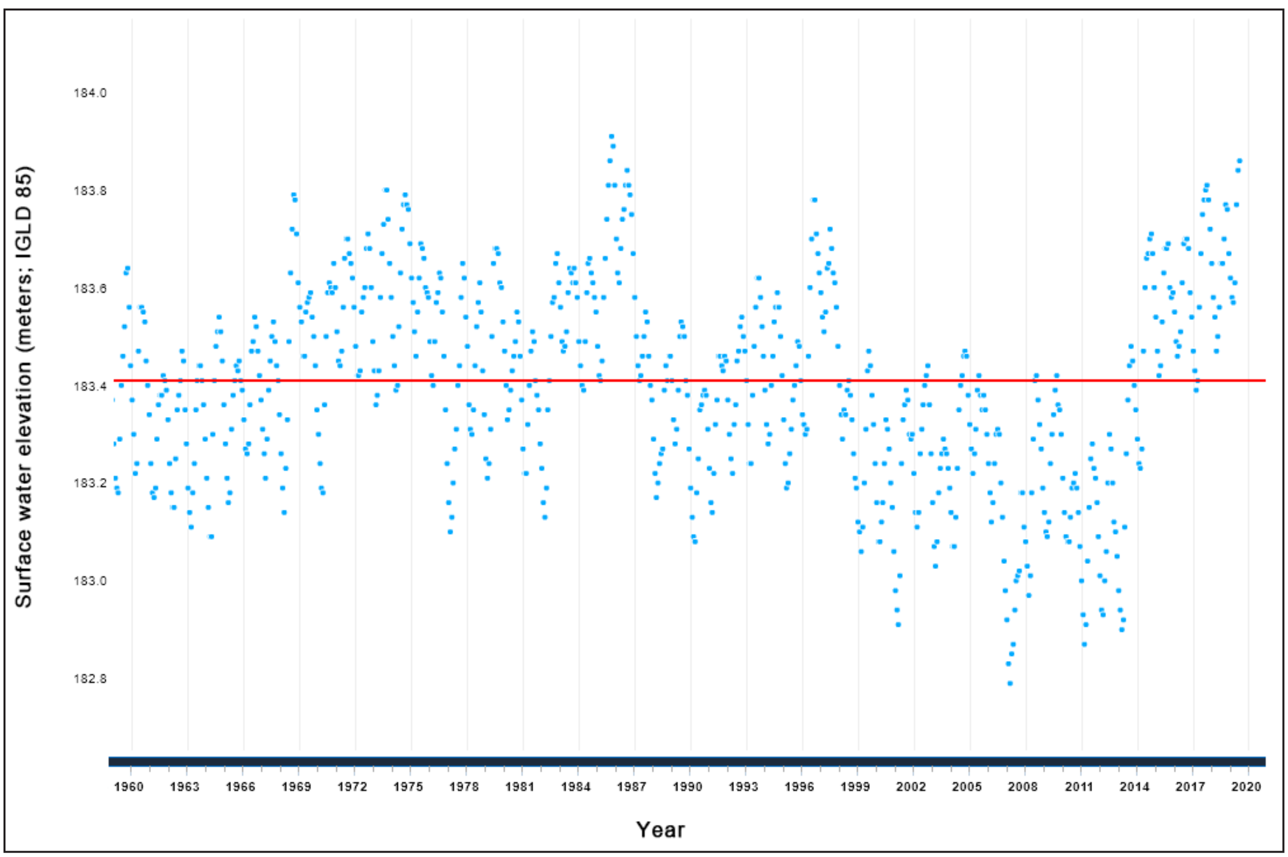


Figure 7. Monthly average water level for Lake Superior from 1960 to 2019. The red line indicates the long-term average water level from 1918 to present. From Gronewold et al. (2013a).

BOX 3: Lake Superior Rising (and Falling)

It's no surprise that there has been intense interest around the question of whether climate change will lead to higher or lower levels on the Great Lakes. Substantial lake level changes would require immense efforts to redesign and update infrastructure in coastal cities, roads, and shipping facilities. The impacts to terrestrial and aquatic ecosystems would also be dramatic. Early models that used relatively high levels of greenhouse gas emissions projected a decline of about half a meter for Lake Superior by 2060 (Hartmann 1990). Other projections show more modest lake level declines or no change by the end of the century across a range of climate scenarios (Hayhoe et al. 2010). More recent work suggested that these potential declines have been over-stated relative to long-term variability in Lake Superior levels, and also that potential evapotranspiration may have been overestimated (Gronewold et al. 2013b, Lofgren et al. 2011, Lofgren and Rouhana 2016). Complicated interactions associated with regional temperature and precipitation, Arctic snow and ice effects on Great Lakes weather patterns, and other factors means that we will likely have to accept and plan for a great deal of uncertainty with respect to water levels in Lake Superior (Gronewold and Rood 2019).

detailed comparison study between different methods of estimating future lake levels and different GCM/RCP combinations found that the interquartile range (25% quartile to 75% quartile) extends from +4 inches to −8 inches at the end of the century (Lofgren and Rouhana 2016). The extreme outcomes from different GCM/RCP model runs included projected increases or decreases of up to 20 inches by the end of the century. In a separate study, model projections relying only on RCP 8.5 show a range of projected lake levels from +5.3 inches to −3.8 inches by the end of the century (Notaro et al. 2015a). These models generally project that the seasonal lake level will peak in March–May, and that the lowest levels will occur in August–October. Regardless of long-term trends in average lake levels, Lake Superior will still vary on seasonal, annual, and multi-year scales, with high lake levels being followed by low levels in the next period and vice versa.

Wind Speed and Direction

Wind speed has been increasing in the summer months over Lake Superior, at a rate of 0.07 to 0.16 feet per second per year (Austin and Colman 2007, Bennington et al. 2010), or about 5% per decade (Desai et al. 2009). This trend is caused by water warming faster than the surrounding air, which reduces the temperature gradient at the boundary layer between water and air (Desai et al. 2009). Lake Superior is also experiencing a longer stratified season as it warms, so there is a longer period during the summer when warm water lies at the surface (Austin and Colman 2007).

From 1979 to 2013, annual mean wind direction shifted clockwise by about 1 degree per year (Anderson et al. 2015). This means that winds are generally shifting from northwest to north, which could lead to greater wave heights because northerly winds travel over a longer stretch of Lake Superior before reaching the Apostle Islands.

Detailed projections of future wind speed and direction over Lake Superior are not available.

Lake Currents

Currents in Lake Superior are complex and controlled by many factors, but especially wind. In the region of the Apostle Islands, currents primarily come from the northeast in the winter and from the west in the summer. Lake currents have generally increased as wind speeds have increased over the past several decades, and they are expected to continue to increase under future climate scenarios (Bennington et al. 2010).

Wave Action

Significant wave height has been increasing in the Apostle Islands area, at a rate of 0.5 to 2.0% per year (Anderson et al. 2015). Mean wave height increased between 0.10 and 0.20 inches/yr for the Apostle Islands between 1979 and 2013 (Figure 8). The largest waves increased about four times as rapidly as mean waves, with 99% quantile waves increasing by 0.4 to 1.6 inches/year over the same time period. Wave height is increasing more rapidly within the interior of the archipelago than the exterior islands. (Anderson et al. 2015). Reduced ice cover over the past several decades has exposed more surface water during the winter, which is the season with highest winds and largest wave heights. Increasing wave heights can increase bluff erosion, so that even during periods of low lake levels erosion remains steady (Anderson et al. 2015).

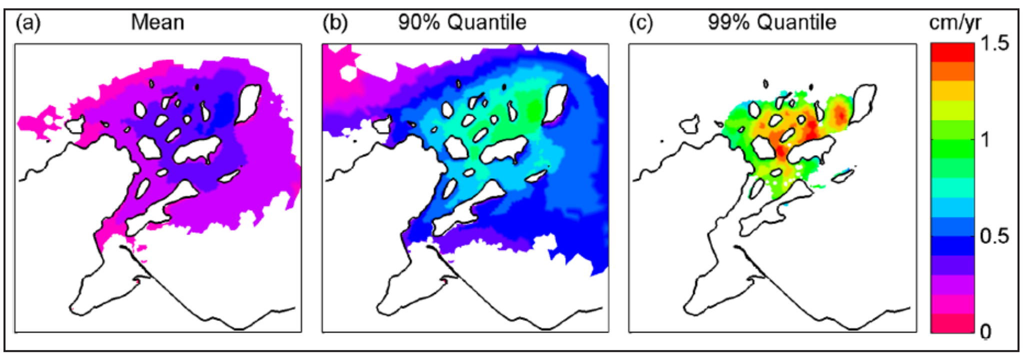


Figure 8. Trends in significant wave heights (SWH) from 1979 to 2013 in the Apostle Islands. Trends are displayed for different size categories of SWH: mean (panel A), 0.90 quantile (panel B), and 0.99 quantile (panel C). Only significant trends (95% confidence) are shaded. From Anderson et al. (2015)

Meteorological conditions such as atmospheric pressure, strong storms, and straight-line winds can cause large waves called "meteotsunamis," which are similar to seismic tsunamis. In Lake Superior, these kinds of waves happen most commonly in June, but they may become more common earlier in the spring as climate change continues (Bechle et al. 2016).

Strong Storms

General circulation models do not operate at a scale small enough to model thunderstorms, so studies of strong storms and other convective processes require downscaling methods that are still being developed. This is an evolving field of study, but numerous studies point to an increase in the frequency of severe thunderstorm environments in the U.S. during the mid- to late 21st century, based on an analysis of changes in atmospheric stability that lead to vertical cloud development and storm organization (Seeley and Romps 2015). This finding is particularly robust in the Midwest during March, April, and May (Diffenbaugh et al. 2013, Gensini et al. 2014). Evidence also suggests that temperature increases may lead to conditions more favorable to convective storms such as thunderstorms due to increased atmospheric water vapor in the lower portions of the atmosphere (Kunkel et al. 2008, Trapp et al. 2007). However, short-term weather uncertainty remains with these kinds of projections because an environment that is more conducive to severe thunderstorms does not necessarily mean a thunderstorm will develop. Overall, it is expected that hazardous weather conditions (tornadoes, large hail, and damaging wind) will increase in frequency in the Midwest by the end of the century (Hoogewind et al. 2017).

Cloud Cover

Lake Superior is not a very sunny place during winter, with cloud cover averaging more than 70% for November through March (Ackerman et al. 2013). An analysis of daily satellite imagery from 1982 to 2012 revealed a significant trend of decreasing cloudiness across the surface of Lake Superior of 2% per decade (Ackerman et

al. 2013). Cloud cover has decreased across the entire year, but summer and fall have experienced the largest decreases compared to other seasons.

Conclusion

This chapter has summarized the available information on observed and projected trends in a wide range of topics related to the climate of the Apostle Islands. As indicated above, many of these factors interact with each other and they operate in concert rather than as independently changing variables. Authors of this assessment considered a range of plausible climate conditions at the end of the century in order to bracket the potential outcomes. The next chapter describes how the authors attempted to integrate this information and assess how these trends might affect important ecosystem processes, species, and stressors in the Apostle Islands.

Sand deposition on Rocky Island after a strong storm in 2017.
NPS PHOTO/P. BURKMAN

Chapter 3: Potential Climate Change Impacts on Apostle Islands Ecosystems

This chapter explains how the ongoing and expected climate changes described in the previous chapter will affect characteristic species, ecosystem drivers, and ecosystem stressors that are most important for ecosystems in the Apostle Islands. Information on climate change effects on the region's tree species is summarized from a climate impact model, and information on most other topics is derived from a synthesis of existing literature. For each topic, we also disclose significant uncertainties or information gaps.

Tree Species Projections

One tool used to estimate changes in suitable habitat for tree species is the Climate Change Tree Atlas (hereafter Tree Atlas) (Prasad et al. 2014). This tool does not attempt to forecast the future growth and migration of trees across the landscape, but rather it provides an indication of where the best growing conditions (suitable habitat) for a particular species will be in the future. Therefore, a projected decrease in suitable habitat over time suggests that trees that persist in a given area may be exposed to additional stress and decline. Conversely, a projected increase in suitable habitat indicates that a species may have more favorable growing conditions in an area over time, not necessarily that the species will be able to migrate to the area without intervention.

The Tree Atlas uses climate scenarios and a statistical analysis of current tree distribution information to project future habitat suitability for individual species. Current distribution information is derived from national USDA Forest Service Forest Inventory and Analysis data (www.fia.fs.fed.us/), and several variables related to soils, topography, climate, and land use are used to develop statistical models that describe suitable habitat (See Appendix 4 for more information). Future habitat suitability is projected for two future greenhouse gas concentration pathways that bracket a wide range of possible futures for the year 2100. The "low" scenario is based on RCP4.5 and the "high" scenario is based on RCP 8.5 (see Chapter 2 for a discussion of RCPs). Results presented here are averages from three general circulation models (CCSM4, HadGEM2, and GFDL CM3) (Moss et al. 2008, Jones et al. 2011, Donner et al. 2011). Tree Atlas model results can be summarized over a large landscape, such as northern Wisconsin (Janowiak et al. 2014), or in smaller areas for a more localized estimate of potential change. For this vulnerability assessment, Tree Atlas results were calculated for the area bounded by 46° to 47° north latitude and 90° to 91° west longitude (Figure 9). The Tree Atlas model evaluates changes in suitable habitat for over 130 eastern tree species, including many that do not currently occur within the Apostle Islands National Lakeshore or the neighboring mainland.

Figure 9. Tree Atlas analysis area for tree species suitable habitat projections (*red line*). The area bounded by 46° to 47° north latitude and 90° to 91° west longitude was selected for this assessment because this area encompasses the Apostle Islands National Lakeshore and the neighboring mainland.

Two kinds of information are produced by the Tree Atlas model (Table 4). The first is based on importance value. Importance value is an index of the relative abundance of a species in a given community, and can

range from 0 (not present) to 100 (only species present in the area) in a single 12.4-mile grid cell (Iverson et al. 2008). Each species is assigned a "Change Class" according to the ratio of projected future importance value compared to current modeled importance value. Change Class is calculated for both the low and high climate change scenarios. The Change Class results indicate whether a species is projected to gain or lose suitable habitat across the range of climate scenarios by the end of the century. Second, the Tree Atlas provides an "Adaptability" score based on a literature review of the species' life-history traits, known stressors, and other environmental factors that might make a species more or less likely to persist on the landscape (Matthews et al. 2011). Factors such as drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases can help determine whether a given species is likely to perform better or worse than the projections of suitable habitat change. See Appendix 4 for a more complete description of the Tree Atlas modelling process and complete results.

Species Projected to Gain Suitable Habitat

Suitable habitat is projected to increase under both scenarios by the end of the century for a handful of species. Of these, northern red oak is already present throughout the Apostle Islands and is also among the more adaptable species according to its life-history traits (including drought and fire tolerance). Eastern white pine and bigtooth aspen (azaadi, *Populus grandidentata*) are both able to regenerate in open areas following disturbance and could naturally increase within the park. White pine in particular has been observed in post-fire regeneration in the Apostle Islands (Martin and Johnson, in preparation). Other species that are projected to experience increases in suitable habitat under future climatic conditions include black cherry (ookwemin), white ash (aagimaak, *Fraxinus americana*), American elm, green ash (*Fraxinus pennsylvanica*), northern pin oak, bur oak (mitigomizh, *Quercus macrocarpa*), silver maple (*Acer saccharinum*), and ironwood (maananoons, *Ostrya virginiana*). Dutch elm disease and emerald ash borer may prevent elm and ash species from fully taking advantage of projected suitable habitat increases.

Species Projected to Lose Suitable Habitat

By the end of the century, eight species are projected to undergo declines in suitable habitat across both low and high climate scenarios. Mountain maple, serviceberry, and pin cherry (bawa'iminaan, *Prunus pensylvanica*) are projected to lose nearly all suitable habitat within the analysis area, while sugar maple, quaking aspen, balsam fir, northern white-cedar, black spruce, black ash, and yellow birch are projected to experience lesser declines under at least one scenario. Of these potential declining species, sugar maple has one of the higher adaptability scores because of its life-history traits (including shade tolerance and vigorous seedling establishment). Suitable habitat of northern or boreal-associated species such as quaking aspen, northern white-cedar, black spruce, yellow birch, and mountain maple is also projected to decline across the larger region under a range of climate scenarios (Janowiak et al. 2014).

Species with No Change in Suitable Habitat

Several species are projected to have relatively stable suitable habitat across the analysis area by the end of the century. Red maple, tamarack, paper birch, eastern hemlock, jack pine, and white spruce are all expected to undergo less than a 20% change in suitable habitat under both climate scenarios. Red maple and jack pine have high adaptability scores. These species are tolerant of many disturbances and may perform better than expected in locations where they already exist. Several of these species are projected to decline across the larger region of northern Wisconsin and western Upper Michigan (Janowiak et al. 2014), suggesting that the smaller region surrounding the Apostle Islands and the Lake Superior coast may retain more suitable habitat through the end of the century for

Table 4. The Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area according to recent forest inventory data. **Change Class RCP4.5/8.5** = class of change in suitable habitat by 2100. Classes are based on ratios of future to current importance value for common species. ***No Change*** = ratio 0.8-1.2; ***Small increase*** = ratio 1.2-2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5-0.8; ***Large decrease*** = ratio <0.5; ***Very Large Decrease*** = 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adaptability rankings** (***Low***, ***Moderate***, ***High***) for the species are according to a literature review of 12 disturbance and nine biological characteristics and indicate whether a species has traits that might cause it to perform better or worse than the model indicates. See Appendix 4 for more detail, including modified change class ratios for rare species. Asterisk (*) indicates the Ojibwe name of the species was unknown by the authors at the time of publication. Hash mark (#) indicates a species has been documented in the local area, but is not currently recorded in FIA surveys.

Common Name	Ojibwe Name (Anishinaabemowin)	Scientific Name	Change Class – RCP4.5	Change Class – RCP8.5	Adaptability
sugar maple	ziinzibaakwadwaatig	*Acer saccharum*	Small decrease	Small decrease	High
quaking aspen	azaadi	*Populus tremuloides*	Small decrease	Small decrease	Medium
red maple	zhiishiigimiiwanzh	*Acer rubrum*	No change	No change	High
balsam fir	zhingob	*Abies balsamea*	Large decrease	Small decrease	Low
northern white-cedar	giizhikaatig	*Thuja occidentalis*	No change	No change	Medium
black ash	baapaagimaak	*Fraxinus nigra*	No change	Small decrease	Low
paper birch	wiigwaasaatig	*Betula papyrifera*	No change	No change	Medium
yellow birch	wiinisik	*Betula alleghaniensis*	Small decrease	Small decrease	Medium
American basswood	wiigobaatig	*Tilia americana*	Small increase	No change	Medium
tamarack	mashkiigwaatig	*Larix laricina*	No change	No change	Low
black spruce	zesegaandag	*Picea mariana*	Small decrease	Small decrease	Medium
eastern hemlock	gagaagi wanzh	*Tsuga canadensis*	No change	No change	Low
red pine	bapakwanagemag	*Pinus resinosa*	Small increase	Small increase	Low
eastern white pine	biisaandago-zhingwaak	*Pinus strobus*	Large increase	Large increase	Low
white spruce	gaawaandag	*Picea glauca*	No change	No change	Medium
northern red oak	wiisagi-mitigomizh	*Quercus rubra*	Large increase	Large increase	High
bigtooth aspen	azaadi	*Populus grandidentata*	Small increase	Small increase	Medium
black cherry	ookwemin	*Prunus serotina*	Large increase	Large increase	Low
ironwood	maananoons	*Ostrya virginiana*	Small increase	Small increase	High
American elm	aniib	*Ulmus americana*	Large increase	Large increase	Medium
white ash	aagimaak	*Fraxinus americana*	Large increase	Large increase	Low
green ash	*	*Fraxinus pennsylvanica*	Large increase	Large increase	Medium
serviceberry	gozigwaakomin	*Amelanchier* sp.	Large decrease	Very Large decrease	Medium
American hornbeam	maananoons	*Carpinus caroliniana*	No change	No change	Medium

Table 4 (continued). The Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area according to recent forest inventory data. **Change Class RCP4.5/8.5** = class of change in suitable habitat by 2100. Classes are based on ratios of future to current importance value for common species. ***No Change*** = ratio 0.8-1.2; ***Small increase*** = ratio 1.2-2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5-0.8; ***Large decrease*** = ratio <0.5; ***Very Large Decrease*** = 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adaptability rankings** (***Low***, ***Moderate***, ***High***) for the species are according to a literature review of 12 disturbance and nine biological characteristics and indicate whether a species has traits that might cause it to perform better or worse than the model indicates. See Appendix 4 for more detail, including modified change class ratios for rare species. Asterisk (*) indicates the Ojibwe name of the species was unknown by the authors at the time of publication. Hash mark (#) indicates a species has been documented in the local area, but is not currently recorded in FIA surveys.

Common Name	Ojibwe Name (Anishinaabemowin)	Scientific Name	Change Class – RCP4.5	Change Class – RCP8.5	Adaptability
jack pine	akikaandag	***Pinus banksiana***	No change	No change	High
chokecherry	asasaweminagaawanzh	***Prunus virginiana***	Unknown	Unknown	Medium
northern pin oak	mitigomizh	***Quercus ellipsoidalis***	Large increase	Large increase	High
Norway spruce	*	***Picea abies***	Unknown	Unknown	NA
pin cherry	bawa'iminaan	***Prunus pensylvanica***	Large decrease	Very Large decrease	Medium
mountain maple	*	***Acer spicatum***	Large decrease	Large decrease	High
black willow	zasgogmizh	***Salix nigra***	No change	Small increase	Low
bur oak	mitigomizh	***Quercus macrocarpa***	Large increase	Large increase	High
peachleaf willow	*	***Salix amygdaloides***	Unknown	Unknown	Medium
Scotch pine	*	***Pinus sylvestris***	Unknown	Unknown	NA
silver maple #	*	***Acer saccharinum***	Large increase	Large increase	High
eastern redcedar	miskwaawaak	***Juniperus virginiana***	New Habitat	New Habitat	Medium
red spruce	*	***Picea rubens***	New Habitat	New Habitat	Low
boxelder	ajigobi'mak	***Acer negundo***	New Habitat	New Habitat	High
pawpaw	*	***Asimina triloba***	Unknown	Unknown	Medium
sweet birch	*	***Betula lenta***	New Habitat	New Habitat	Low
bitternut hickory	mitigwaabaak	***Carya cordiformis***	New Habitat	New Habitat	High
pignut hickory	*	***Carya glabra***	New Habitat	New Habitat	Medium
shagbark hickory	mitigwaabaak	***Carya ovata***	New Habitat	New Habitat	Medium
sugarberry	*	***Celtis laevigata***	Unknown	New Habitat	Medium
hackberry	*	***Celtis occidentalis***	New Habitat	New Habitat	High
American beech	gawe'mik	***Fagus grandifolia***	New Habitat	New Habitat	Medium
black walnut	*	***Juglans nigra***	New Habitat	New Habitat	Medium
yellow-poplar	*	***Liriodendron tulipifera***	New Habitat	New Habitat	High

Table 4 (continued). The Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area according to recent forest inventory data. **Change Class RCP4.5/8.5** = class of change in suitable habitat by 2100. Classes are based on ratios of future to current importance value for common species. ***No Change*** = ratio 0.8-1.2; ***Small increase*** = ratio 1.2-2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5-0.8; ***Large decrease*** = ratio <0.5; ***Very Large Decrease*** = 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adaptability rankings** (***Low***, ***Moderate***, ***High***) for the species are according to a literature review of 12 disturbance and nine biological characteristics and indicate whether a species has traits that might cause it to perform better or worse than the model indicates. See Appendix 4 for more detail, including modified change class ratios for rare species. Asterisk (*) indicates the Ojibwe name of the species was unknown by the authors at the time of publication. Hash mark (#) indicates a species has been documented in the local area, but is not currently recorded in FIA surveys.

Common Name	Ojibwe Name (Anishinaabemowin)	Scientific Name	Change Class – RCP4.5	Change Class – RCP8.5	Adaptability
blackgum	*	*Nyssa sylvatica*	New Habitat	New Habitat	High
sycamore	*	*Platanus occidentalis*	New Habitat	New Habitat	Medium
balsam poplar	maanazaadi	*Populus balsamifera*	Unknown	Unknown	Medium
eastern cottonwood	*	*Populus deltoides*	New Habitat	New Habitat	Medium
white oak	wiishkobi-mitigomizh	*Quercus alba*	New Habitat	New Habitat	High
swamp white oak	*	*Quercus bicolor*	New Habitat	New Habitat	Medium
scarlet oak	*	*Quercus coccinea*	New Habitat	New Habitat	Medium
pin oak	*	*Quercus palustris*	New Habitat	New Habitat	Low
chestnut oak	*	*Quercus prinus*	New Habitat	New Habitat	High
black oak	mitigomizh	*Quercus velutina*	New Habitat	New Habitat	Medium
black locust #	*	*Robinia psuedoacacia*	New Habitat	New Habitat	Medium
sassafras	*	*Sassafras albidum*	New Habitat	New Habitat	Medium

species such as tamarack, paper birch, red maple, and jack pine.

Species with New Suitable Habitat

The Tree Atlas model projects that 23 tree species will have newly available suitable habitat in the 1° × 1° area encompassing the Apostle Islands by the end of the 21st century. This projection does not necessarily mean that a given species will be able to migrate to available habitat and colonize successfully, but rather that conditions may be suitable for a species to occupy the site if it does arrive. Many species that are not currently present in the analysis area would require long-distance movement in order to establish and occupy suitable habitat. Species most likely for natural migration, or perhaps most eligible for assisted migration, based on distance from current locations and historic distances of colonization, include boxelder, bitternut hickory, shagbark hickory, American beech, white oak, swamp white oak, and black oak. Several of these potential new migrants have large seeds (hickories, oaks, and black walnut) that are relatively unlikely to reach the Apostle Islands without human assistance. Some species in this list have seeds that are transported by wind or birds, such as eastern cottonwood (*Populus deltoides*), and may be more likely to reach the Apostle Islands without human intervention. Additionally, some species listed as new migrants according to Tree Atlas have already been documented within and/or near the Apostle Islands (black locust, slippery elm), even though they have not been recorded in FIA surveys. Most of these potential new migrant species have moderate to high adaptability scores.

Key Uncertainties

It is perhaps best to think of Tree Atlas projections as indicators of possibility and potential change. The Tree Atlas provides broad projections that can be informed with experience and information about local site conditions. Although the Tree Atlas Adaptability scores attempt to account for some factors that can be modified by climate change, such as droughts, wildfire activity, invasive species, future phenological mismatches, extreme weather events, deer herbivory, or new insect pests and diseases, these are not specifically modeled at the local scale (Janowiak et al. 2014). In addition, if a species is rare or confined to a small area (e.g., mountain maple), Tree Atlas results may have lower reliability. Human choices will also continue to influence forest distribution, especially for tree species that are projected to gain new suitable habitat. Planting programs may assist migration of future-adapted species, particularly in areas of actively managed forest and after stand disturbances, but this will depend on management decisions.

Although these Tree Atlas results are provided for a relatively small area that includes the Bayfield Peninsula, the Apostle Islands, and the adjacent mainland, there is still a large amount of spatial heterogeneity within the analysis area. Within the 1° × 1° boundary, there are areas as diverse as the clay plain of the Bad River watershed, the sandy interior of the Bayfield Peninsula, shorelines along Lake Superior, and the diverse habitats among the Apostle Islands. These different environments will undoubtedly lead to localized changes in suitable habitat for an individual tree species. For example, if the Tree Atlas projects that suitable habitat for a tree species will decline by 40% by the end of the century, it is more likely that the suitable habitat will “retreat” to areas that remain favorable on the landscape. So core areas of suitable habitat may remain suitable into the future, while areas of marginal habitat may be first to experience declines.

It is also uncertain how the local effects of Lake Superior might influence future tree habitat suitability in the Apostle Islands. The Apostle Islands have more of a maritime climate and a shorter, cooler growing season than inland areas in Wisconsin (see Chapters 1 and 2). Although this effect may be lessening as Lake Superior continues to warm, it is reasonable to expect that northern and boreal species that are projected to decline will continue to be buffered from change by the moderating effects of the lake for the near term. Additionally, Lake Superior will provide a

natural barrier to migration for some of the tree species expected to increase or migrate to northern Wisconsin. Conversely, it is possible that the moderating effects of Lake Superior could also help support some more temperate tree species, particularly as the lake continues to warm in the decades ahead. Temperate species that might be limited by the more continental climate in inland Wisconsin may be sheltered somewhat by the maritime climate of the Apostle Islands, if they are somehow able to colonize the area. The Tree Atlas model does not directly account for these lake effects, particularly the changing dynamics of Lake Superior under the range of future climate scenarios.

Climate Change Information for Herbaceous Species

Species distribution models that account for projected climate change do not exist for many herbaceous species. This is an area of active research, though, and recent attempts to project range shifts for herbaceous species in Wisconsin have yielded some interesting results. One recent study relies on herbarium records to construct current species distribution for over 1,800 vascular plants in Wisconsin (Spalink et al. 2018). This study identified the Apostle Islands as a distinct bioregion in the state due to several species that occur in the park and nowhere else in the state. By the year 2070, however, the Apostle Islands are projected to be floristically similar to the neighboring Lake Superior Shoreline bioregion (Figure 10). The park may gain suitable climate habitats for as many as 400 new species, but may only retain 50%–75% of the current phylogenetic diversity (Spalink et al. 2018). This analysis does not account for microhabitats and potential refugia in the Apostle Islands, but it does outline broad trends and expectations.

In many cases, it is possible to assume whether a species has temperature or precipitation thresholds based on species range maps that align with known climatic gradients. For example, arctic disjunct species that occur in the Apostle Islands such as butterwort, reach the southern edge of their range in Wisconsin, and sometimes the Apostle Islands are the only known

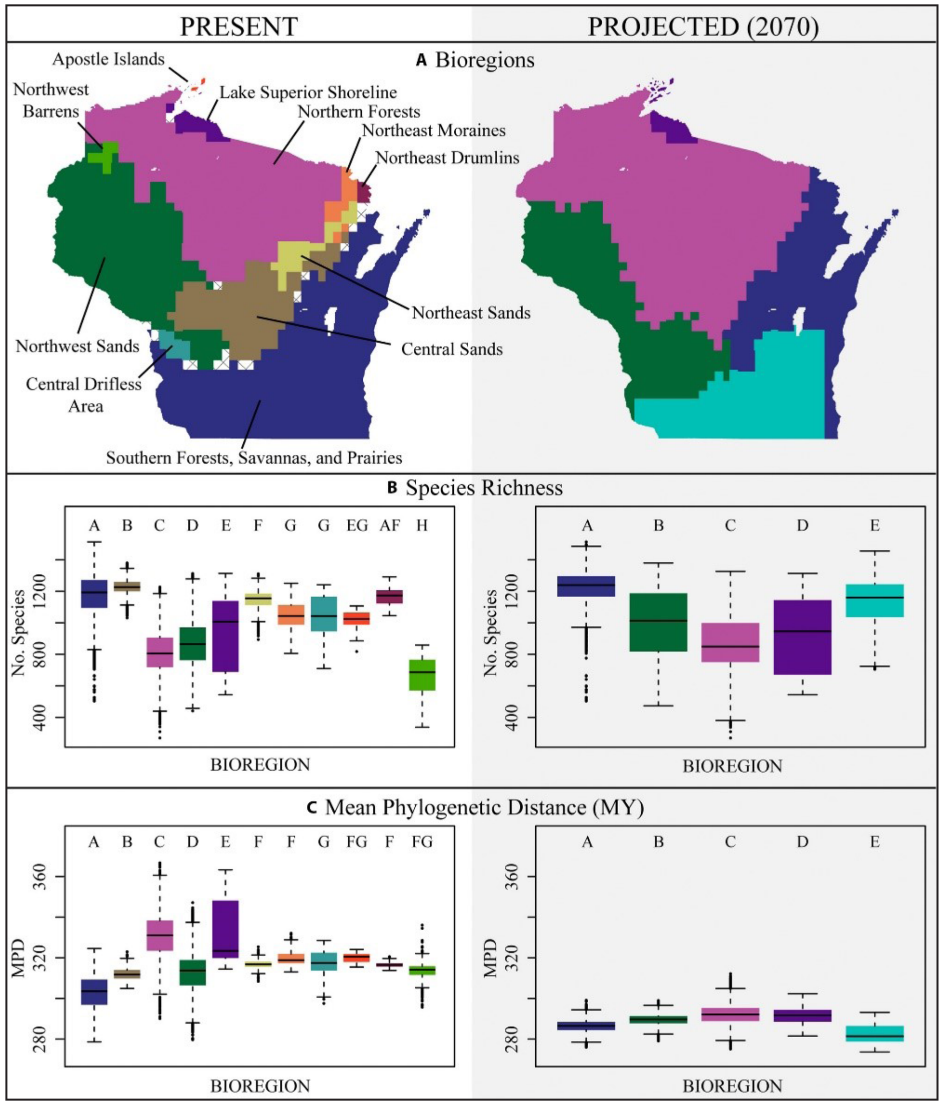


Figure 10. Present and projected bioregions as constructed based on congruent distributions of species, from Spalink et al. (2018). Panel A: Current bioregions. White areas with hash marks represent areas that are floristically distinct, but here treated as noise due to their occurrence along the margins of larger bioregions and small spatial extents. Panel B: Box plot depicting the distribution of species richness among the assemblages that comprise each of the bioregions, with box plot colors corresponding to the map. Panel C: Box plot depicting the distribution of mean phylogenetic distance (millions of years) among species within each of the cell-level assemblages comprising the bioregions. Letters above box plots represent the significant differences among the bioregion based on ANOVA and Tukey–Kramer tests.

location in the state (Figure 11). In situations like these, it is reasonable to expect that a climatic threshold is limiting and that future warmer conditions may be beyond the physiological tolerance of the species.

In many other cases, however, range maps for a particular species do not give an indication of a clear climatic threshold. In these cases, we attempt to use our best understanding to assess whether climate change may influence an ecological driver such as wildfire, moisture availability, or water chemistry that might influence habitat suitability for a species or a class of species. Soil and moisture requirements may also be a surrogate to estimate the potential impacts of climate change on a species. Species with a wide geographic range and broad tolerance of soil and moisture conditions are generally anticipated to be less vulnerable to changing environmental conditions than species with more precise requirements (Thuiller et al. 2005).

Climate Change Effects on Ecosystem Drivers and Stressors

In the sections that follow, we discuss several of the climate change vulnerabilities that may affect the terrestrial ecosystems in the Apostle Islands. Many of these potential impacts involve interactions among two or more climate changes discussed in Chapter 2, and are therefore more uncertain.

Soil Moisture and Drought Stress

Soil moisture is governed by the balance between evapotranspiration (the combined amount of water lost through evaporation from soils and transpiration from plants) and precipitation. This relationship is dependent on local site characteristics such as the water-holding capacity of soils (Crausbay et al. 2017). The Apostle Islands are projected to experience warmer annual and seasonal temperatures, which generally increases evapotranspiration because warmer air can hold more water. Additionally, as the

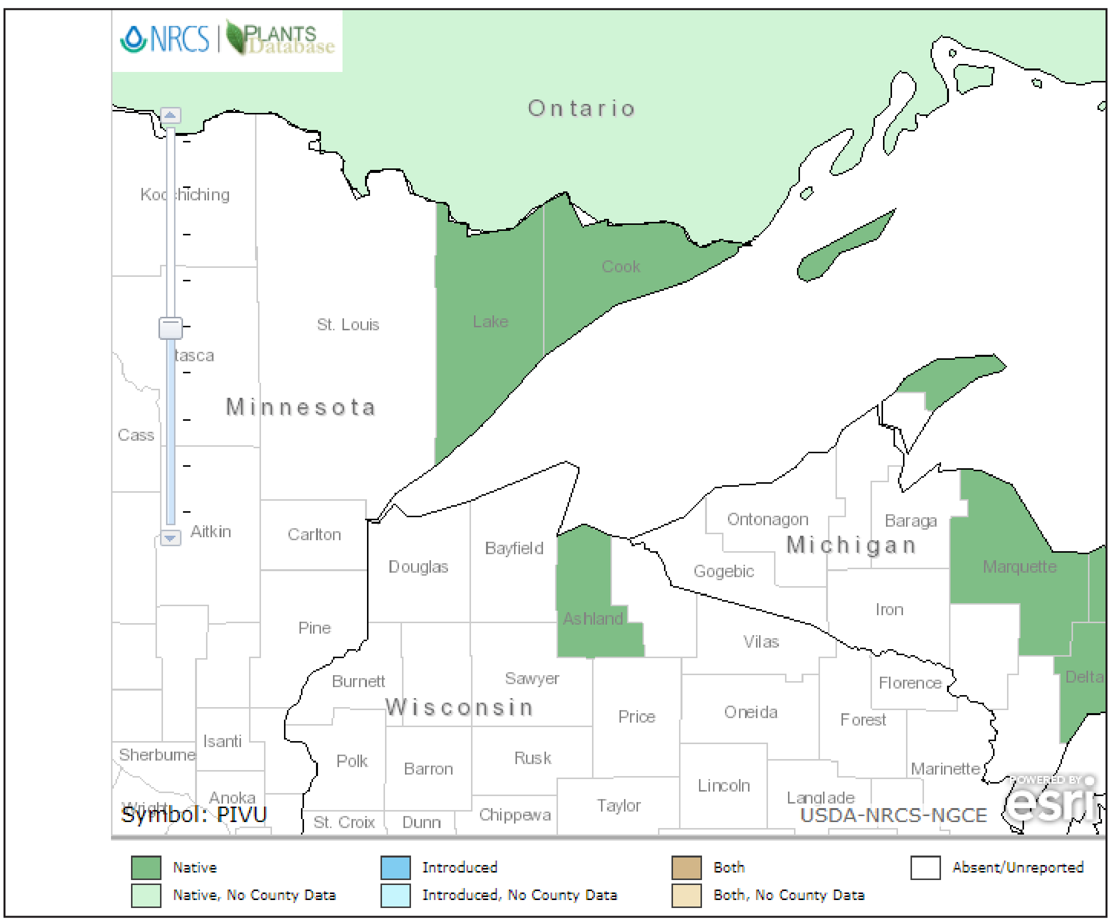


Figure 11. Range map of common butterwort (*Pinguicula vulgaris*) from the USDA Plants Database (USDA NRCS 2019). The species' occurrence in the Apostle Islands is indicated only by green shading in Ashland County.

growing season continues to lengthen, vegetation will be drawing water from the soil for longer periods of time each year, further adding to evapotranspiration. Annual precipitation is also projected to increase in the region, but seasonal projections are mixed for the summer.

The *Forest Ecosystem Vulnerability Assessment for Northern Wisconsin and Western Upper Michigan* includes a thorough discussion of the potential effects of climate change on soil moisture (Janowiak et al. 2014). Model projections of the evapotranspiration to precipitation ratio across northern Wisconsin indicated that summer conditions may get slightly drier or dramatically drier by the end of the century, even though annual values are not expected to change. The assessment found evidence for an increased risk of drought stress across the region due to climate change, although site-specific factors such as soils, topographic position, and forest density will influence local risk.

The Midwest Chapter of the 2018 National Climate Assessment also describes the effects of increasing vapor pressure deficit (VPD) (Angel et al. 2018). VPD is the difference between how much moisture is in the air and the amount of moisture in the air at saturation (100% relative humidity), essentially providing an index of atmospheric demand on plants. As air temperature increases, VPD is projected to increase (Figure 12). Increasing VPD will likely increase stress on forests across the region, although the effects may be most observable in dense stands of trees and in transition areas between forests and non-forested ecosystems (Angel et al. 2018, Gleason et al. 2017).

Given this overall expectation of increasing drought stress, the variety of soils and landforms in the Apostle Islands present different levels of risk. Areas of coarse-textured soils, such as sandscapes, pine forests, and upland areas of larger islands may be most likely to experience drier conditions. Poorly drained, flat, clay soils with intact litter and duff layers may be more buffered from drying conditions, as might north-facing ravines or ravines with persistent groundwater seepage.

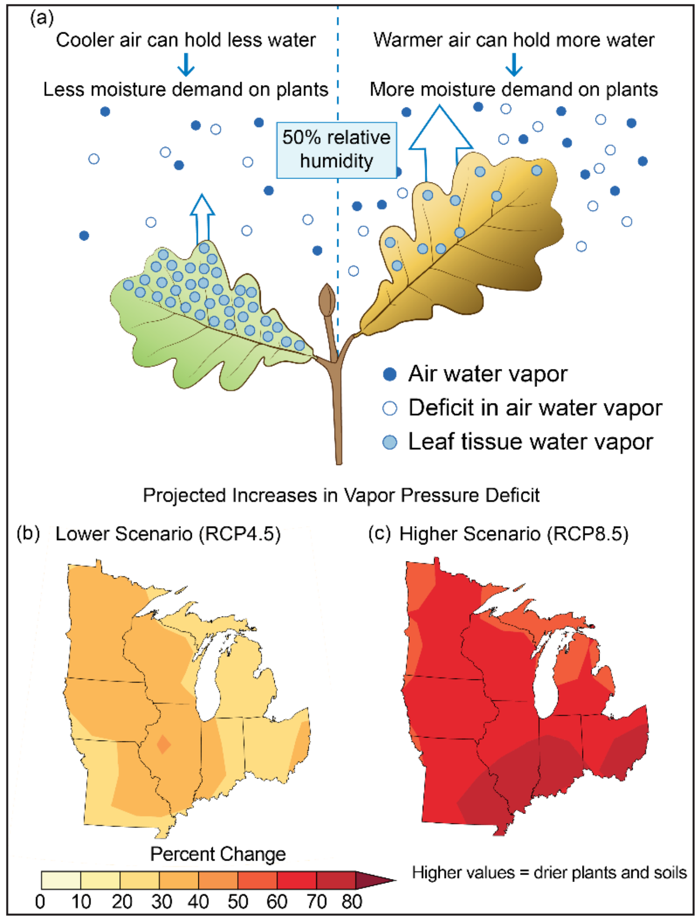


Figure 12. Interactions between air temperature and vapor pressure deficit (VPD), from the 2018 National Climate Assessment (Angel et al. 2018). VPD is the difference between how much moisture is in the air and the amount of moisture that can be held in the air at saturation (at 100% relative humidity). Increased VPD has a drying effect on plants and soils, as moisture transpires (from plants) and evaporates (from soil) into the air. **(a)** Cooler air can maintain less water as vapor, putting less demand for moisture on plants, while warmer air can maintain more water as vapor, putting more demand for moisture on plants. The maps (**b**, **c**) show the percent change in the moisture deficit of the air based on the projected maximum 5-day VPD by the late 21st century (2070–2099) for **(b)** lower (RCP4.5) and **(c)** higher (RCP8.5) GHG concentration pathways.

Key Uncertainties

Plant communities that occur along the rocky cliffs or clay bluffs of the Apostle Islands may depend on wave spray and fog for a substantial portion of their moisture requirements. Foggy conditions can also help to maintain the cool microclimate near Lake Superior shorelines. It is unclear how changing conditions of Lake Superior

Flood scouring in a mainland ravine after a heavy rain.
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may interact with potential changes in temperature, VPD, and wind conditions to affect the frequency and duration of fog.

Flooding

The Midwest is projected to continue experiencing more extreme precipitation events under climate change (Chapter 2). Additionally, winter rain events and rain-on-snow events are likely to occur more frequently in the Great Lakes region, particularly in areas that traditionally experience lake-effect snow (Chapter 2). Other research has projected that total winter runoff values may more than double across much of northern Wisconsin by the end of the 21st century (Cherkauer and Sinha 2010). Earlier peak flows caused by more rapid snowmelt may increase flood frequency earlier in the year, and high-intensity rain events may cause more frequent flooding in the warmer months. Soil moisture conditions, upstream landuse, and local topography strongly influence the magnitude of flooding after a heavy rain event, and certain locations in the Apostle Islands may be more vulnerable to flooding than others. Steep ravines in the park may be most susceptible to erosion and deposition from flooding. The mainland unit of the park includes several large ravines that are connected to larger upstream watersheds, which contain a mix of forestland (including recently harvested areas), agricultural land, and development. These basins are at a greater risk of flood damage than the islands within the park, which generally contain smaller watersheds and are mostly intact, undisturbed landscapes.

Key Uncertainties

Recent extreme rainfall events in 2016 and 2018 have highlighted the effects of these events for many people in northern Wisconsin. Unfortunately, extreme precipitation events remain difficult to model. Although dynamically downscaled climate models are better able to approximate the effects of Lake Superior on local weather conditions (Chapter 2), uncertainty remains in the projections for frequency and intensity of heavy rainfall events. Additionally, the timing of these events and the soil conditions at the time of the event have a major influence over how much water can be absorbed through soil infiltration and how much overland flow will be generated. Extreme rain events can also be highly variable in the amount of water that is delivered across the landscape. For example, the immense June 2018 rainstorm that passed through Bayfield County dropped as much as 15 inches of rain near Drummond, Wisconsin. During this same event, Bayfield (less than 50 miles away), only received 3 inches of rain (National Weather Service 2018).

Wildfire

Wildfire and human-origin fire is an important driver for some ecosystems in the Apostle Islands, particularly in pine forests and barrens. Boreal forests and some coastal wetlands are also adapted to regenerate after more episodic fire, and the absence of fire disturbance is a contributor to the development of the mixed conifer hardwoods and upland hardwood forests that blanket most of the park. Climate change has the potential to alter the fire regime in the Apostle Islands in a variety of ways.

The *Forest Ecosystem Vulnerability Assessment for Northern Wisconsin and Western Upper Michigan* includes a synthesis of the potential effects of climate change

A prescribed fire on the Stockton Island tombolo in October 2017. NPS PHOTO/P. BURKMAN

on wildfire in the region (Janowiak et al. 2014). Fire can be a catalyst for ecosystem change, perhaps resulting in more rapid change than would be expected based only on the projected changes in temperature and moisture availability. As with wind disturbances, the potential exists for novel successional pathways following wildfire if climatic conditions, seed sources, or management decisions change.

Large-scale model simulations tend to agree that there will be increases in conditions favorable to wildfire ignition and spread by the end of the century, particularly in boreal forests, temperate conifer forests, and temperate broadleaf and mixed forests (Moritz et al. 2012). Models in Canadian boreal forest systems also support the idea of increasing wildfire extent and wildfire season that peaks later in the year (Flannigan et al. 2009, Le Goff et al. 2009). Drier conditions due to warmer temperatures and increasing VPD may increase flammability of available fuels, and wind events, drought, or forest pests and diseases could increase the amount of available fuel for future wildfires in the park. As described in Chapter 2, it is generally expected that climate change will result in increased frequency of severe thunderstorms, tornadoes, and damaging wind. Analysis of wildfire occurrence and daily weather records from 1980 to 2016 in the Apostle Islands indicates that most wildfires occur in warmer and drier months (months with average temperatures above 57.2°F and with Palmer Drought Severity Index below 0) (Martin and Johnson, in preparation). Natural-ignition fires also occur more often during a multi-week duration of below-normal precipitation.

Key Uncertainties

Despite the general expectation that climate change will result in more frequent wildfires in the region, there is still significant uncertainty about whether the Apostle Islands may experience more fire in the future. The park's island setting is a primary constraint on the ability of wildfires to have a large influence. Any wildfires that occur are likely to be constrained to a single island, and topographic features such as wetlands, ravines, or shorelines may limit fire spread. The mainland unit may be susceptible to wildfires crossing into the park from

neighboring ownerships, but the islands will be sheltered from mainland fires.

There are also lingering uncertainties about the effects of climate change on the future frequency of lightning strikes that could ignite wildfires. National-scale projections indicate that lightning strikes will increase about 50% over the 21st century, as warmer temperatures increase the convective available potential energy (Romps et al. 2014). This national-level research does not account for local effects of the Great Lakes on storm and lightning conditions, however. A more local analysis of lightning strikes for Bayfield County indicates increasing lightning strike frequency over the past 25 years, although there is significant year-to-year variability (Martin and Johnson, in preparation). Larger islands with higher peaks may attract lightning strikes more frequently due to the elevation difference between the flat lake surface and the island (Drobyshev et al. 2010). There is uncertainty about the future of "dry lightning" in particular, where lightning strikes occur without accompanying rainfall. Human ignitions are another potential source of fire in the Apostle Islands, as increased visitation and a longer visitor season (Fisichelli and Ziesler 2015) may increase the likelihood of human-caused fires in high-use areas.

As mentioned above, the complex interactions between drying climatic conditions and disturbances may result in more available fuel for fires. Additionally, the continued warming of Lake Superior may complicate the overall trend toward drying, as decreased lake ice and greater evaporation over the lake leads to increases in atmospheric moisture (Martin and Johnson, in preparation). These interactions are uncertain, however, and have not been included in explicit fire risk studies for the park. Additionally, it is unknown if National Park Service policies on wildfire suppression, cultural use of fire, or other forms of prescribed fire will shift due to climate change or other factors.

Shoreline Disturbance Processes

As discussed in Chapter 1, the ecosystems in the Apostle Islands are directly and indirectly shaped by Lake Superior. The park contains 160 miles of shoreline, and the beaches, dunes, wetlands, cliffs, and bluffs that occur on these shorelines are a result of the interplay between the lake and the land.

The Apostle Islands contain a wide variety of coastal landforms, which are exposed to differing amounts of wave action, ice scour, lake currents, wind, and other forces. A recent assessment evaluated the potential for the shorelines to change throughout the Apostle Islands, based on features such as geomorphology, historical rate of change, regional slope, and exposure to significant wave heights (Pendleton et al. 2007). According to this analysis, 51% of the shoreline in the Apostle Islands is classified as having very high or high change potential (Figure 13). In particular, this assessment calls attention to the high potential for change where sand and gravel beaches are not backed by dunes, which occur on Long Island, Outer Island, Michigan Island, the Stockton Island Tombolo, and other isolated locations in the park. Several of the more distant islands (e.g., Devils, Rocky, North and South Twin) are also highlighted for having lower coastal slopes, which increases the potential for shoreline change.

Chapter 2 describes a variety of projected changes that have the potential to increase the effects of shoreline erosion in the park. Taken together, the interaction between these changes may result in a more dynamic coastal environment in the Apostle Islands, with stronger and more frequent wave action. For example, summer wind speed has been increasing across the surface of Lake Superior over the past few decades. Wind speeds over the lake are expected to continue to increase as the temperature gradient between air and water above the lake is reduced. Faster winds lead to larger, more forceful waves and faster lake currents. Longshore currents develop and transport sediment when winds or waves strike the shore at an angle. Monitoring has also revealed that the annual mean wind direction across Lake Superior has shifted clockwise over the past several decades

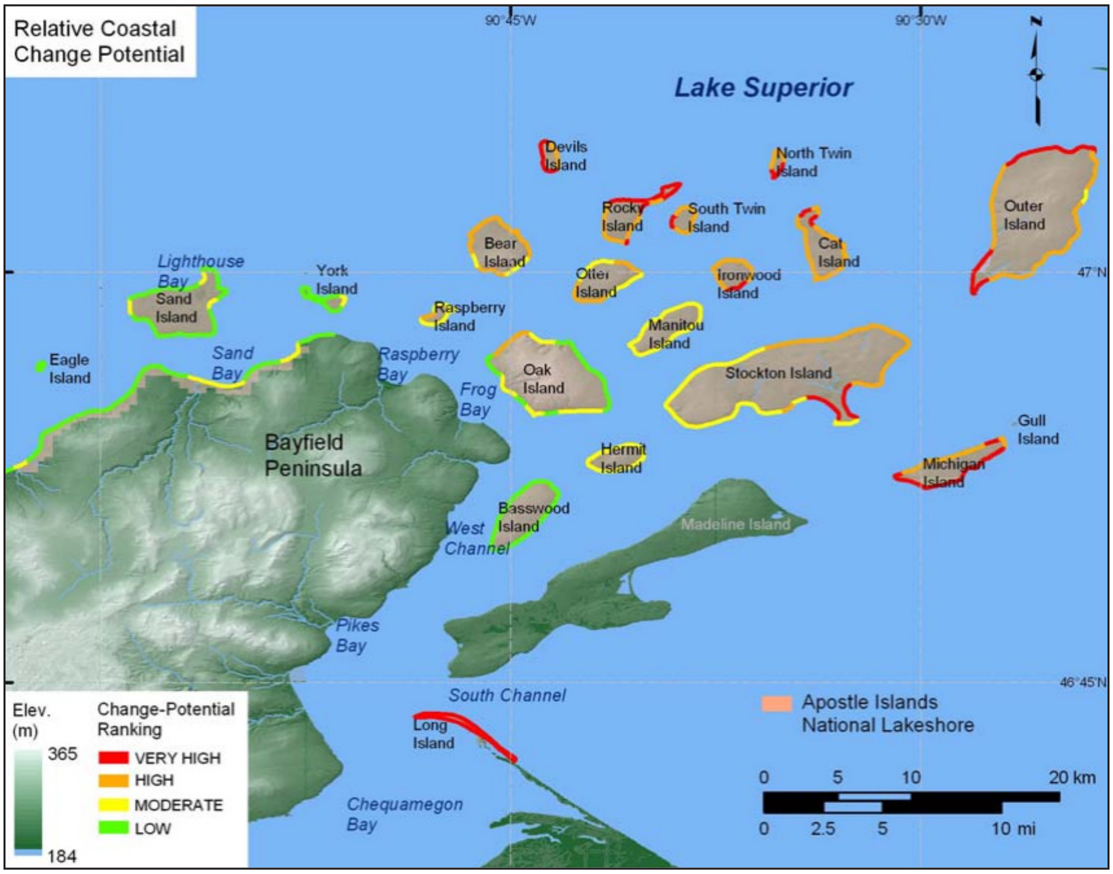

Figure 13. Relative coastal change potential for the Apostle Islands National Lakeshore (Pendleton et al. 2007). The colored shoreline represents the relative coastal change-potential index determined from six variables. The very high change-potential shoreline is located along sandy stretches where significant wave heights are highest. The low change potential shoreline is located along bluffs where wave heights are low.

(Anderson et al. 2015). This means that winds are generally shifting from northwest to north, which could lead to greater wave heights because northerly winds travel over a longer stretch of Lake Superior before reaching the Apostle Islands. It appears that these factors are already resulting in larger wave heights, particularly for larger classes of waves (see Chapter 2, Anderson et al. 2015). Wave heights are increasing more rapidly for the interior of the archipelago than the exterior, meaning that coastlines that were historically sheltered from intense waves are increasingly exposed to larger waves.

Although the prevailing winds are typically from the northwest or north in the Apostle Islands, the strongest winds generally blow from the northeast. These winds also generate the largest waves because they travel the longest distance over Lake Superior (Anderson et al. 2015). These winds most often occur during the winter, when ice cover on the lake can protect the shorelines from direct wave impacts. However, this protective feature is diminishing because lake ice has declined markedly over the past several decades (Howk 2009, Mason et al. 2016). This interaction means that shorelines in the Apostle Islands are more often exposed to the strongest winds and most powerful waves during the winter months.

Key Uncertainties

A key uncertainty when considering these potential changes is whether the fundamental equilibrium of shoreline erosion and deposition will be disrupted by more frequent and intense wave action. Natural, undeveloped shorelines, such as those in the Apostle Islands, tend to respond flexibly to changing lake levels and wave action (Dean 1991, Komar and Holman 1986), as the processes of erosion,

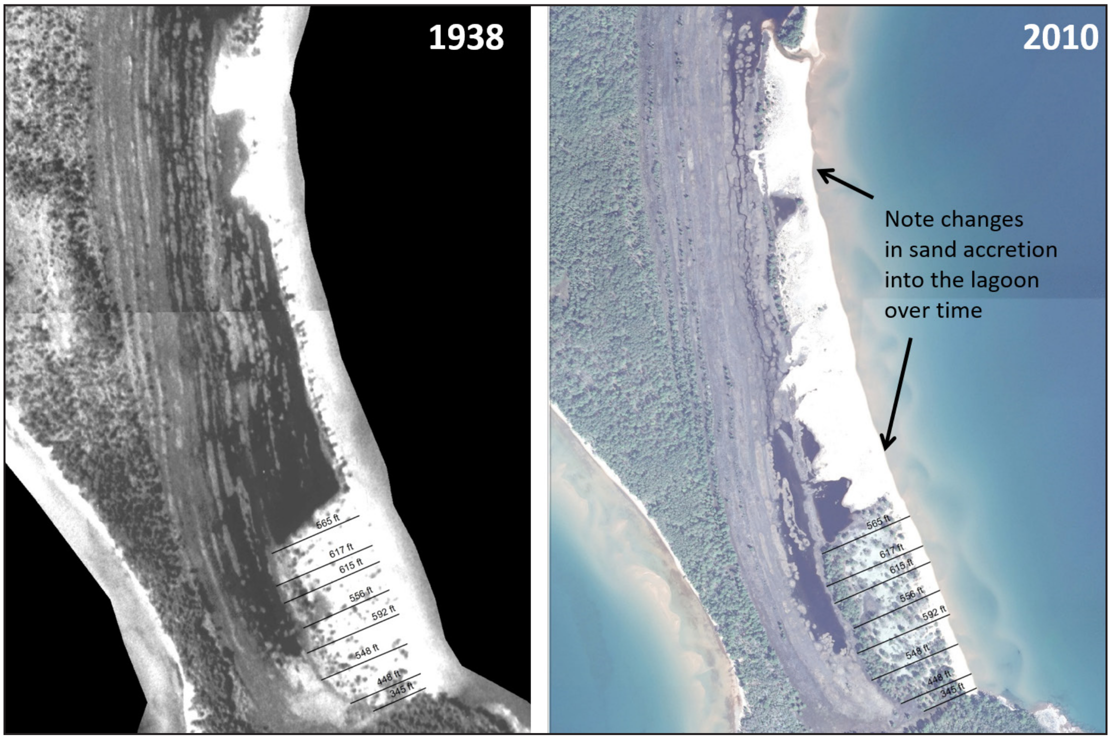

Figure 14. Aerial imagery of the Stockton Island tombolo formation in the Apostle Islands. These photos from 1938 (*left*) and 2010 (*right*) show the beach expanding into the neighboring lagoon. The aerial extent of the beach in this area increased from 12 acres to 32.5 acres during this timeframe.

sediment transport, and deposition are uninterrupted. In shorelines that have been altered by development, more dramatic changes are possible. It is also possible that changes to wave action in the Apostle Islands are dramatic enough that some shorelines experience an identity shift. For example, a low-energy sandscape could conceivably convert to a high-energy cobble beach, with beach sediments being transported to offshore bars. Beaches might also retreat inland and store sediment onshore (Figure 14). These changes are not necessarily permanent, because coastal systems can recover from disturbance over several years. But it is also possible for a system to cross a threshold when change is too dramatic (Sweet and Park 2014). It is difficult to forecast these transformations ahead of time, due to the complicated interactions that are involved.

Additionally, projections of future lake levels under climate change are mixed for Lake Superior, and slight increases and decreases are both possible over the 21st century (Chapter 2). There will certainly be periods of time when the lake is higher or lower than average, as multi-year cycles continue. When lake levels are high, the effect of larger and stronger waves may be even more impactful on shorelines in the Apostle Islands. When lake levels are low, these effects may be dampened and shoreline habitats will increase in area.

The generations of beach ridges and interdunal wetlands across the Apostle Islands are clear evidence that the area has adapted to periods of changing lake levels over the past several thousand years. Future change may present novel conditions, however, and time will reveal how the park responds.

Deer Herbivory

Chapter 1 gives a brief overview of the effects of white-tailed deer herbivory on forest understory communities among some islands in the park. Regional assessments have highlighted the fact that winter survival rates for deer may be increased by climate change, and also that wintertime foraging behavior may change as snow conditions

change (WICCI Wildlife Working Group 2011, Janowiak et al. 2014). Research from Alberta, Canada, indicates that decreasing winter severity over the past several decades has been the primary factor allowing deer to expand their range northward (Dawe and Boutin 2016). Persistent deer herbivory in the Great Lakes region may effectively be counteracting the presumed competitive advantage of temperate tree species over boreal tree species (Fisichelli et al. 2012). Due to the preference of deer to browse on certain temperate species such as red maple, sugar maple, and northern red oak at greater levels than boreal species such as white spruce and balsam fir, the expansion of temperate species is being slowed substantially (Fisichelli et al. 2012). Other important species in the Apostle Islands may be harmed by increased deer herbivory, such as Canada yew, eastern white pine, eastern hemlock, and several projected "new migrant" species mentioned earlier in this chapter (e.g., oak species). Deer herbivory may also favor temperate species that are not preferred browse species, such as ironwood and black cherry, or invasive species like Eurasian buckthorn (*Rhamnus cathartica*).

Canada yew repeatedly browsed by deer.
NPS PHOTO/P. BURKMAN

Key Uncertainties

There are some notable uncertainties regarding how climate change may influence deer population levels and browse pressure in the Apostle Islands. As discussed in Chapter 1, several of the islands in the park historically had very low deer populations or may have never contained any deer. This suggests that inaccessible shorelines or the distance from the mainland has prevented deer from colonizing these islands, and therefore climate change may not have a meaningful influence on herbivory in these places. The mainland unit may be more likely to experience higher deer populations as winters become milder, although the steep shoreline and browse accessibility may continue to limit deer numbers. Hunting is currently employed as the primary population control for deer within the park, but management options such as extended seasons and contracted herd reduction are available. The park successfully culled substantial portions of the deer herd on Sand and York Islands in 2009, but it is uncertain if funding and public input will allow future interventions. Wolves (ma'iingan, *Canis lupus*) and coyotes (wiisagi-ma' iingan, *Canis latrans*) also help control the deer populations in the Apostle Islands. While wolves are currently protected under the Endangered Species Act, it is uncertain how climate change and future delisting decisions will affect the population of this apex predator. Finally, chronic wasting disease has been documented in a handful of counties in northern Wisconsin as of February 2019 (Wisconsin Department of Natural Resources 2019a). If this lethal prion disease continues to spread, it could substantially reduce the deer herd but could also reduce hunting pressure if the public is deterred from hunting in infected areas.

Invasive Species

The *Forest Ecosystem Vulnerability Assessment for Northern Wisconsin and Western Upper Michigan* discusses general information regarding the potential for climate change to magnify the effects of invasive species in the region (Janowiak et al. 2014). Although species distribution models do not exist for most invasive species

in the region, there are many reasons to expect that climate change will indirectly benefit invasive species. Interactions among projected climate trends (Chapter 2) and other factors may increase the potential for invasive species in the Apostle Islands. Climate change could increase the ability of a species to invade as warmer temperatures, earlier springs, longer growing seasons, and reduced snowpack make conditions more favorable (Vose et al. 2012). The risk may be higher from easily-dispersed invasive species, such as buckthorn.

National parks, in particular, may be susceptible to invasion from non-native species due to high visitation rates and visitors who come from a wide geography. Campsites, sandscapes, and coastal areas that experience high visitor use may be the most likely introduction sites for invasive species in the Apostle Islands. Old home sites, settlements, and logging areas in the Apostle Islands already host a higher proportion of non-native species (Judziewicz and Koch 1993). Weedy species that aggressively occupy disturbed areas may also find more open areas if climate change results in more frequent wind events, fire, or forest pests that disturb the forest canopy (Dukes et al. 2009) or the Canada yew understory (Mudrak et al. 2009). Flood events can transport invasive species, and soil erosion and deposition can create locations for invasive species to colonize. Ravines on the mainland may be particularly vulnerable to invasive species being transported from upstream. Popular trails and campsites on the islands with high visitation rates are also more vulnerable.

Insect Pests and Diseases

Janowiak et al. (2014) concluded that forest pests and diseases are also generally expected to become more damaging to northern Wisconsin forests in a changing climate. Changing conditions may facilitate the spread of pests and diseases, and native ecosystems may also be more susceptible to damage when stressed by climate change. We still lack basic information about climate tolerances for many forest pests, so considerable uncertainty exists when assessing the risk of a particular pest or disease. The relatively recent gypsy moth introduction to the Apostle Islands, described in Chapter 1, provides an interesting example. Gypsy moths were

Invasive plant species such as ox-eye daisy (*Leucanthemum vulgare*), hawkweed (*Hieracium aurantiacum*), and common sheep sorrel (*Rumex acetosella*) line a boardwalk on South Twin Island.
© S. Johnson/Northland College

certainly transported to the islands via a park visitor, but a warming climate may have also facilitated the success of the inadvertent introduction. Recent modeling suggests that climate constraints have historically limited gypsy moth's historical range in Europe, and warming may allow this insect to expand to new areas in the future (Vanhanen et al. 2007). Similarly, hemlock wooly adelgid (*Adelges tsugae*) is limited by winter low temperatures of −10°F to −15°F (Paradis et al. 2008). As winter minimum temperatures continue to rise rapidly, northern Wisconsin and the Apostle Islands may become susceptible to this pest.

Pests and pathogens are generally expected to become more damaging in forest ecosystems as the climate changes because they will be able to adapt more quickly to new climatic conditions, migrate more quickly to suitable habitat, and reproduce at faster rates than host tree species (Janowiak et al. 2014). Uncertainty remains high, however, because there are often complex modes of transmission and infection for forest diseases. A case study on white pine blister rust (*Cronartium ribicola*) suggests some of the complex interactions that may lead to increasing tree disease damage under a changing climate (Sturrock et al. 2011). White pine blister rust requires cool, moist conditions for germination and infection, so wetter conditions may promote the fungus while warmer, drier summers may ultimately limit the damage from this disease. Oak wilt (*Bretziella fagacearum*) is a fungal disease that kills oak trees by blocking the water transport tissue inside the bark. This disease has been confirmed in Bayfield County as of February 2019, but not yet in the immediate vicinity of the park (Wisconsin Department of Natural Resources 2019b). Fungal spores can be spread by sap-feeding beetles that are attracted to the fungal masses. Current risk periods for oak wilt (April to October) are typically determined by when the fungus and the oak sap beetles are both active, but these species may respond differently to future climate change and the risk periods for this disease may shift.

Visitor Use Impacts

There are many possible interactions between climate change and visitation patterns to the Apostle Islands National Lakeshore. These vulnerabilities may be speculative at this point, but they are worth considering. As discussed above, visitors to the Apostle Islands National Lakeshore can cause direct and indirect impacts to the park's ecosystems through necessary infrastructure, trampling, and transport of non-native species. It is also likely that the effects of climate change on the park's resources may affect visitor behaviors. For example, ice caves typically draw large numbers of visitors to the park, but the long-term trend of warmer winters and declining lake ice may make it increasingly rare for ice caves to develop. Conversely, warmer spring and fall conditions could extend the visitor season over time.

Saunders et al. (2011) examined several potential implications of climate change on the visitation patterns of national parks in the Great Lakes region. Increased wave action at the Apostle Islands, particularly during the winter time, could damage docks, campgrounds, and trails. Erosion or transformation of sandscapes, forest health declines, and damage to historical sites such as lighthouses could diminish visitor enjoyment of these destinations. Climate change could also intensify several safety risks for park visitors,

Signs are used in some areas to direct visitors away from fragile vegetation communities.
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including increased risk of heat stress during warm summers, more dangerous boating conditions with stronger wind and waves, unstable ice in the wintertime, and expanding spread of tick-borne diseases.

Visitation is generally expected to increase under climate change for the Apostle Islands National Lakeshore in particular and for regional outdoor recreation sites in general. A recent national-level study found a strong historical relationship between mean monthly air temperature and national park visitation, and extended this relationship to assess expected national park visitation by the middle of the 21st century (Fisichelli et al. 2015). According to these methods, Apostle Islands National Lakeshore may see 22%–65% more visitors across the entire year, and the peak visitation season may extend by 18–46 days (Fisichelli and Ziesler 2015). In a regional analysis, Bowker and Askew (2013) found that the number of visitors to developed recreation sites (i.e., campgrounds, picnic areas) will increase by roughly 30% by the middle of the century, while visitation to primitive natural areas (backpacking or camping in designated wilderness or backcountry areas) is expected to hold relatively steady. Analysis of visitor surveys along Minnesota's North Shore have suggested that climate change is not likely to affect overall levels of winter tourism, but individuals who preferred more outdoor-based forms of tourism generally had a more negative impression of expected climate scenarios (Smith et al. 2016). Projections for provincial parks in Ontario have suggested that visitation may increase by 15% to 56% by the middle of the century due to warmer conditions (Jones and Scott 2006).

Conclusion

This chapter has presented the major climate change vulnerabilities that could influence the terrestrial ecosystems of the Apostle Islands. This synthesis of existing information is a necessary foundation for considering the more precise vulnerabilities of the park's ecosystems in the chapter that follows. After reading this chapter, it should be evident that some of the most profound potential impacts of climate change will depend on the interactions between biotic and abiotic factors. Many of these interactions are still areas of considerable uncertainty, and we have attempted to transparently disclose those uncertainties. These uncertainties also factor into the vulnerability determinations and conclusions in the following chapter.

Shoreline erosion on Stockton Island after a strong storm. NPS PHOTO/P. BURKMAN

Chapter 4: Apostle Islands Ecosystem Vulnerability Assessment

This chapter explores the potential effects of climate change on eleven terrestrial Apostle Islands ecosystems. The drivers, stressors, and key plant species of the ecosystems are discussed in detail, along with the adaptive capacity of these ecosystems. Chapter 1 presents a summary of major drivers, stressors, and representative plant species for each ecosystem covered in this assessment.

Climate change will continue to affect the drivers and stressors that shape the ecosystems of the Apostle Islands. Individual plant species may respond distinctly and separately to these changes, which means that ecosystems and natural communities will vary in their capacity to adapt to expected changes. Some ecosystems may withstand change and others may be highly susceptible. Some may even experience an ecological transformation or "identity shift" as dominant or keystone species decline or key drivers are altered.

This assessment provides a summary of the vulnerability determination for each ecosystem in question. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the susceptibility of a system to the adverse effects of climate change" (IPCC 2007). It is a function of the potential impacts to a system and the adaptive capacity of that system to tolerate these impacts. Authors qualitatively evaluated the potential impacts of climate change on each system on a scale that ranged from "supportive to the ecosystem" to "disruptive to the ecosystem" (Figure 15). Adaptive capacity was evaluated on a scale from high to low. Authors considered potential impacts and adaptive capacity rankings as two axes on a common chart, in order to encourage thinking about the terms as related elements rather than separate and distinct factors. See Appendix 5 for more details on the vulnerability determination process.

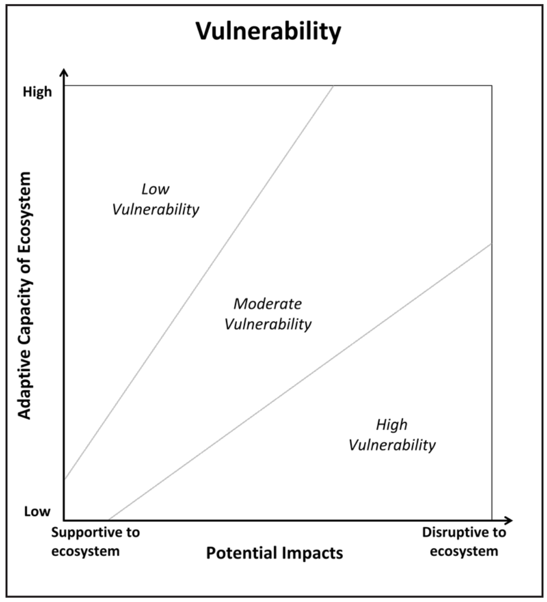


Figure 15. Chart used to consider and rank climate change vulnerability of terrestrial Apostle Islands ecosystems, illustrating the relationship among potential impacts and adaptive capacity. Modified from Swanston et al. (2011).

We consider an ecosystem to be vulnerable if it:

- is at risk of changes leading to a new ecological state;
- may have reduced ability to fulfill key ecosystem functions; or
- is anticipated to suffer substantial declines in health, productivity, or geographic extent.

This broad definition of vulnerability is warranted because natural ecosystems are valued both for their particular character and mix of species, and for the services they provide. For this assessment, we limited the scope of our consideration to the Apostle Islands National Lakeshore boundary, so if a particular ecosystem is expected to decline within the park but persist elsewhere in the region, that ecosystem would still be judged to be highly vulnerable. Additionally, the timeframe of this assessment is the year 2100, so vulnerability conclusions reflect the range of expected conditions at that time.

The climate change vulnerability determinations are based on the conclusions of a panel of experts assembled from a variety of organizations and disciplines. These experts were selected based on their familiarity with the Apostle Islands, knowledge of similar ecosystems, and ability to contribute information from a variety of perspectives. A full list of panelists can be found in Appendix 5. The 17 panelists considered the information presented in previous chapters, and contributed their own expertise and judgement.

For many of the potential climate change impacts considered in this assessment, there is a degree of uncertainty about the range of plausible future outcomes, as well as uncertainty in the degree to which impacts may interact with each other. Additionally, some ecosystems are less understood than others, and some fundamental questions remain about potential climate change impacts to ecosystem drivers. To appropriately recognize these uncertainties, the expert panelists also determined their confidence in the vulnerability determination for each ecosystem. Confidence is represented according to a confidence determination diagram from the IPCC's guidance for authors (Mastrandrea et al. 2010) (Figure 16). Confidence was determined by gauging both the level of evidence and level of agreement among information sources. Evidence is robust when there are multiple lines of evidence, as well as an established theoretical understanding to support the vulnerability determination. Agreement refers to the agreement among the available sources of evidence, not the level of agreement among authors of this assessment. Agreement was rated as high if theories, observations, and models tended to suggest similar outcomes.

For each ecosystem, panelists considered the potential impacts and adaptive capacity to assign a vulnerability determination and a level of confidence in that determination. For a complete description of the methods used to determine vulnerability and confidence, see Appendix 5. Overall vulnerability determinations ranged from

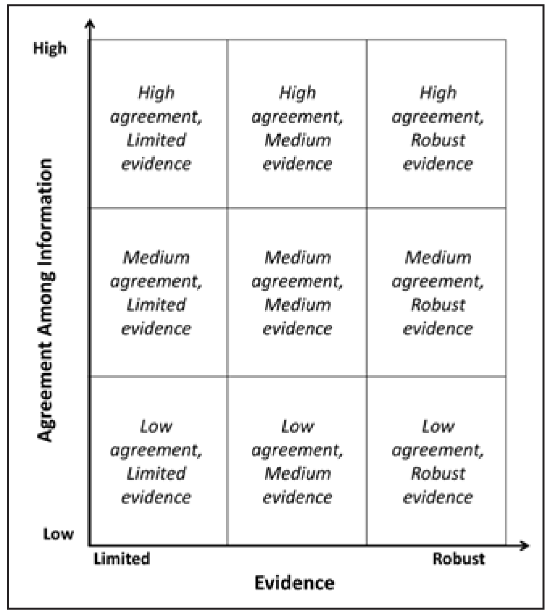


Figure 16. Confidence determination diagram used in the assessment workshop. Adapted from Mastrandrea et al. (2010).

low (Erodible Maritime Cliffs, Great Lakes Pine Forests and Barrens, and Interior Alder Thickets) to moderate-high (Boreal Forests, Coastal Wetlands, and Rock Cliffs and Ledges) (Table 5).

Panelists tended to rate the amount of evidence as medium (between limited and robust) for most ecosystems. Incomplete knowledge of future Lake Superior dynamics, interactions among stressors, and rare plant species were common factors limiting this component of overall confidence. The ratings of agreement among information also tended to be in the medium range, but there appeared to be greater agreement among information for some ecosystems, particularly Erodible Maritime Cliffs, Interior Alder Thickets, and Upland Hardwood Forests. These three ecosystems were judged to have relatively low vulnerability, and panelists felt that they would either be resilient to climate change impacts or that they may even be supported by future conditions. Contrasting information related to precipitation regimes and the water level of Lake Superior under the two climate change pathways were important factors that limited the level of agreement for several other ecosystems.

In the pages that follow, we summarize

the climate-related impacts on drivers, stressors, and dominant species that were major contributors to the vulnerability determination for each ecosystem, with ecosystems presented alphabetically. In addition, we summarize the main factors contributing to the adaptive capacity of each community type.

Table 5. Determinations of climate change vulnerability and confidence for the 11 terrestrial Apostle Islands ecosystems. Potential impacts are rated on a scale from Disruptive to Supportive, and adaptive capacity is rated on a scale from Low to High. Evidence is rated on a scale from Limited to Robust, and agreement is rated on a scale from Low to High. See Appendix 5 for more detail.

Ecosystem	Potential Impacts	Adaptive Capacity	Vulnerability[1]	Evidence	Agreement	Confidence[2]
Beaches and Dunes	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate	Moderate
Boreal Forests	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low-Moderate
Coastal Wetlands	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low
Deep Ravine Forests	Moderate	High	Low-Moderate	Moderate	Moderate	Moderate
Erodible Maritime Bluffs	Moderate-Supportive	High	Low	Moderate	Moderate-High	High
Great Lakes Pine Forests and Barrens	Moderate-Supportive	Moderate-High	Low	Limited-Moderate	Moderate	Moderate
Interior Alder Thickets	Moderate-Supportive	High	Low	Moderate-Robust	High	High
Interior Peat Swamps and Bogs	Disruptive-Moderate	High	Moderate	Moderate	Moderate	Moderate
Mixed Conifer Hardwoods	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Rock Cliffs and Ledges	Disruptive-Moderate	Moderate	Moderate-High	Moderate	Moderate	Moderate
Upland Hardwood Forests	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate-High	High

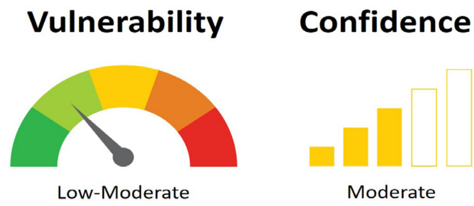
[1] Potential impacts and adaptive capacity are combined to reach a vulnerability determination (Low to High), following Figure 15.

[2] Evidence and agreement are combined to reach a confidence determination, following Figure 16.

Beaches and Dunes

Vulnerability: Low-Moderate

Confidence: Moderate



This ecosystem is adapted to continual disturbance from wind, waves, and ice, and it is expected to tolerate more intense and frequent disturbance in the future.

Apostle Islands Beaches and Dunes depend on frequent wind and wave disturbance, and they occur on a wide variety of formations depending on local topography, exposure, and sediment transport. See Chapter 1 for a more complete description.

Potential Impacts: Moderate

Drivers: Changing lake levels could lead to limited expansion or contraction of this ecosystem, although topography and offshore water depth tend to constrain Beaches and Dunes to particular locations. Reduced winter ice cover, increased wave action, and stronger winds could lead to more intense and frequent disturbance (both erosion and deposition), particularly in locations that have northern or eastern exposure such as Long Island and Stockton Island. There is a low probability that wave action could increase to such a degree that low-energy sandy beaches may convert to high-energy cobble and stone beaches, which could cause an ecological transformation. Similarly, there is a small chance that lake currents and storm cycles could change dramatically enough to cause a physical loss of sandscapes and habitat for associated species. Additionally, increasing wind and warmer growing season temperatures could cause more desiccation in these communities.

Key Species: Beach grass is the keystone species in this ecosystem, particularly for foredune development. This species is adapted to thrive with frequent sand deposition, as well as low-nutrient and droughty conditions. This species and several other beach and dune plants have native ranges that extend well to the south of the Apostle Islands, such as common juniper, beach pea, and evening primrose. Lichens thrive in this ecosystem on low-nutrient sandy substrates in backdune and older dune areas where disturbance is less prevalent.

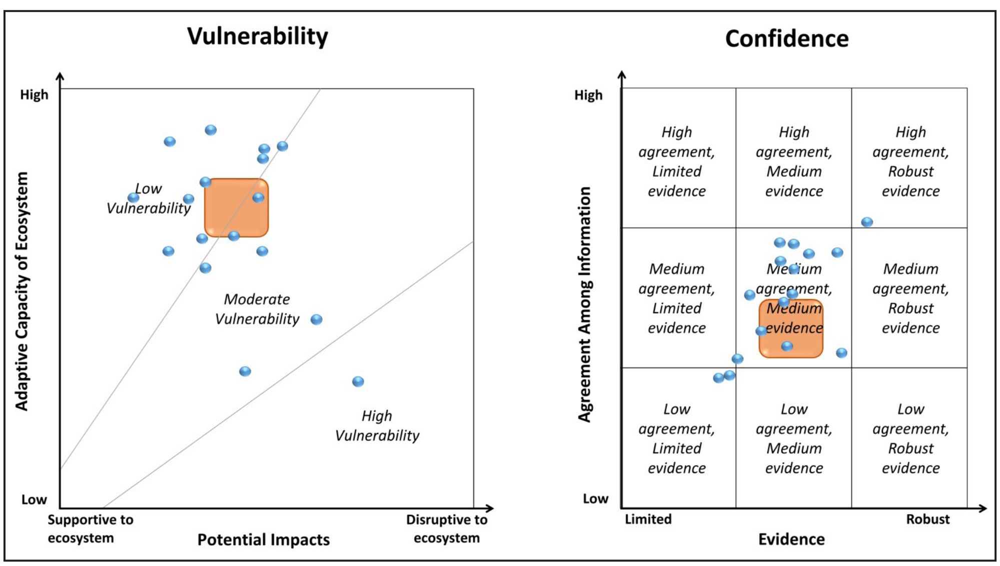
Stressors: Beaches and dunes may be at greater risk of invasion from non-native and invasive species under future climate conditions due to combined effects of shifting climate suitability and potentially increased transport and disturbance from more frequent park visitation. Particularly concerning invasive plants include non-native species such as spotted knapweed, ox-eye daisy, tansy, baby's breath (*Gypsophila* spp.), and aggressive native species such as poison ivy (maji-aniibiish, *Toxicodendron rydbergii*). Backdunes may be more vulnerable to invasion than beaches because they are more sheltered. As climate change results in longer tourist seasons and more visitation, disturbance from foot traffic and boats may increase, which is concerning for lichen communities and other dune vegetation. Non-native insect pests might become a bigger concern with longer growing seasons and milder winters. For example, pale juniper webworm can defoliate common juniper.

Adaptive Capacity: Moderate-High

Beaches and Dunes are "primary" ecosystems, adapted to frequent disturbance from wind, waves, and ice. They should be able to thrive in more dynamic and disturbed conditions, even if the balance shifts between foredune and backdune

Rhizomes of beach grass, exposed by coastal erosion in 2014. © S. Johnson/Northland College

communities. Beaches and Dunes tend to be located on southern ends of the Apostle Islands, and these locations should remain relatively stable for beach and dune formation over time, because sand migration, erosion, and accretion are part of a regular cycle. Also, these locations are not as exposed to wind and waves as northern ends of the islands. Plants that occur in this ecosystem are able to survive in droughty, low-nutrient conditions with large temperature fluxes. So even though low species richness in these communities could increase their vulnerability, the species that exist are specialized. Increasingly harsh conditions may also limit the invasion potential for some non-native species, particularly in foredune areas.



Vulnerability and confidence determinations for the Beaches and Dunes ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Boreal Forests (including krummholz)

Vulnerability: Moderate-High

Confidence: Low-Moderate

Vulnerability

Moderate-High

Confidence

Low-Moderate

Warmer conditions are expected to reduce the future suitable habitat of several dominant species in this ecosystem, and other forest types may gain a competitive advantage as conditions change.

Apostle Islands Boreal Forests are limited to cold areas with nutrient-poor soils on northern Devils Island, while krummholz is a stunted, wind-shaped forest formation that occurs on exposed coastlines. See Chapter 1 for a more complete description.

Potential Impacts: Disruptive

Drivers: Boreal Forests and krummholz in the Apostle Islands are limited to the areas with the coolest summers, shortest growing seasons, and exposed windy shorelines and bluff tops. They are confined to very limited territory in outermost northern reaches of the Apostle Islands. Warmer future conditions could further reduce the areas where Boreal Forests are able to maintain a competitive advantage and regenerate successfully. Warmer conditions leading to water loss from evaporation and transpiration could also disrupt these forests, which require consistent moisture throughout the year from rain, fog, snow, and lake spray. A warmer Lake Superior may remain stratified for longer periods in the summer, which would result in warmer onshore winds during the growing season. Higher winds could increase the potential for blowdowns and increase the prevalence of krummholz along the coastlines of some exposed islands. More wildfire might also support Boreal Forests as long as favorable conditions exist for regeneration, because they are adapted to regenerate after fire.

Key Species: Several of the dominant tree species in Apostle Islands Boreal Forests are projected to lose suitable habitat under a range of future climate conditions: white spruce, balsam fir, northern white-cedar, and quaking aspen. Tamarack and paper birch are projected to maintain suitable habitat over the next century. It would be a substantial identity change/ecological transformation if this ecosystem experienced a reduced conifer component and shifted to an aspen/birch ecosystem or a shrub-dominated "heath" ecosystem. Showy mountain ash is present in Apostle Islands Boreal Forests, but is not common enough to have reliable climate model projections.

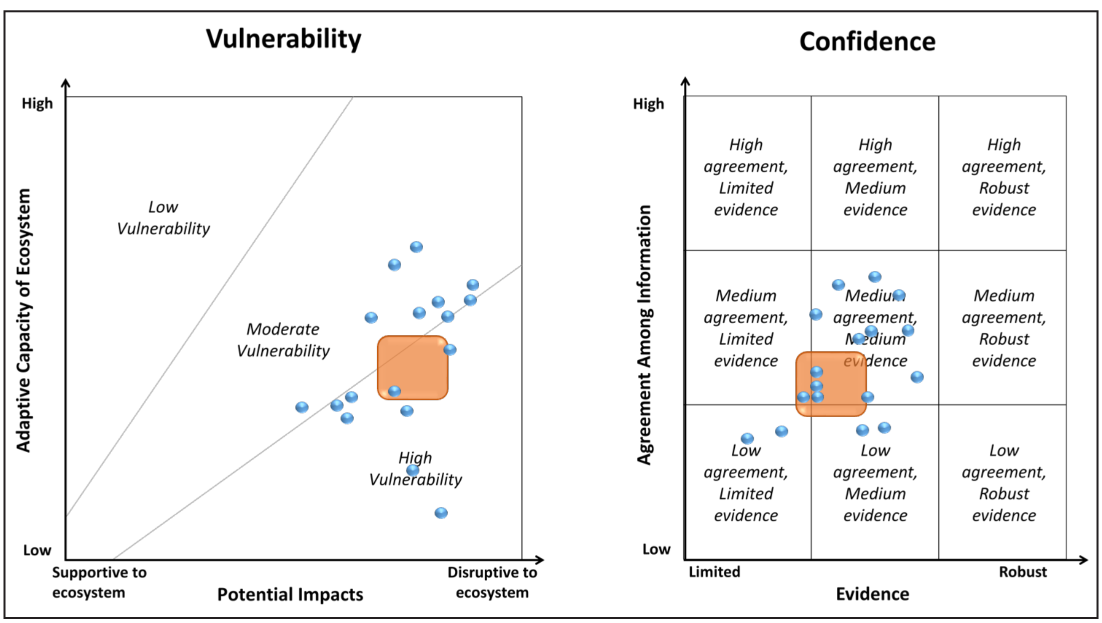
Stressors: Insect outbreaks of native pests like spruce budworm could become more damaging if forests are already stressed due to warmer, drier conditions. Milder, shorter winters may benefit these native pests, and future conditions may allow new insect pests to thrive in the Apostle Islands.

Adaptive Capacity: Moderate

Boreal Forests may already be limited to the few locations where they are able to persist. It seems unlikely that this ecosystem would expand to new locations under projected future climates. Natural disturbances such as wildfires that typically support Boreal Forests could become disruptive if conditions after the disturbance do not allow for successful regeneration of boreal species. Conversely, Boreal Forests currently exist in harsh environments with short growing seasons and shallow, acidic, and nutrient-poor soils, which reduces competition from other species. Also, because these forests currently exist on exposed, northern tips of outer islands, they may be somewhat

Boreal forest on the exposed shoreline of Devils Island. NPS PHOTO

buffered from temperature increases. The species that occur in Boreal Forests regenerate well after fire, high wind events, and other episodic disturbances. Additionally, these tree species are generally long-lived and abundant regeneration is present in many locations, so there may be an extended lag time of several decades before climate impacts are apparent.

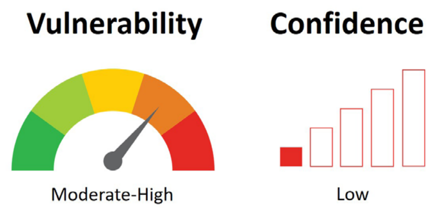


Vulnerability and confidence determinations for the Boreal Forest ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Coastal Wetlands

Vulnerability: Moderate-High

Confidence: Low



Physical damage from strong storms and waves, as well as changes to water temperature and chemistry from Lake Superior breaches, could be severe and long-lasting impacts to this ecosystem.

Apostle Islands Coastal Wetlands span a gradient of water temperature and nutrient availability and host a range of wetland plants. Sand spits or dunes provide complete or partial protection from Lake Superior. See Chapter 1 for a more complete description.

Potential Impacts: Disruptive

Drivers: Several related potential impacts could increase the likelihood of protected Coastal Wetlands and lagoons being breached more frequently and connecting with Lake Superior. Higher lake levels, increased wave heights, more frequent strong storms, and less protective ice cover in the winter may erode or diminish protective barrier spits that separate Coastal Wetlands from Lake Superior. More frequent lake connection has the potential to change the water temperature, chemistry, and level in these Coastal Wetlands, which would be particularly disruptive for coastal poor fens. More frequent breaching of the sandspits could also damage the floating sedge mats that characterize these ecosystems, particularly during strong storms. Larger precipitation events could also lead to more sedimentation and nutrient inputs from uplands, particularly on the mainland, which can lead to eutrophication.

Key Species: Warmer water temperatures could lead to a loss of sphagnum moss and increased decomposition. Warming waters and changes in water chemistry (increases in nutrient availability and pH) may also reduce suitable habitat for coastal fen and poor fen species, such as woolyfruit sedge; coast sedge; smooth sawgrass (*Cladium mariscoides*); white beak-rush; sundews; sweet gale; ericaceous shrubs (Ericaceae spp.); and orchids such as the tuberous grass pink orchid (*Calopogon tuberosus*) and dragon's-mouth orchid (*Arethusa bulbosa*).

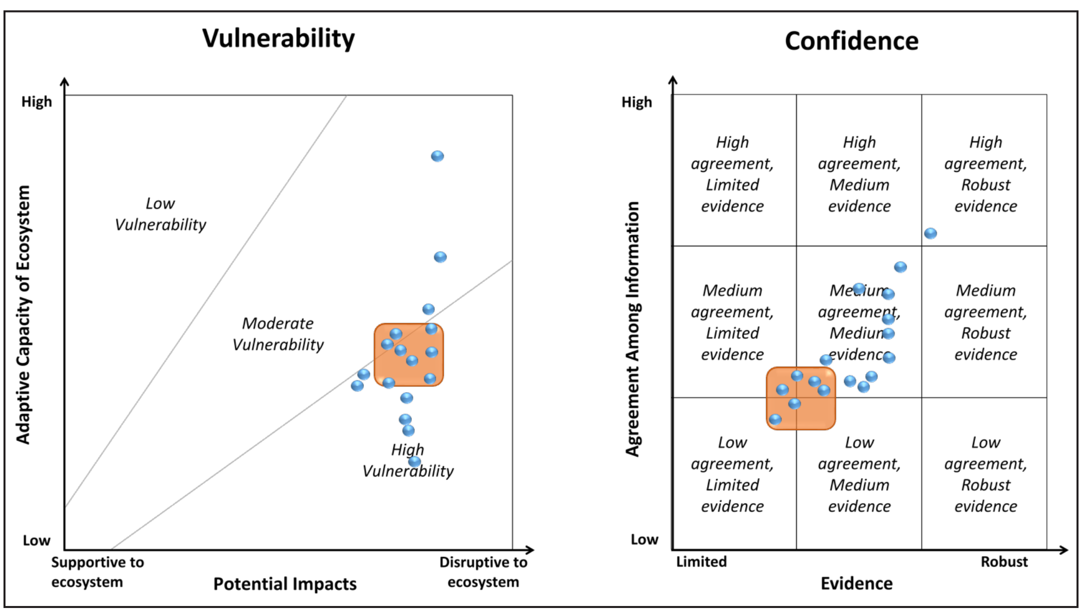
Stressors: Warmer water conditions, habitat changes, more frequent disturbance, and altered water chemistry could encourage more invasive species in Coastal Wetlands. Non-native cattails, *Phragmites*, purple loosestrife, and Eurasian buckthorn are all invasive species of high concern. Long-term isostatic rebound is also changing water levels in these habitats, and wetlands that are slowly being "drowned" by natural lake level changes may see increased disruption with stronger storms and higher waves. Similarly, on-going atmospheric nitrogen deposition is altering water chemistry in Apostle Islands wetlands, and these changes may be further accelerated due to the interactions mentioned above. Coastal Wetlands on the mainland experience greater sedimentation and nutrient runoff, because their drainage basins generally contain more developed or agricultural land.

Adaptive Capacity: Moderate

These ecosystems are typically very dynamic, thriving with year-to-year fluctuations in water levels and varying connections with Lake Superior. Floating sedge mats can move, and this general ecosystem category contains a gradation of specific community types that can shift with changing water levels. Lower water levels typically lead to an increase in woody shrubs, while

An interdunal wetland with a shore fen community. © S. Johnson/Northland College

increasing water levels lead to more marsh species. There are limits to the plasticity of Coastal Wetlands, however, and large shifts in lake level (higher or lower) would be disruptive. Coastal fen communities (Poor Fen and Shore Fen) may be particularly at risk due to changing decomposition and water chemistry, and may tend to convert to emergent and floating-leaved marsh communities. These kinds of fen-to-marsh conversions may be permanent or irreversible. Coastal Wetlands on sheltered island locations may be the most buffered from change, while wetlands on the mainland or exposed islands may be most susceptible—particularly nutrient-limited systems.

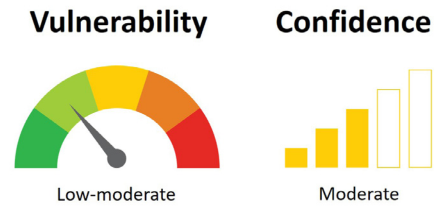


Vulnerability and confidence determinations for the Coastal Wetland ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Deep Ravine Forests

Vulnerability: Low-Moderate

Confidence: Moderate



Sheltered, shaded landscape positions and consistent moisture availability should help this ecosystem persist in current locations, although risks exist from more frequent strong storms and invasive species.

Apostle Islands ravine forests are limited to steep, sheltered ravines such as those on Oak Island and the mainland unit. These protected locations feature dense conifer canopies and consistent soil moisture. See Chapter 1 for a more complete description.

Potential Impacts: Moderate

Drivers: Heavy rain events are anticipated to cause more erosion, washouts, slumps, sedimentation, and flooding in Deep Ravine Forests. These are natural processes, but they have been intensified by more frequent heavy rains. Ravines on the mainland may experience greater erosion and sedimentation due to upland land-use change and forest harvesting, and because they have larger upland drainage basins than island ravines. Climate change is not expected to substantially affect groundwater seepage in these ravines, so soils should continue to be moist.

Key Species: Climate impact models project that suitable habitat may remain stable for eastern hemlock and red maple, while suitable habitat is projected to decline slightly for sugar maple, yellow birch, and northern white-cedar. Deep ravines are likely to provide important refugia for the more sensitive mesic species, however, so they are expected to continue to do well in this ecosystem into the future. Hemlock could be at risk if hemlock wooly adelgid is transported to the Apostle Islands, or if deer herbivory increases with less snow cover and larger deer herds. Rare species such as the broad-lipped twayblade, rattlesnake plantain, Chilean sweet cicely, or white mandarin may be affected by more frequent disturbances in ravines, and changing forest composition may also reduce habitat for these species. Scientific and traditional ecological knowledge both support the idea that orchids do not tend to co-exist with sugar maple, so a conversion to a maple-dominated forest in these ravines (prompted by hemlock wooly adelgid or deer browse) could be a concern for orchids.

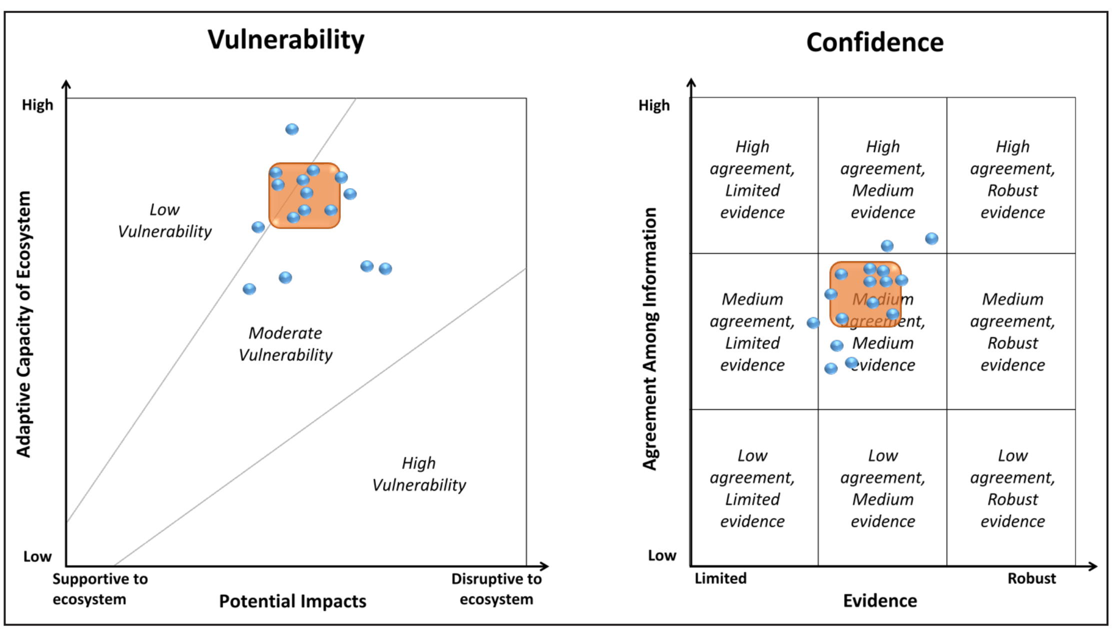
Stressors: As heavy rains cause more erosion, slumping, and sedimentation in Apostle Islands ravines, invasive species may have more opportunities to colonize exposed soil. Heavy rain events could also transport invasive species from upland areas on the mainland to ravines on the mainland unit of the Apostle Islands National Lakeshore. Reduced snowpack could also lead to increased deer browse, particularly in ravines on the mainland and some island areas that are not protected by steep terrain.

Adaptive Capacity: High

Deep ravines may continue to provide cooler conditions than the surrounding landscape, because they are shaded by a dense forest canopy and will continue to experience cold-air drainage. These locations will also be slower to dry out than adjacent uplands, and groundwater seepage will likely persist unless exceptional drought conditions occur in the future. High species richness increases the adaptive capacity of these forests. Similarly, the complex terrain with many microsites offers a variety of conditions for species to find suitable locations. Ravines

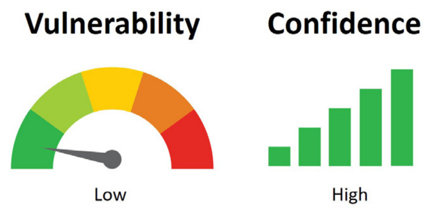
A small stream in a forested ravine.

with different aspects offer even more variety, although north-facing ravines may be more buffered from change. Some Apostle Islands ravines have acted as refugia for rare species over time. Conversely, these ecosystems are confined to deep ravine locations and they are unlikely to expand to new habitats within the Apostle Islands.



Vulnerability and confidence determinations for the Deep Ravine Forests ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Erodible Maritime Bluffs



Vulnerability: Low

Confidence: High

This widespread, generalist ecosystem is adapted to tolerate frequent disturbance, so intensified impacts from waves, storms, and freeze-thaw events are not particularly concerning.

Apostle Islands Erodible Maritime Bluffs occur on about half of the coastline of all islands, and they feature a mostly generalist vegetation community on constantly eroding clay or loamy sand. See Chapter 1 for a more complete description.

Potential Impacts: Moderate-Supportive

Drivers: Several factors could cause increased erosion of Apostle Islands bluffs. Larger waves, higher lake levels, stronger storms, heavier precipitation events, and more freeze-thaw events during winter could all lead to more steady erosion as well as large-scale erosion events. Ice scour may become less frequent as lake ice continues to decline, but that may also expose maritime bluffs to more wave action and storms in the winter months.

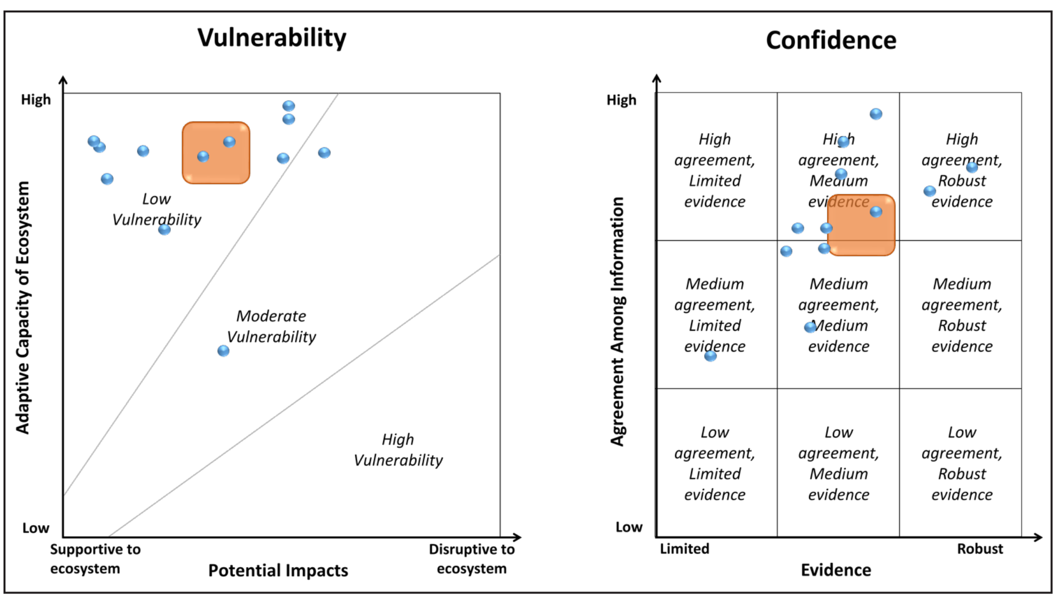
Key Species: The vegetation community within this ecosystem is not particularly specialized, and these bluff ecosystems are defined more by the landform and disturbance processes than a particular species composition. Species that occur on Apostle Islands bluffs tend to be generalists that can colonize bare soil and tolerate maritime microclimates – alder species, willow species, raspberry, juneberries, Canada wild rye, Canada blue grass, clover, fireweed, and aster species. These species are not expected to be greatly stressed by future climate conditions in bluff ecosystems. Rare species such as grass-of-Parnassus on Outer Island or elegant groundsel on Rocky Island could be negatively affected by droughty conditions if fog, seepage, or wave spray are reduced. Trees are not a defining characteristic in this ecosystem, so suitable habitat projections for tree species were not a deciding factor in the determination.

Stressors: Increased soil disturbance from erosion, longer growing seasons, and milder winters could lead to more opportunities for invasive species to colonize coastal bluffs in the Apostle Islands. Bluffs on the mainland have a higher likelihood of being invaded than island bluffs. Species such as crown vetch (*Coronilla varia*), large-leaved lupine (*Lupinus polyphyllus*), bird's foot trefoil (*Lotus corniculatus*), spotted knapweed, and valerian are particularly concerning in the Apostle Islands.

Adaptive Capacity: High

This is a highly dynamic ecosystem that depends on near-constant erosion and disturbance, so increased erosion from heavy precipitation may actually support the ephemeral nature of this ecosystem. While bluff ecosystems are confined to particular locations and landforms, they are common and widespread in the Apostle Islands. Their proximity to Lake Superior may also buffer future temperature increases, and moisture should usually be available from precipitation, seepage, fog, or wave spray. Additionally, this ecosystem features a relatively small biotic community that tends to be composed of opportunistic species which are readily dispersed by wind or birds. This means newly exposed soils are likely to be colonized quickly.

Apostle Islands bluffs are continually eroding and changing. NPS PHOTO/P. BURKMAN



Vulnerability and confidence determinations for the Erodible Maritime Bluffs ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Great Lakes Pine Forests and Barrens

Vulnerability: Low

Confidence: Moderate

This rare ecosystem could benefit from warmer, drier conditions and increased fire frequency, although limited risks exist from forest pests and diseases, non-native species, and trampling.

Apostle Islands Great Lakes Pine Forests and Barrens encompass a gradient of stabilized dunes to closed-canopy forest, based on landform and disturbance frequency. They are limited to sandy, droughty soils. See Chapter 1 for a more complete description.

Potential Impacts: Moderate-Supportive

Drivers: Great Lakes Pine Forests and Barrens occur on sandy, droughty soils, and may be able to tolerate the projected shift toward drier conditions. Wildfires may become more frequent under climate change, and the fire season may extend earlier and later into the growing season. Blowdown events or pest and disease outbreaks could also provide more fuel buildup for fires. Greater wildfire activity could benefit these forests, but it is possible that too much change to the fire regime would hamper regeneration. Rising lake levels could lead to tree mortality in low-lying areas if the lake remains high for an extended duration.

Key Species: The characteristic tree species in Great Lakes Pine Forests and Barrens are generally expected to tolerate future climate conditions. Red pine, jack pine, and northern pin oak are projected to maintain stable suitable habitat in the local area, and white pine is projected to have slightly more suitable habitat by the end of the century. Locations with extensive lichen or moss ground cover may be vulnerable to desiccation from prolonged drought, warmer temperatures, and stronger, warmer winds.

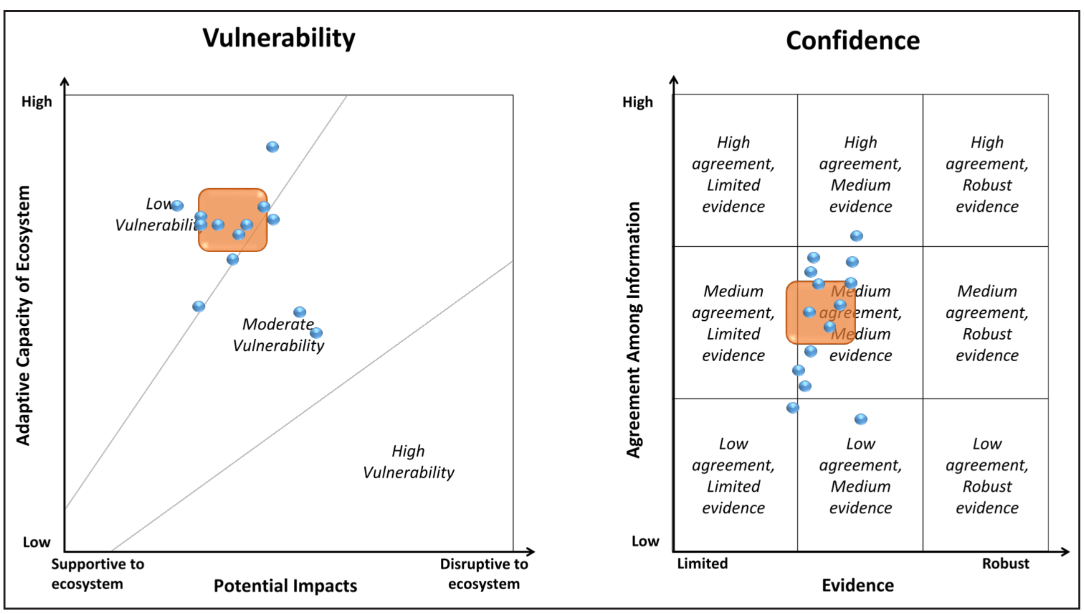
Stressors: Invasive species such as spotted knapweed may have more opportunity to occupy territory in backdunes and barrens with increased disturbance, milder winters, and longer growing seasons. Forest pests such as native and non-native bark beetles may become more damaging under climate change, particularly if outbreaks occur while trees are stressed by drought or other factors. If visitation rates to the Apostle Islands increase and visitation occurs over a longer period, human-caused trampling may become more frequent and damaging to lichen species.

Adaptive Capacity: Moderate-High

Great Lakes Pine Forests and Barrens are tolerant of drought and high winds, as well as sandy, low-nutrient conditions. Few species are able to thrive in these difficult conditions, which makes it less likely that new species will be able to encroach into these habitats. Drier conditions may make these locations less hospitable for mesic species such as balsam fir. Red pine and white pine are long-lived and regenerate well after fire. Additionally, this general ecosystem category includes a range of canopy cover from closed-canopy forests to sparsely forested barrens, so small canopy cover changes would not constitute a meaningful identity change. Pine Forests and

Great Lakes Pine Forest and Barrens on Stockton Island. NPS PHOTO/P. BURKMAN

Barrens occur on multiple islands within the park, which makes it less likely that a single disturbance would affect the entire ecosystem. Conversely, this ecosystem is rare across the larger region, and the Apostle Islands is one of very few known locations.

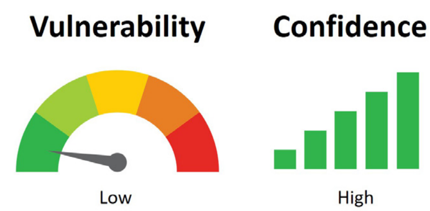


Vulnerability and confidence determinations for the Great Lakes Pine Forest and Barrens ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Interior Alder Thickets

Vulnerability: Low

Confidence: High



This highly adaptable ecosystem is tolerant of water table changes and the dominant species are expected to persist under warmer conditions.

Apostle Islands Interior Alder Thickets occur on sites with moving water and seasonal water table fluctuation. They can be persistent communities or a transitional state between forest and wetland. See Chapter 1 for a more complete description.

Potential Impacts: Moderate-Supportive

Drivers: Interior Alder Thickets require seasonal water table fluctuation to reduce competition from both tree species and marsh species. Climate change has the potential to disrupt this balance. Heavy precipitation events could cause extended inundation that would lead to conversion to open marsh and wetland habitats, while drier conditions could allow tree species (ash and others) to gradually encroach into these areas. Large rain events may also lead to increased sedimentation and nutrient inputs from upland areas.

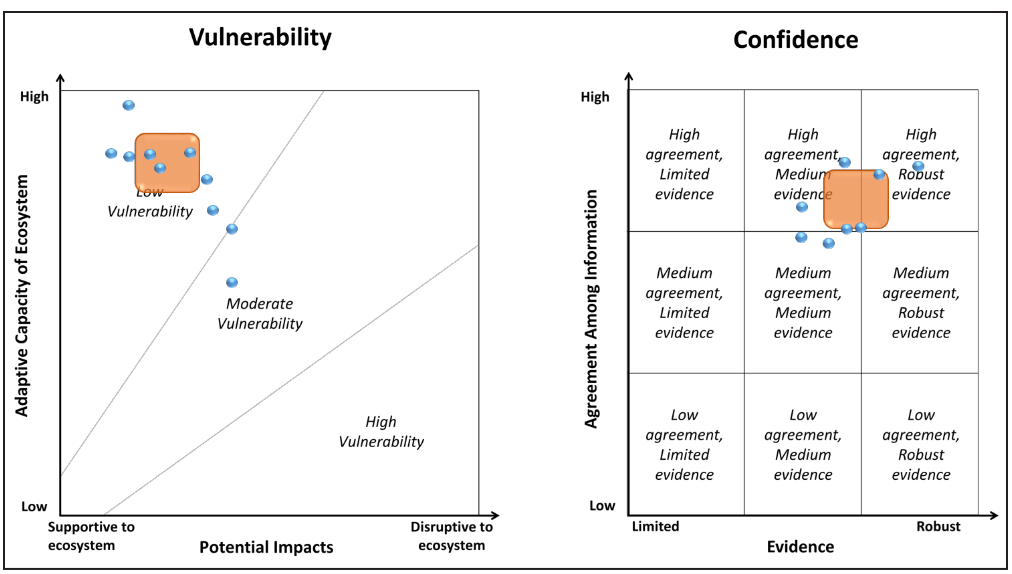
Key Species: Speckled alder (or “tag” alder) is dominant in this ecosystem, and it is generally tolerant of warmer temperatures. This is not a climate-constrained ecosystem because the species that characterize alder thickets—including alder, ninebark, and multiple willow species—occur much further south into Wisconsin and Illinois.

Stressors: Invasive species are not currently a major risk in this ecosystem, but they are the primary risk for future disruption. Eurasian buckthorn, purple loosestrife, and reed canary grass could all benefit from more frequent disturbances, milder winters, nutrient deposition, sedimentation, and longer growing seasons. Changing inundation levels could also benefit some invasive species while also stressing or killing alder stands.

Adaptive Capacity: High

Interior Alder Thickets can be a transitional or early-successional ecosystem that is tolerant of short-term water level changes. High species richness increases the adaptive capacity of this ecosystem. More wind or fire disturbance in moist forested areas could allow this ecosystem to expand to new locations within the Apostle Islands. Similarly, warmer, drier conditions could allow alder thickets to expand into peatlands or fens. Beaver activity tends to create habitat for alder thickets in the Apostle Islands, even though beaver dams may also lead to inundation and drowning of some alder stands. This ecosystem is already widespread across the Apostle Islands, and there are numerous seasonally wet locations and landforms that could support alder thickets under changing conditions.

Alder thickets on Long Island.



Vulnerability and confidence determinations for the Interior Alder Thickets ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Interior Peat Swamps and Bogs

Vulnerability: Moderate

Confidence: Moderate

Vulnerability

Moderate

Confidence

Moderate

Higher or lower water table fluctuations could disrupt this ecosystem, and it is unclear if the cool, wet conditions in these locations will be a sufficient buffer against continued temperature increases.

Apostle Islands Interior Peat Swamps and Bogs are mostly confined to poorly-drained summit plateaus, featuring vegetation that tolerates peat substrates and water that is acidic, cool, and low in oxygen. See Chapter 1 for a more complete description.

Potential Impacts: Disruptive-Moderate

Drivers: Interior Peat Swamps and Bogs in the Apostle Islands tend to have limited or no groundwater connection, and are therefore dependent on precipitation for water and nutrient inputs. This ecosystem depends on a relatively narrow range of water table conditions and can respond in a matter of years to water table changes. Higher water levels could result in a transition to open peatland systems, which could occur with increased precipitation and heavy rainfall events. Lower water levels and warmer conditions would cause peat layers to dry and decompose, which would change the water and soil chemistry and allow a conversion to other ecosystem types. On-going atmospheric nitrogen deposition or increased nutrient inputs from heavy rain events may also increase decomposition rates in this ecosystem.

Key Species: *Sphagnum* mosses are keystone species in this ecosystem, as they retain moisture and reduce soil and water pH. Prolonged dry conditions pose a bigger risk for *Sphagnum* than warming alone, although there is high uncertainty about what conditions would lead to a state change prompted by sphagnum decline. Black spruce is projected to have slightly reduced suitable habitat under a range of future climate conditions, while tamarack, eastern white pine, and paper birch are all projected to have stable or slightly increased suitable habitat. Eastern white pine and paper birch in particular might benefit from slightly drier conditions and become more common in peat swamps and bogs, as would ericaceous shrubs like leatherleaf and bog rosemary.

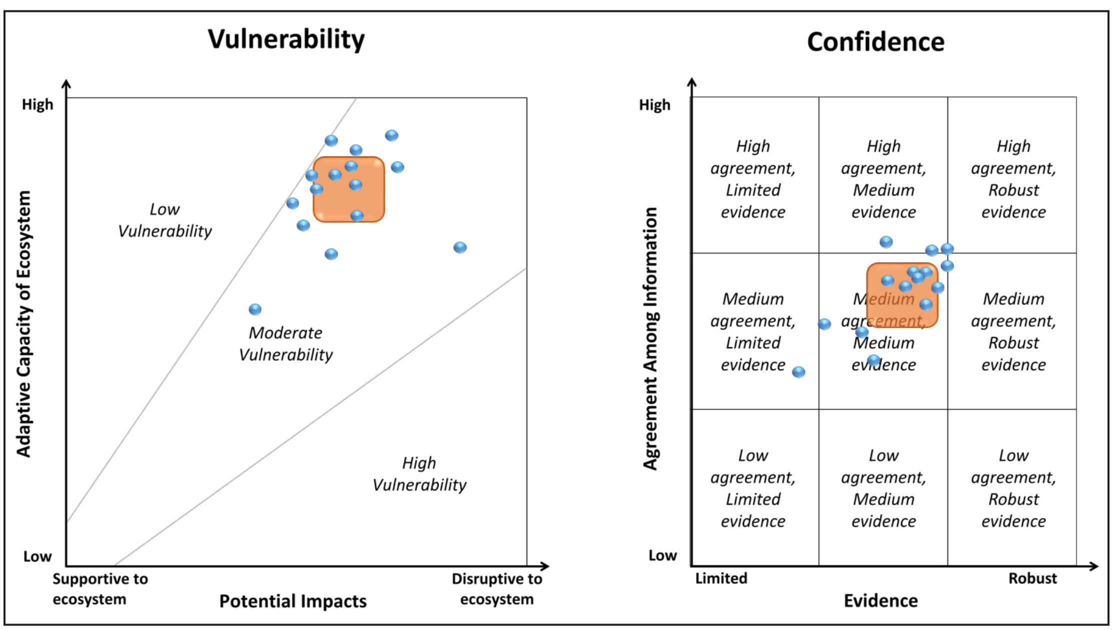
Stressors: Increased wildfire frequency and severity could be disruptive in peatlands, particularly if they occur during extended droughts. Forest pests such as eastern larch beetle, tamarack sawfly, and spruce budworm could become more damaging under climate change, as milder winters may increase larval survival and allow outbreaks to grow more rapidly. Non-native invasive species such as reed canary grass, Eurasian buckthorn, and honeysuckle could have more opportunity to colonize peat ecosystems in the Apostle Islands if sphagnum declines and these systems become less acidic, and if decomposing peat releases more available nutrients.

Adaptive Capacity: High

This ecosystem currently occurs in small, isolated locations across the Apostle Islands, and it is unlikely to expand to new areas under future climate conditions. Peat swamps exist in perched depressions that are likely to retain water in the future, however. The species that occur in this ecosystem are also very good at conserving moisture,

Bog on Sand Island. © S. Johnson/Northland College

making them less vulnerable to seasonal declines in water availability. Sphagnum mosses hold water well so these systems may be able to persist through dry spells and even multi-year droughts. Deep sphagnum layers can also insulate tree roots from warming temperatures. As long as acidic, nutrient-poor conditions persist, many species will be prevented from encroaching into this ecosystem.

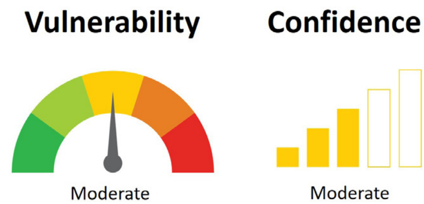


Vulnerability and confidence determinations for the Interior Peat Swamps and Bogs ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Mixed Conifer Hardwoods

Vulnerability: Moderate

Confidence: Moderate



Diverse species composition, dense canopy cover, and moist conditions may help this ecosystem cope with impacts from forest pests, invasive species, and drier conditions.

Mixed Conifer Hardwoods is the dominant forest type that covers approximately 85% of the Apostle Islands. Clay till soils on gentle slopes provide consistent moisture and nutrients, and a dense, multi-aged forest with abundant Canada yew understory develops in the absence of widespread disturbances. See Chapter 1 for a more complete description.

Potential Impacts: Moderate

Drivers: The widespread "matrix" forest in the Apostle Islands depends on consistent soil moisture conditions. Climate change could disrupt this ecosystem as warmer temperatures, longer growing seasons, increased winds, and precipitation declines interact to create drier conditions. Stronger winds and storms may result in more canopy gaps, but this is already the typical disturbance event in mixed conifer forests. With extended drought, less snowpack, and warmer conditions this ecosystem could become susceptible to wildfire, but it seems unlikely that wildfires would affect a substantial portion of the landscape.

Key Species: Sugar maple, yellow birch, balsam fir, northern white-cedar, and mountain maple are projected to have slight declines in suitable habitat by the end of the century. Conversely, red maple, paper birch, American basswood, northern red oak, eastern white pine, and eastern hemlock are expected to have stable or slightly increasing suitable habitat. The maritime conditions in the Apostle Islands are expected to moderate some of the projected suitable habitat declines, and more disturbance could actually benefit early-successional species like paper birch, balsam fir, and mountain maple. Canada yew occurs as far south as Kentucky in sheltered microclimates, so this species may be able to tolerate warmer conditions as long as deer browse pressure remains low.

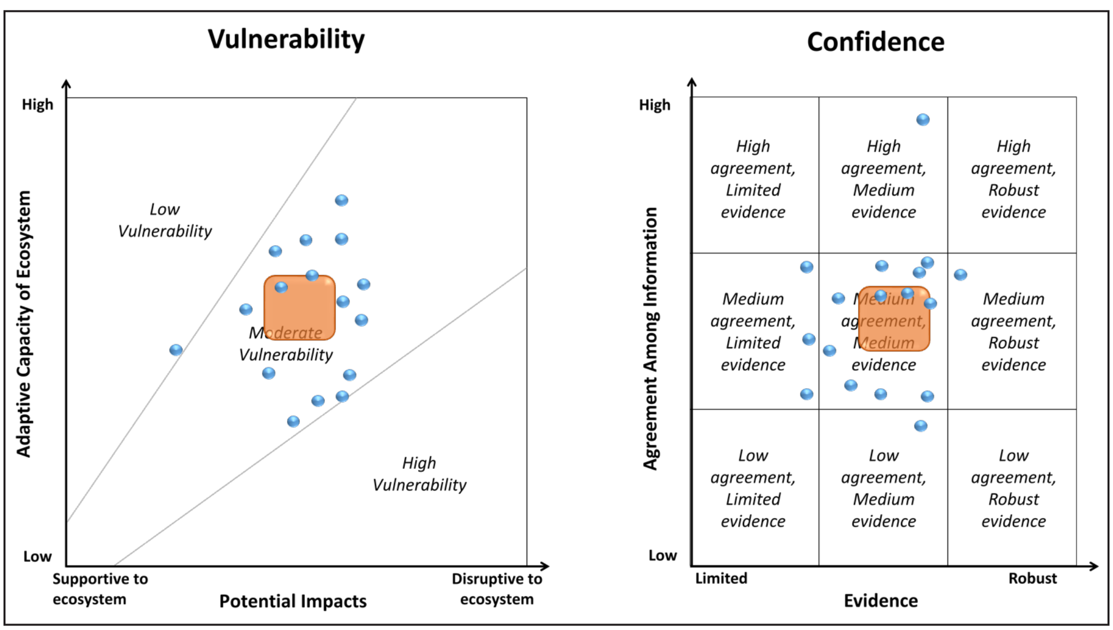
Stressors: Apostle Islands forests may experience more damage from insect pests such as gypsy moth, spruce budworm, and emerald ash borer under future climate conditions, as milder winters may increase larval survival and allow outbreaks to grow more rapidly. Stressed trees may also be more susceptible to pest and disease outbreaks. Invasive understory species such as garlic mustard are currently limited by dense Canada yew cover, but canopy gaps from blowdown events, areas without yew, and recreational sites could be introduction sites for invasive species. Deer herbivory may have a larger effect on regeneration of canopy trees and Canada yew if deer populations increase with milder winters. Deer are more disruptive within Zone 2 of Apostle Islands National Lakeshore (mainland unit and some islands with higher deer densities). Nonnative earthworms are prevalent on the mainland and occur on some islands; they consume litter layers and may increase drought risk while exposing soil for non-native plants.

Adaptive Capacity: Moderate

High species and structural diversity improve the adaptive capacity of this ecosystem. Mixed Conifer Hardwoods typically have large amounts of coarse woody debris, dense

Mixed conifer hardwoods with a dense understory of Canada yew on Raspberry Island.
NPS PHOTO/P. BURKMAN

canopy cover, and intact litter layers. Each of these characteristics helps this ecosystem retain soil moisture during intermittent dry periods. The clay soils and flat or undulating terrain throughout much of the Apostle Islands helps these ecosystems retain water. Although similar forests have been altered substantially throughout much of the region, the protected status of Apostle Islands and the isolation from deer and other stressors has maintained the resiliency of this ecosystem. This ecosystem is common and widespread throughout the park.



Vulnerability and confidence determinations for the Mixed Conifer Hardwoods ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Rock Cliffs and Ledges

Vulnerability: Moderate-High

Confidence: Moderate

Potential declines in rare arctic disjunct species would be a significant change for this ecosystem, which could be triggered by warmer, drier conditions and more intense erosion.

Rock Cliffs and Ledges occur on exposed sandstone shorelines throughout the Apostle Islands. Vegetation communities in these locations are exposed to fog, waves, ice scouring, and freeze-thaw expansion. See Chapter 1 for a more complete description.

Potential Impacts: Disruptive-Moderate

Drivers: Rock Cliff ecosystems receive consistent moisture from groundwater seepage, fog, splash pools, and wave spray. Desiccation could be a risk to cliff vegetation if extended droughts reduce groundwater seepage, if warmer conditions increase evaporation, or if lake levels drop substantially. However, it seems likely that there will always be moisture to support some plant life in these locations. Although ice scour may occur less frequently as lake ice declines, Rock Cliffs and Ledges may experience more erosion from increased winds, more powerful storms and waves, and more frequent freeze-thaw events.

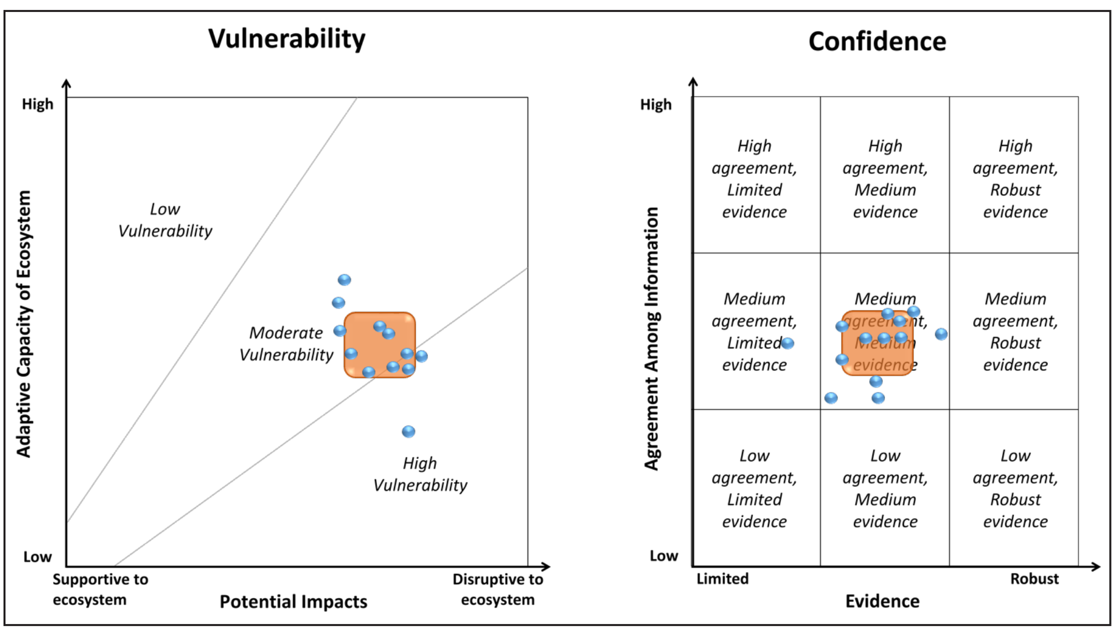
Key Species: North-facing cliffs in the Apostle Islands often contain rare arctic disjunct species such as butterwort, spike trisetum, and bird's-eye primrose. Warmer conditions and lower lake levels may cause declines for these species, while high lake levels have historically benefited these species. Losing these arctic disjunct species would result in a substantial change in character for this ecosystem. Other common species on Rock Cliffs and Ledges tend to be common in the region—several mosses and lichens, fireweed, strawberry, and pearly everlasting. Trees are not a defining feature of this ecosystem, so suitable habitat projections for tree species did not factor into the vulnerability conclusion.

Stressors: Dandelion, yarrow, non-native grass species, and other weedy species have the potential to colonize on ledges, fractures, or other locations that collect mineral soil. This is a limited risk because there is not much growing space in this ecosystem, but the risk may increase as winters become milder and growing seasons extend.

Adaptive Capacity: Moderate

Although it has generally been observed that cooler places on the landscape have tended to warm faster than warm places on the landscape, it is still expected that the close proximity of Lake Superior and the maritime conditions will slow the rate of change for this ecosystem. North-facing cliffs in the Apostle Islands may be the most sheltered and buffered from temperature change, as they have acted as refugia during past periods of climate change. This ecosystem occurs in very limited locations, however, and is unable to expand to new locations. This ecosystem includes several species near the southern edge of their ranges, but they are adapted to exist in a harsh, exposed habitat that may limit potential competitors.

Sandstone forms rock ledges on many of the islands.© S. Johnson/Northland College

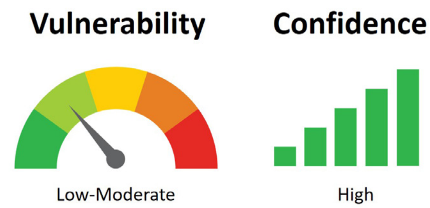


Vulnerability and confidence determinations for the Rock Cliffs and Ledges ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Upland Hardwood Forests

Vulnerability: Low-Moderate

Confidence: High



These forests may be exposed to drier conditions, canopy disturbance, invasive species, and elevated wildfire risk under climate change, but any composition changes are not expected to be dramatic.

Apostle Islands Upland Hardwood Forests occur in higher-elevation portions of the park, which have more well-drained soils than the majority of the landscape. Canada yew is less prevalent in this forest type than in the Mixed Conifer Hardwoods, which leads to a more diverse understory. See Chapter 1 for a more complete description.

Potential Impacts: Moderate

Drivers: Climate change could result in more drought stress for this ecosystem as warmer temperatures, longer growing seasons, increased winds, and precipitation declines interact to create drier conditions. Upland Hardwood Forests exist on more loamy or sandy soils and in higher, better-drained locations than the widespread mixed conifer-hardwood "matrix" forests, and therefore these locations could experience more rapid soil drying under future conditions. High wind events may create more canopy gaps, particularly in upland areas exposed to prevailing winds. Lightning strikes may be more frequent at higher elevations, and combined with higher winds and drier conditions it is possible that wildfire may become a more regular disturbance in Upland Hardwood Forests.

Key Species: Northern red oak, red maple, paper birch, American basswood, eastern white pine, and eastern hemlock are projected to have small increases in suitable habitat or to change only slightly. Sugar maple, yellow birch, balsam fir, and northern white-cedar are projected to decline in suitable habitat by the end of the century. These shifts raise the possibility for this forest type to gradually convert from a mesic to dry-mesic mix of species, dominated by northern red oak and red maple. Northern red oak is generally sensitive to spring frosts, but this concern may be moderated by the influence of Lake Superior. Canada yew is less dominant in this drier upland forest ecosystem, and therefore this ecosystem has a more diverse herbaceous understory.

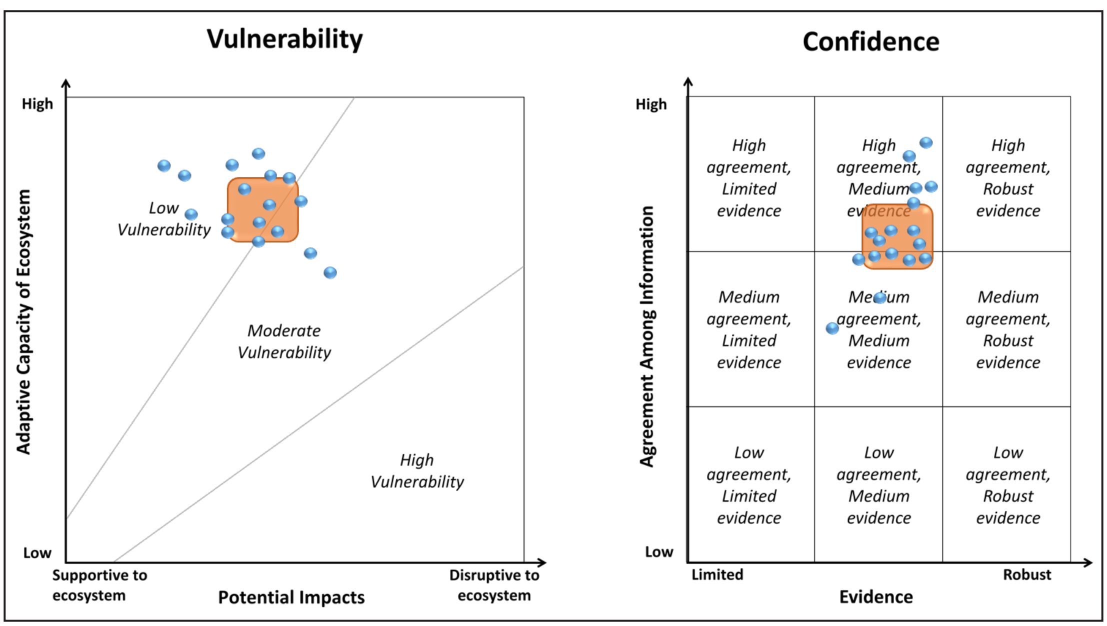
Stressors: Invasive understory species such as garlic mustard and Eurasian buckthorn are more of a concern in Upland Hardwood Forests because of lower Canada yew cover, particularly as human "vectors" increase visitation. Upland Hardwood Forests may experience more damage from insect pests such as two-lined chestnut borer, gypsy moth, and forest tent caterpillar under future climate conditions, as milder winters may increase larval survival and allow outbreaks to grow more rapidly. Pest outbreaks may be more damaging if forests are already stressed by drought. Oak wilt is not currently present in the Apostle Islands, but this disease may affect red oaks under future conditions. Deer herbivory is not a current stressor in this ecosystem, but deer may have a larger effect on forest regeneration if mainland populations increase with milder winters.

Adaptive Capacity: Moderate-High

This ecosystem is adapted to tolerate drier conditions than the widespread "matrix" forest, so it is possible that Upland

Upland hardwood forest with dense regeneration.
NPS PHOTO/P. BURKMAN

Hardwood Forests will be able to gradually expand into new areas that become too dry for Mixed Conifer Hardwoods. These diverse forests have many species that could thrive under future conditions. There is currently good regeneration of several tree species within this ecosystem because of lower deer populations, and therefore any composition changes are unlikely to be dramatic. Upland Hardwood Forests have less coarse woody debris and less litter than mixed conifer forests, however, so they are less able to retain moisture during droughts.



Vulnerability and confidence determinations for the Upland Hardwood Forest ecosystem. Circles indicate individual determinations by each vulnerability assessment workshop panelist and squares indicate the group determination after consensus was reached.

Conclusion

Overall, it appears that most of the terrestrial ecosystems in the Apostle Islands have low or moderate vulnerability to climate change over the next century. This does not directly translate to the overall degree of impact that the park will experience, because many of these ecosystems occupy a relatively small land area but may feature iconic vegetation or be culturally important (e.g. Great Lakes Pine Forests and Barrens, or Coastal Wetlands). Additionally, an ecosystem with moderate vulnerability to climate change may still end up experiencing substantial effects. It is generally expected that ecosystems that are adapted to a narrow range of conditions or that exist near their range limits will be more vulnerable to changing conditions. Ecosystems occurring in isolated locations may also be less able to migrate to suitable locations. Boreal Forests, Coastal Wetlands, and Rock Cliffs and Ledges are the most vulnerable ecosystems in the park, largely for these reasons. Communities with higher plant diversity or that are adapted to tolerate disturbances are expected to be better able to persist under a range of plausible climates. For example, Beaches and Dunes, Deep Ravine Forests, Erodible Maritime Bluffs, Great Lakes Pine Forests and Barrens, Interior Alder Thickets, and Upland Hardwood Forests were all rated low or low-moderate vulnerability.

These vulnerability determinations only represent general expectations, because even across the limited geography of the Apostle Islands there is considerable variability. It is essential to consider local characteristics such as past management history, soils, topographic features, species composition, deer levels, visitation patterns, and recent disturbances when applying these general vulnerabilities to local scales. Some site-level factors may amplify these expected vulnerabilities, yet others may buffer the effects of climate change. Therefore, local knowledge and management experience will be critical for identifying particular sites in the Apostle Islands that may have higher or lower vulnerability to climate change.

Fall colors crown a section of sandstone cliff shoreline. NPS PHOTO/M. BURKMAN

Chapter 5: Conclusion

The Apostle Islands National Lakeshore has experienced dramatic changes through time. Chapter 1 briefly describes how the Apostle Islands ecosystems have been shaped by this dynamism. Previous warm and cold eras have come and gone, and Lake Superior has risen and fallen. Indigenous people lived in and managed these lands for millennia, followed by roughly a century of intense disruption and extraction following European settlement. Human influence in the Apostle Islands has been more limited for the 50 years following designation as a national park.

Now climate change is adding a new context of change and unpredictability, as the park experiences unprecedented conditions throughout this century and beyond. Chapter 2 of this assessment describes observed and anticipated climate trends in the local area and the larger region, and Chapter 3 provides a summary of the major potential impacts to the park's terrestrial ecosystems.

Vulnerability Conclusions

Ecosystems of the Apostle Islands will be affected by climate change, although the specific effects may be complex and variable across the park. The vulnerability determinations in Chapter 4 represent the best understanding of local experts regarding ecosystem vulnerability and potential ecological changes over the next century. Overall, we expect ecosystems that are adapted to a narrow range of conditions or that exist near their geographical range limits to be more vulnerable to changing conditions (Boreal Forests, Coastal Wetlands, and Rock Cliffs and Ledges, in particular). Communities with higher plant diversity or that are adapted to tolerate disturbances are expected to be better able to persist under a range of plausible climates (Beaches and Dunes, Deep Ravine Forests, Erodible Maritime Bluffs, Great Lakes Pine Forests and Barrens, Interior Alder Thickets, and Upland Hardwood Forests). Site-specific conditions and land-use history may increase or decrease climate change vulnerability from location to location within the park.

Uncertainty

This assessment relies upon current information from the scientific literature, locally-specific ecosystem modeling results, and the input of a large team of local experts. Even so, there are limitations and unknowns involved in drawing conclusions about the effects of climate change on the ecosystems of the Apostle Islands during the coming century. This assessment has endeavored to be transparent about knowledge gaps and uncertainties that limit our understanding. Chapter 3 contains summaries of key uncertainties related to the major potential climate change impacts in the park. The vulnerability determinations in Chapter 4 also include statements about the confidence of the authors in each conclusion. As authors considered this information during the expert panel workshop and in subsequent conversations, we attempted to describe the range of potential outcomes associated with these uncertainties and characterize how the various ecosystems might be affected across that range. As a brief recap, some of the major uncertainties discussed in this assessment include:

Lake Superior levels: Will climate change lead to more extended periods or record events of low or high lake levels?

Lake Superior temperature: How long will Lake Superior continue to provide a cooling "buffer" to moderate against warmer conditions?

Shoreline disturbance processes: Will intensifying wave and wind disturbance to beaches and dunes cross a threshold that upsets the natural equilibrium of erosion and deposition? Similarly, will increasing disturbance disrupt coastal wetlands beyond what they are able to tolerate? How will these factors interact with on-going isostatic rebound?

Wildfire: Will drier conditions lead to more widespread or frequent fires across the Apostle Islands, and will more fire change ecosystem regeneration patterns?

Forest regeneration and disturbances: Will new climate conditions affect the ability of the various forest ecosystems to regenerate after disturbances such as pest outbreaks, wind events, or fires? Will increasing wind speeds over the lake result in more blowdown, drying of dead woody debris, and shift the dominant disturbance regime from wind to more fire?

Deer populations: Will milder winters promote larger deer populations within the Apostle Islands?

Herbaceous species, particularly rare plants: Will future climate conditions surpass the tolerable thresholds for keystone herbaceous species such as dune grass or sphagnum moss, or iconic species such as rare orchids or arctic disjunct species? How will relatively isolated island locations influence species dispersal?

Invasive species, pests, or diseases: How will climate change influence invasive species colonization and establishment? Will climate change facilitate the establishment of new insect pests or diseases that could affect native ecosystems in the Apostle Islands?

Visitation patterns: How will visitor use patterns change in response to shifting climate conditions locally and regionally?

As new information becomes available, staff at the Apostle Islands National Lakeshore may wish to revisit or supplement this assessment.

Supplemental Questions

Through the process of completing this assessment, it was possible to consider the supplemental questions posed by National Park Service managers. Below, we provide summary answers based on the information presented in different sections of the assessment.

Question 1: How vulnerable to climate change are rare and character-defining terrestrial features and natural communities of the park, specifically sandscapes and boreal, krummholz, and old-growth forests? How vulnerable are iconic species, including eastern hemlock, yellow birch, northern white-cedar, and Canada yew? And how does the park's island setting influence these vulnerabilities?

The island context of the park is a critical factor to consider when assessing the vulnerability of these features to climate change. During the expert panel workshop, our conclusions about climate change vulnerability often hinged on the group's understanding of how ecosystems in the Apostle Islands might differ from those found on the mainland, and how climate change effects might be modified in some way by the park's local context. This report examined the climate change vulnerability of Beaches and Dunes (low-moderate) and Boreal Forests (moderate-high) in particular, and readers can refer to Chapter 4 for a more complete discussion of those systems. Similarly, Chapter 3 of this assessment includes results of forest impact models for individual tree species within a relatively small geographic area around the Apostle Islands (1 degree latitude × 1 degree longitude). Of the species mentioned specifically in this question, yellow birch and northern white-cedar are expected to experience a small decline in suitable habitat over the next century, and suitable habitat for eastern hemlock is not expected to change significantly. Canada yew is expected to decline across Wisconsin, as the projected future suitable climate range of the species overlaps with the current range by only 7% (Spalink et al. 2018). These species may be expected to perform better within the Apostle Islands than on the mainland, because they are currently regenerating well and deer herbivory will likely be less of an issue than on the mainland.

This assessment did not attempt to determine the climate change vulnerability of krummholz or old-growth forests. This is because park managers decided early in the process that these features are special growth forms or successional stages, but they are not necessarily distinct ecosystems

in and of themselves. It is reasonable to expect that old-growth forests in the Apostle Islands may look different in the future if pest outbreaks and other disturbances occur more frequently or with greater intensity under climate change. Barring a large-scale, stand-replacing disturbance, old-growth forests in the Apostle Islands will retain a more complex, multi-aged growth form.

Question 2: Could the park serve as an important refugium for some terrestrial plant species or community types?

The Apostle Islands hosts more plant species with narrow distributions than anywhere else in Wisconsin (Spalink et al. 2018), including several arctic disjunct species. This suggests that it has been and is currently functioning as a climate refugium (Morelli et al. 2016). Similarly, the Apostle Islands contain plant species that are much less common on the mainland, such as Canada yew. So the Apostle Islands are clearly also acting as a refugium from certain kinds of ecosystem disturbances, such as deer herbivory.

It is interesting to compare the vulnerability determinations in this assessment to the conclusions from a larger, regional assessment of climate change vulnerability (Janowiak et al. 2014). Judging between relatively similar mainland ecosystems that were considered under a similar assessment process, ecosystems in the Apostle Islands were rated as less vulnerable to climate change by the end of the century (Table 6). The relatively lower climate vulnerability rating was in most cases based on the anticipated continuation of the milder, maritime climate in the Apostle Islands, along with less anthropogenic disturbance as compared to the mainland.

As noted in Chapter 3, there are several key uncertainties that will determine whether the Apostle Islands will continue to serve as a climate refugium. It remains to be seen how quickly Lake Superior will warm and how the maritime climate patterns may shift over the coming decades.

Question 3: Will Lake Superior function as a barrier to northward migration of species, and what are the implications?

It is reasonable to conclude that Lake Superior will continue to function as a barrier to northward range expansion of some species. Looking at the list of tree species that are anticipated to have newly available suitable habitat in the Apostle Islands by the end of the century, several have large seeds that would be less likely to disperse across open water, such as hickory and oak species (Chapter 3). Wind-carried and bird-dispersed plants, however, may be able to colonize the islands as plant communities change on the mainland. Plants with larger seeds that are expected to increase in suitable habitat on the mainland will likely not reach the islands without intentional management intervention.

Table 6. A comparison of climate change vulnerability determinations for Apostle Islands forest ecosystems and for forest ecosystems across the larger landscape of mainland northern Wisconsin and western Upper Michigan (Janowiak et al. 2014). Vulnerability determinations were based on a similar expert elicitation process and similar available information, albeit with different panel members.

Apostle Islands Ecosystem	Vulnerability	Comparable Mainland Forest Ecosystem	Vulnerability
Boreal Forests	Moderate-High	Upland spruce-fir	High
Great Lakes Pine Forests and Barrens	Low	Jack pine	Moderate
		Red pine	Moderate-High
Interior Peat Swamps and Bogs	Moderate	Lowland conifer	High
Mixed Conifer Hardwoods	Moderate	Northern hardwoods	Moderate
Upland Hardwood Forests	Low-Moderate	Northern hardwoods	Moderate

Question 4: How will increasing lake temperatures and wind speeds alter the natural disturbance regimes in the park? What are the implications for both wind and fire processes?

Chapter 3 summarizes many ways that anticipated changes in temperature, precipitation, wind speed, and other factors may influence disturbance regimes in the Apostle Islands. During the expert panel workshop there was a lot of attention devoted to fire regimes in particular. The experts were not confident that there will be a large increase in wildfire activity across most of the park's acreage. The mixed-conifer hardwoods matrix forest is not expected to have substantially more wildfire, because the relatively flat topography and clayey soils are expected to remain relatively moist in most conditions. Also, the island setting will prevent fires from spreading very far. More fuel buildup due to blowdown events or pest outbreaks could create conditions for stand-replacing fires on individual islands.

The expert panel also discussed how interactions among several factors could change shoreline processes and disturbance from storms and wave action (see Chapter 3). We generally expect that shorelines in the Apostle Islands, including sandscapes, coastal wetlands, erodible bluffs, and rock cliffs, will experience more disturbance from wave action. This may be particularly evident in winter months as the islands are more exposed to strong storms without protective ice cover along the shoreline.

Importance of Monitoring and Assessment

Climate change may prompt rapid or unexpected changes in the park's ecosystems over the next several decades, and therefore monitoring and assessment efforts will be increasingly important. Past and current monitoring campaigns can help establish the baseline conditions for many ecosystems in the park and provide a reference point to gauge future change. Field-based vegetation sampling such as the National Park Service Great Lakes Inventory and Monitoring Program (Sanders and Grochowski 2012), as well as remotely sensed data (Thayn 2013, Kirschbaum et al. 2012) will help track changes through time. Park managers may opt to establish additional monitoring programs specifically designed to assess some of the key uncertainties raised in Chapter 3 of this assessment, such as the cumulative effect of increased disturbance on the extent and character of coastal habitats in the Apostle Islands, and recruitment rates for key species.

Implications Beyond Ecosystem Change

As climate change affects the conditions and ecosystems in the Apostle Islands, it is reasonable to expect that many other valuable resources may also be vulnerable. It is beyond the scope of this assessment to fully consider these implications of climate change, but park managers may wish to examine these further effects.

Wildlife habitat: Changing climate conditions, phenology, and disturbance regimes may reduce suitable wildlife habitat for important wildlife species in the Apostle Islands, such as nesting habitat for the federally endangered piping plover. Recent research suggests how bird species distributions may shift through time, for example (Schuurman and Wu 2018).

Iconic or rare plants: The Apostle Islands are home to several iconic species that are rare on the mainland (e.g. Canada yew) or rare in the entire region (e.g. arctic disjunct species such as butterwort). The Apostle Islands also contain old-growth forests and krummholz forests, which are rare elsewhere in the state and the larger region. If these distinguishing plants and growth stages are affected by climate change, it could change the character of the park.

Aquatic ecosystems: This assessment is focused primarily on terrestrial ecosystems and particularly the vegetation within those ecosystems. The Apostle Islands host an equally impressive diversity of aquatic ecosystems, which are likely to be affected by changing conditions in Lake Superior as well as changes to the uplands in the park.

Cultural resources: The Apostle Islands are valued for their cultural heritage. Ojibwe people continue to reside in the area and maintain long-established relationships with the landscape. Numerous historical sites also reflect the history of European settlement of the area. Stronger storms and changing conditions can disrupt and damage physical sites and buildings, but also expose new archaeological artifacts. Changing phenology or abundance of plants and animals can also affect the relationships that local people have with those beings.

The variety of habitats makes the Apostle Islands a popular destination for birders. NPS PHOTO

Visitor experience: Climate change will likely have numerous consequences for how and when visitors choose to come to the Apostle Islands, with likely increases during the traditional visitation season and a longer overall season. Climate change may also influence visitor experience through changing risks to health and safety.

Park infrastructure: The Apostle Islands National Lakeshore has already begun the process of adjusting physical infrastructure to changing conditions, but climate change may warrant a further and more comprehensive review of the risks to park trails, campgrounds, boat launches, and other facilities.

Adapting to Climate Change

Managers at the Apostle Islands National Lakeshore may decide, based on this assessment and other information, to take action to preemptively reduce climate change vulnerabilities. Further adaptation may also be required as effects of climate change on the park's ecosystems become increasingly apparent in the future. Vulnerability assessments provide information about what resources are vulnerable and why they are vulnerable, but it is a manager's job to use this information, alongside additional considerations, to decide how to proceed. Therefore it is not the role of this assessment to identify adaptation actions.

The National Park Service is developing resources to help park managers incorporate climate change into management decisions, including a library of adaptation resources (National Park Service 2019). Adaptation decision-making processes such as *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers* can also help park managers systematically assess climate change vulnerabilities relative to their management goals, and develop appropriate adaptation actions (Swanston et al. 2016). These planning tools can help managers at Apostle Islands address climate change in a variety of ways, ranging from passive management and monitoring to more intensive actions. Managers may opt to manage to support critical ecosystem functions and on-going natural processes, as opposed to attempting to maintain a particular successional state or vegetation composition. Additionally, adaptation might consist of managing park visitors or upgrading park infrastructure to reduce harmful impacts and maintain safety under future conditions.

Land managers, scholars, and members of the public are asking important questions about the suitability of management interventions to respond to climate change in National Parks, particularly in parks that have a high proportion of designated Wilderness Areas such as Apostle Islands National Lakeshore. A recent review of the federal Wilderness Act found that many active management options are available to manage wilderness areas for climate adaptation, despite the common misconception that active management is prohibited in these areas (Long and Biber 2014). This review highlights situations where wilderness managers may choose to intervene to protect valuable resources and resist climate change effects, as well as situations were managers may choose to intentionally direct change in a system to better accommodate changing conditions. Procedural requirements to demonstrate the necessity of such interventions can function as safeguards to make sure that climate adaptation is designed to help achieve the goals of the Wilderness Act. Wilderness areas such as most of the Apostle Islands National Lakeshore may also serve as important areas to employ passive or restrained management under climate change, in contrast with more aggressive adaptation actions that may be employed on neighboring lands outside the wilderness boundary. Similarly, a recent review of the NPS Organic Act concludes that the National Park Service has sufficient discretion to pursue management options for climate change adaptation (Biber and Esposito 2016).

As managers continue to grapple with these questions, locally relevant information will be essential to help guide their decisions and weigh potential options. We hope that this assessment will provide a useful foundation for park managers, conservation partners, and members of the public who value the Apostle Islands.

A piping plover chick on Long Island. NPS PHOTO/T. GOSTOMSKI

Literature Cited

Abatzoglou, J. T., and T. J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32(5):772–780.

Ackerman, S., A. Heidinger, M. Foster, and B. Maddux. 2013. Satellite regional cloud climatology over the Great Lakes. Remote Sensing 5(12):6223.

Anderson, J. D., C. H. Wu, and D. J. Schwab. 2015. Wave climatology in the Apostle Islands, Lake Superior. Journal of Geophysical Research: Oceans 120(7):4869–4890.

Angel, J., C. Swanston, B. M. Boustead, K. C. Conlon, K. R. Hall, J. L. Jorns, K. E. Kunkel, M. C. Lemos, B. Lofgren, T. A. Ontl, J. Posey, K. Stone, G. Takle, and D. Todey. 2018. Midwest. *In* D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. 21. Washington, D.C., USA: U.S. Global Change Research Program: 872–940. Available at: doi: 10.7930/NCA4.2018

Apostle Islands National Lakeshore. 2014. Harvestable species plan. National Park Service, Bayfield, Wisconsin. Available at: www.nps.gov/apis/learn/management/hwp.htm.

Austin, J., and S. Colman. 2008. A century of temperature variability in Lake Superior. Limnology and Oceanography 53(6):2724–2730.

Austin, J. A., and S. M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophysical Research Letters 34(6):L06604.

Bechle, A. J., C. H. Wu, D. A. R. Kristovich, E. J. Anderson, D. J. Schwab, and A. B. Rabinovich. 2016. Meteotsunamis in the Laurentian Great Lakes. Scientific Reports 6:37832.

Bennington, V., G. A. McKinley, N. Kimura, and C. H. Wu. 2010. General circulation of Lake Superior: Mean, variability, and trends from 1979 to 2006. Journal of Geophysical Research: Oceans. 115(C12). Available at: https://doi.org/10.1029/2010JC006261.

Biber, E., and E. L. Esposito. 2016. The National Park Service Organic Act and climate change. Natural Resources Journal 56(1):193–246.

Bowker, J. M., and A. E. Askew. 2013. Outlook for outdoor recreation in the northern United States. A technical document supporting the Northern Forest Futures Project with projections through 2060. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at: www.fs.fed.us/nrs/pubs/gtr/gtr_nrs120.pdf.

Breckenridge, A. 2013. An analysis of the late glacial lake levels within the western Lake Superior basin based on digital elevation models. Quaternary Research 80(3):383–395.

Briley, L. J., W. S. Ashley, R. B. Rood, and A. Krmenec. 2017. The role of meteorological processes in the description of uncertainty for climate change decision-making. Theoretical and Applied Climatology 127(3):643–654.

Busch, J. C. 2008. People and places: A human history of the Apostle Islands. Unpublished report prepared under contract to the Midwest Regional Office, National Park Service, United States Department of the Interior. Available at: www.nps.gov/apis/learn/

historyculture/upload/historic%20resource%20study.pdf.

Byun, K., and A. F. Hamlet. 2018. Projected changes in future climate over the Midwest and Great Lakes region using downscaled CMIP5 ensembles. International Journal of Climatology 38(S1):e531–e553.

Cherkauer, K. A., and T. Sinha. 2010. Hydrologic impacts of projected future climate change in the Lake Michigan region. Journal of Great Lakes Research 36(SP2):33–50.

Collins, M., R. Knutti, J. Arblaster, J. -L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner. 2013. Long-term climate change: Projections, commitments and irreversibility. Pages 1029–1136 *in* T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, New York. Available at: www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf.

Crausbay, S. D., A. R. Ramirez, S. L. Carter, M. S. Cross, K. R. Hall, D. J. Bathke, J. L. Betancourt, S. Colt, A. E. Cravens, M. S Dalton, J. B. Dunham, L. E. Hay, M. J. Hayes, J. McEvoy, C. A. McNutt, M. A. Moritz, K. H. Nislow, N. Raheem, and T. Sanford. 2017. Defining ecological drought for the twenty-first century. Bulletin of the American Meteorological Society 98(12):2543–2550.

Cronon, W. 2003. The riddle of the Apostle Islands. Orion (May/June):36–42.

Cubasch, U., D. Wuebbles, D. Chen, M. C. Facchini, D. Frame, N. Mahowald, and J. -G. Winther. 2013. Introduction. *In* T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Dawe, K. L., and S. Boutin. 2016. Climate change is the primary driver of white-tailed deer (*Odocoileus virginianus*) range expansion at the northern extent of its range; land use is secondary. Ecology and Evolution 6(18):6435–6451.

Dean, R. G. 1991. Equilibrium beach profiles: Characteristics and applications. Journal of Coastal Research 7(1):53–84.

Desai, A. R., J. A. Austin, V. Bennington, and G. A. McKinley. 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nature Geoscience 2:855.

Dickmann, D. I., and D. T. Cleland. 2002. Fire return intervals and fire cycles for historic fire regimes in the Great Lakes region: A synthesis of the literature (Draft). Great Lakes Ecological Assessment. Available at www.ncrs.fs.fed.us/gla/reports/LSFireCycles.pdf.

Diffenbaugh, N. S., M. Scherer, and R. J. Trapp. 2013. Robust increases in severe thunderstorm environments in response to greenhouse forcing. Proceedings of the National Academy of Sciences 110(41):16361–16366.

Donner, L. J., B. L. Wyman, R. S. Hemler, L. W. Horowitz, Y. Ming, M. Zhao, J. -C. Golaz, P. Ginoux, S. J. Lin, and M. D. Schwarzkopf. 2011. The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. Journal of Climate 24:3484–3519.

Drobyshev, I., M. Flannigan, Y. Bergeron, M. Girardin, and B. Suran. 2010. Variation in local weather explains differences in fire regimes within a Québec south-eastern boreal forest landscape. International Journal of Wildland Fire 19:1073–1082.

Dukes, J. S., J. Pontius, D. Orwig, J. R. Garnas, V. L. Rodgers, N. Brazee, B. Cooke, K. A. Theoharides, E. E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerdau, K. Stinson, R. Wick, and M. Ayres. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Canadian Journal of Forest Research 39(2):231–248.

Fei, L. Y. J. Orsolini, H. Wang, Y. Gao, and S. He. 2018. Atlantic multidecadal oscillation modulates the impacts of Arctic sea ice decline. Geophysical Research Letters 45(5):2497–2506. Available at: https://doi.org/10.1002/2017GL076210.

Fisichelli, N., L. E. Frelich, and P. B. Reich. 2012. Sapling growth responses to warmer temperatures 'cooled' by browse pressure. Global Change Biology 18(11):3455–3463.

Fisichelli, N., and P. S. Ziesler. 2015. Apostle Islands National Lakeshore: How might future warming alter visitation? Park Visitation and Climate Change. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2222466.

Fisichelli, N. A., G. W. Schuurman, W. B. Monahan, and P. S. Ziesler. 2015. Protected area tourism in a changing climate: Will visitation at U.S. national parks warm up or overheat? PLoS ONE 10(6):e0128226.

Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton. 2009. Impacts of climate change on fire activity and fire management in the circumboreal forest. Global Change Biology 15(3):549–560.

Frerker, K., A. Sabo, and D. Waller. 2014. Long-term regional shifts in plant community composition are largely explained by local deer impact experiments. PLoS ONE 9(12):e115843.

Gao, Y., L. R. Leung, L. Jian, and G. Masato. 2015. Persistent cold air outbreaks over North America in a warming climate. Environmental Research Letters 10(4):044001.

Gensini, V., C. Ramseyer, and T. Mote. 2014. Future convective environments using NARCCAP. International Journal of Climatology 34(5):1699–1705. Available at: https://doi.org/10.1002/joc.3769.

Gleason, K. E., J. B. Bradford, A. Bottero, A. W. D'Amato, S. Fraver, B. J. Palik, M. A. Battaglia, L. Iverson, L. Kenefic, and C. C. Kern. 2017. Competition amplifies drought stress in forests across broad climatic and compositional gradients. Ecosphere 8(7):e01849.

GLISA (Great Lakes Integrated Sciences and Assessments). 2019a. Great Lakes Climate Divisions web page. Great Lakes Integrated Sciences and Assessments, Ann Arbor, Michigan. Available at http://glisa.umich.edu/resources/great-lakes-climate-divisions (accessed 16 August 2019).

GLISA (Great Lakes Integrated Sciences and Assessments). 2019b. Lake-effect snow in the Great Lakes region. Great Lakes Integrated Sciences and Assessments, Ann Arbor, Michigan. Available at http://glisa.umich.edu/climate/lake-effect-snow-great-lakes-region (accessed 16 August 2019).

Gronewold, A. D., A. H. Clites, J. P. Smith, and T. S. Hunter. 2013. A dynamic graphical interface for visualizing projected, measured, and reconstructed surface water elevations on the Earth's largest lakes. Environmental Modelling and Software 49:34–39.

Gronewold, A. D., V. Fortin, B. Lofgren, A. Clites, C. A. Stow, and F. Quinn. 2013. Coasts, water levels, and climate change: A Great Lakes perspective. Climatic Change 120(4):697–711.

Gronewold, A. D., and R. B. Rood. 2019. Recent water level changes across Earth's largest lake system and implications for future variability. Journal of Great Lakes Research 45(1):1–3.

Hartmann, H. C. 1990. Climate change impacts on Laurentian Great Lakes levels. Climatic Change 17(1):49–67.

Hawkins, E., and R. Sutton. 2009. The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society 90(8):1095–1108.

Hayhoe, K., J. VanDorn, T. Croley, N. Schlegal, and D. Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. Journal of Great Lakes Research 36:7–21.

Hoogewind, K. A., M. E. Baldwin, and R. J. Trapp. 2017. The impact of climate change on hazardous convective weather in the United States: Insight from high-resolution dynamical downscaling. Journal of Climate 30(24):10081–10100.

Hop, K., S. Menard, J. Drake, S. Lubinski, and J. Dieck. 2010. National Park Service Vegetation Inventory Program: Apostle Islands National Lakeshore, Wisconsin. Natural Resource Report NPS/GLKN/NRR—2010/199. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2124841.

Howk, F. 2009. Changes in Lake Superior ice cover at Bayfield, Wisconsin. Journal of Great Lakes Research 35(1):159–162.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: Synthesis report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R. K. Pachauri, and A. Reisinger, editors. Intergovernmental Panel on Climate Change, Geneva, Switzerland. Available at: www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

Iverson, L. R., A. M. Prasad, S. N. Matthews, and M. Peters. 2008. Estimating potential habitat for 134 eastern U.S. tree species under six climate scenarios. Forest Ecology and Management 254(3):390–406.

Janowiak, M. K., L. Iverson, D. J. Mladenoff, E. Peters, K. R. Wythers, W. Xi, L. A. Brandt, P. R. Butler, S. D. Handler, P. D. Shannon, C. W. Swanston, L. R. Parker, A. J. Amman, B. Bogaczyk, C. Handler, E. Lesch, P. B. Reich, S. Matthews, M. Peters, A. Prasad, S. Khanal, F. Liu, T. Bal, D. Bronson, A. Burton, J. Ferris, J. Fosgitt, S. Hagan, E. Johnston, E. Kane, C. Matula, R. O'Conner, D. Higgins, M. St. Pierre, J. Daley, M. Davenport, M. R. Emery, D. Fehringer, G. Johnson, D. Neitzel, M. Notaro, A. Rissman, C. Rittenhouse, and R. Ziel. 2014. Forest ecosystem vulnerability assessment and synthesis for northern Wisconsin and western Upper Michigan: A report from the Northwoods Climate Change Response Framework. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at: www.nrs.fs.fed.us/pubs/46393.

Johnson, S. E., J. S. Mead, M. J. Widen, and E. E. Leonard. 2015. The challenging past and precarious future of Canada Yew (*Taxus canadensis*) in the Apostle Islands National Lakeshore. Unpublished report to the National Park Service, Bayfield, Wisconsin.

Johnson, S. E., M. Sinclair, E. E. Leonard, and F. Rosenbower. 2017. Development of strategies for monitoring and managing sandscape vegetation in the

Apostle Islands National Lakeshore and assessment of declining vegetation. Unpublished report to the National Park Service, Bayfield, Wisconsin.

Jones, B., and D. Scott. 2006. Implications of climate change for visitation to Ontario's provincial parks. Leisure/Loisir 30(1):233–261.

Jones, C. D., J. K. Hughes, N. Bellouin, S. C. Hardiman, G. S. Jones, J. Knight, S. Liddicoat, F. M. O'Connor, R. J. Andres, and C. Bell. 2011. The HadGEM2-ES implementation of CMIP5 centennial simulations. Geoscientific Model Development 4:543–570. Available at: doi:10.5194/gmd-4-543-2011.

Judziewicz, E. J., and R. G. Koch. 1993. Flora and vegetation of the Apostle Islands National Lakeshore and Madeline Island, Ashland and Bayfield Counties, Wisconsin. The Michigan Botanist 32(2):43–193.

Kaeding, D. 2017. Visitors, spending drop in the Apostle Islands National Lakeshore. Wisconsin Public Radio, 2 May 2017. Available at: www.wpr.org/visitors-spending-drop-apostle-islands-national-lakeshore.

Kirschbaum, A. A., U. B. Gafvert, and W. B. Monahan. 2012. Landsat-based monitoring of landscape dynamics at Apostle Islands National Lakeshore, 2004–2009. Natural Resource Technical Report. NPS/GLKN/NRTR—2012/608. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/DataStore/Reference/Profile/2188193.

Komar, P. D., and R. A. Holman. 1986. Coastal processes and the development of shoreline erosion. Annual Review of Earth and Planetary Sciences 14(1):237–265.

Kraft, G. J., C. Mechenich, D. J. Mechenich, and S. W. Szczytko. 2007. Assessment of coastal water resources and watershed conditions at Apostle Islands National Lakeshore, Wisconsin. Natural Resource Technical Report NPS/NRWRD/NRTR—2007/367. National Park Service, Fort Collins, Colorado.

Kretschmer, M., D. Coumou, L. Agel, M. Barlow, E. Tziperman, and J. Cohen. 2018. More-persistent weak stratospheric polar vortex states linked to cold extremes. Bulletin of the American Meteorological Society 99(1):49–60.

Kunkel, K., P. Bromirski, H. Brooks, T. Cavazos, A. Douglas, D. Easterling, K. Emanuel, P. Y. Groisman, G. Holland, and T. Knutson. 2008. Observed changes in weather and climate extremes. *In* Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, D.C.

Le Goff, H., M. D. Flannigan, and Y. Bergeron. 2009. Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Canadian Journal of Forest Research 39(12):2369–2380.

Lofgren, B. M., T. S. Hunter, and J. Wilbarger. 2011. Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. Journal of Great Lakes Research 37(4):744–752.

Lofgren, B. M., and J. Rouhana. 2016. Physically plausible methods for projecting changes in Great Lakes water levels under climate change scenarios. Journal of Hydrometeorology 17(8):2209–2223.

Long, E., and E. Biber. 2014. The Wilderness Act and climate change adaptation. Environmental Law Review 44(2):623–694.

Loope, W. L., and J. B. Anderton. 1998. Human versus lightning ignition of presettlement surface fires in coastal

pine forests of the upper Great Lakes. American Midland Naturalist 140(2):206–218.

Martin, J. G., and S. E. Johnson. *In preparation*. The legacy of small wild fires for Canada Yew management and future fire risk in the Apostle Islands National Lakeshore.

Mason, L. A., C. M. Riseng, A. D. Gronewold, E. S. Rutherford, J. Wang, A. Clites, S. D. P. Smith, and P. B. McIntyre. 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. Climatic Change 138(1):71–83.

Mastrandrea, M. D., C. B. Field, T. F. Stocker, O. Edenhofer, K. L. Ebi, D. J. Frame, H. Held, E. Kriegler, K. J. Mach, P. R. Matschoss, G. -K. Plattner, G. W. Yohe, and F. W. Zwiers. 2010. Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at: www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf.

Matthews, S. N., L. R. Iverson, A. M. Prasad, M. P. Peters, and P. G. Rodewald. 2011. Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. Forest Ecology and Management 262(8):1460–1472.

Midwestern Regional Climate Center. 2020. cli-MATE online data portal: Midwestern Regional Climate Center. Available at: https://mrcc.illinois.edu/CLIMATE/ (accessed 17 January 2020).

Miles, J., and P. Burkman. 2018. Exotic species report. Unpublished resource management report. Apostle Islands National Lakeshore, Bayfield, Wisconsin.

Morelli, T. L., C. Daly, S. Z. Dobrowski, D. M. Dulen, J. L. Ebersole, S. T. Jackson, J. D. Lundquist, C. I. Millar, S. P. Maher, W. B. Monahan, K. R. Nydick, K. T. Redmond, S. C. Sawyer, S. Stock, and S. R. Beissinger. 2016. Managing climate change refugia for climate adaptation. PLoS ONE 11(8):e0159909.

Moritz, M. A., M. -A. Parisien, E. Batllori, M. A. Krawchuk, J. V. Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 6(6):22.

Moss, R., W. Babiker, S. Brinkman, E. Calvo, T. Carter, J. Edmonds, I. Elgizouli, S. Emori, L. Erda, and K. Hibbard. 2008. Towards new scenarios for the analysis of emissions, climate change, impacts, and response strategies. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Mudrak, E. L., S. E. Johnson, and D. M. Waller. 2009. Forty-seven year changes in vegetation at the Apostle Islands: Effects of deer on the forest understory. Natural Areas Journal 29(2):167–176.

National Park Service. 2015. Home of the Ojibwe. Available at: www.nps.gov/apis/learn/historyculture/ojibwe.htm (accessed 3 August 2015).

National Park Service. 2019. Adaptation resources. Available at: www.nps.gov/subjects/climatechange/adaptationresources.htm (accessed 1 March 2019).

National Weather Service. Major June flooding in the northland. Available at: www.weather.gov/dlh/June15-17_2018flooding (accessed 11 February 2019).

Notaro, M., V. Bennington, and B. Lofgren. 2015a. Dynamical downscaling-based projections of Great Lakes water levels. Journal of Climate 28(24):9721–9745.

Notaro, M., V. Bennington, and S. Vavrus. 2015b. Dynamically downscaled projections of lake-effect snow in the Great Lakes basin. Journal of Climate 28(4):1661–1684.

Notaro, M., D. Lorenz, C. Hoving, and M. Schummer. 2014. Twenty-first-century projections of snowfall and winter severity across central-eastern North America. Journal of Climate 27(17):6526–6550.

Nuhfer, E. B., and M. P. Dalles. 2004. A Guidebook to the Geology of Lake Superior's Apostle Islands National Lakeshore and Nearby Areas of the Bayfield Peninsula of Wisconsin (revised edition). Eastern National, Fort Washington, Pennsylvania.

Paradis, A., J. Elkinton, K. Hayhoe, and J. Buonaccorsi. 2008. Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (*Adelges tsugae*) in eastern North America. Mitigation and Adaptation Strategies for Global Change 13(5):541–554.

Paulson, A. K., S. Sanders, J. Kirschbaum, and D. M. Waller. 2016. Post-settlement ecological changes in the forests of the Great Lakes national parks. Ecosphere 7(10):e01490.

Pendleton, E. A., E. R. Thieler, and S. J. Williams. 2007. Coastal change-potential assessment of Sleeping Bear Dunes, Indiana Dunes, and Apostle Islands National Lakeshores to lake-level changes. U.S. Department of the Interior, US Geological Survey, Reston, Virginia. Available at: https://pubs.usgs.gov/of/2005/1249/images/pdf/report.pdf.

Prasad, A. M., L. R. Iverson, M. Peters, and S. N. Matthews. 2014. Climate Change Atlas. USDA Forest Service, Northern Research Station, Delaware, Ohio. Available at: www.fs.fed.us/nrs/atlas/.

Pryor, S. C., and D. Scavia. 2014. Midwest. Pages 418–440 *in* J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. Available at: doi:10.7930/J0Z31WJ2.

Romps, D. M., J. T. Seeley, D. Vollaro, and J. Molinari. 2014. Projected increase in lightning strikes in the United States due to global warming. Science 346(6211):851–854.

Salk, T. T., L. E. Frelich, S. Sugita, R. Calcote, J. B. Ferrari, and R. A. Montgomery. 2011. Poor recruitment is changing the structure and species composition of an old-growth hemlock-hardwood forest. Forest Ecology and Management 261(11):1998–2006.

Sanders, S., and J. Grochowski. 2012. Implementation of a long-term vegetation monitoring program at Apostle Islands National Lakeshore. Natural Resource Technical Report NPS/GLKN/NRTR—2012/613. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2188650.

Sanders, S., and J. Grochowski. 2014. Alternative metrics for evaluating forest integrity and assessing change at four northern-tier U.S. national parks. The American Midland Naturalist 171:185–203.

Saunders, S., D. Findlay, T. Easley, and T. Spencer. 2011. Great Lakes national parks in peril: The threats of climate disruption. The Rocky Mountain Climate Organization and the Natural Resources Defense Council.

Saunders, S., D. Findlay, T. Easley, and T. Spencer. 2012. Double trouble: More Midwestern extreme storms. The Rocky Mountain Climate Organization and the Natural Resources Defense Council.

Schuurman, G., and J. Wu. 2018. Birds and climate change—Apostle Islands National Lakeshore. Available at: www.nps.gov/subjects/climatechange/upload/APIS_2018_Birds_-_CC_508Compliant.pdf.

Screen, J. A., and J. A. Francis. 2016. Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability. Nature Climate Change 6:856.

Seeley, J. T., and D. M. Romps. 2015. The effect of global warming on severe thunderstorms in the United States. Journal of Climate 28(6):2443–2458.

Smith, J. W., E. Seekamp, A. McCreary, M. Davenport, M. Kanazawa, K. Holmberg, B. Wilson, and J. Nieber. 2016. Shifting demand for winter outdoor recreation along the north shore of Lake Superior under variable rates of climate change: A finite-mixture modeling approach. Ecological Economics 123(Supplement C):1–13.

Spalink, D., R. Kriebel, P. Li, M. C. Pace, B. T. Drew, J. G. Zaborsky, J. Rose, C. P. Drummond, M. A. Feist, W. S. Alverson, D. M. Waller, K. M. Cameron, T. J. Givnish, and K. J. Sytsma. 2018. Spatial phylogenetics reveals evolutionary constraints on the assembly of a large regional flora. American Journal of Botany 105(11):1938–1950.

Sturrock, R. N., S. J. Frankel, A. V. Brown, P. E. Hennon, J. T. Kliejunas, K. J. Lewis, J. J. Worrall, and A. J. Woods. 2011. Climate change and forest diseases. Plant Pathology 60(1):133–149.

Sugiyama, N., S. Kravtsov, and P. Roebber. 2018. Multiple climate regimes in an idealized lake–ice–atmosphere model. Climate Dynamics 50(1–2):655–676.

Swanston, C., M. Janowiak, L. Iverson, L. Parker, D. Mladenoff, L. Brandt, P. Butler, M. S. Pierre, A. Prasad, S. Matthews, M. Peters, D. Higgins, and A. Dorland. 2011. Ecosystem vulnerability assessment and synthesis: A report from the Climate Change Response Framework Project in northern Wisconsin. General Technical Report NRS-82. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania.

Swanston, C. W., M. K. Janowiak, L. A. Brandt, P. R. Butler, S. D. Handler, P. D. Shannon, A. Derby Lewis, K. Hall, R. T. Fahey, L. Scott, A. Kerber, J. W. Miesbauer, and L. Darling. 2016. Forest adaptation resources: Climate change tools and approaches for land managers (2nd edition). U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at: www.nrs.fs.fed.us/pubs/52760.

Sweet, W. V., and J. Park. 2014. From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. Earth's Future 2(12):579–600.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93(4):485–498.

Thayn, J. B. 2013. Using a remotely sensed optimized disturbance index to detect insect defoliation in the Apostle Islands, Wisconsin, USA. Remote Sensing of Environment 136:210–217.

Thomas, C. C., L. Koontz, and E. Cornachione. 2018. 2017 national park visitor spending effects: Economic contributions to local communities, states, and the nation. National Park Service, Fort Collins, Colorado.

Thuiller, W., S. Lavorel, and M. B. Araújo. 2005. Niche properties and geographical extent as predictors of species sensitivity to climate change. Global Ecology and Biogeography 14(4):347–357.

Titze, D. J. 2016. Characteristics, influence, and sensitivity of ice cover on the Great Lakes. Dissertation, University of Minnesota.

Tobin, P. C., J. Van Stappen, and L. M. Blackburn. 2010. Human visitation rates to the Apostle Islands National Lakeshore and the introduction of the non-native species *Lymantria*

dispar (L.). Journal of Environmental Management 91(10):1991–1996.

Trapp, R. J., N. S. Diffenbaugh, H. E. Brooks, M. E. Baldwin, E. D. Robinson, and J. S. Pal. 2007. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. Proceedings of the National Academy of Sciences 104(50):19719.

USDA NRCS (U.S. Department of Agriculture, Natural Resource Conservation Service). 2019. The PLANTS database. National Plant Data Team, Greensboro, North Carolina. Available at: http://plants.usda.gov (accessed 11 February 2019).

USGCRP (U.S. Global Change Research Program). 2017. Climate science special report: Fourth National Climate Assessment, volume I. U.S. Global Change Research Program, Washington, D.C. Available at: https://science2017.globalchange.gov/.

Vanhanen, H., T. O. Veteli, S. Päivinen, S. Kellomäki, and P. Niemelä. 2007. Climate change and range shifts in two insect defoliators: Gypsy moth and nun moth—A model study. Silva Fennica 41(4):621–638.

Vose, J. M., D. L. Peterson, and T. Patel-Weynand (editors). 2012. Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the US. General Technical Report PNW-GTR-870. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Waller, D. M. 2007. White-tailed deer impacts in North America and the challenge of managing a hyperabundant herbivore. Pages 135–147 *in* Proceedings from the Research Group on Introduced Species 2002 Symposium. Lessons from the Islands: Introduced Species and What They Tell Us About How Ecosystems Work. Queen Charlotte City, Queen Charlotte Islands, British Columbia.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, and J. Willis. 2014. Our changing climate. Pages 19–67 *in* J. M. Melillo, T. C. Richmond and G. W. Yohe, editors. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.

White, M. A. 2012. Long-term effects of deer browsing: Composition, structure and productivity in a northeastern Minnesota old-growth forest. Forest Ecology and Management 269:222–228.

WICCI Wildlife Working Group. 2011. Wildlife Working Group report. Nelson Institute for Environmental Studies, University of Wisconsin-Madison, and the Wisconsin Department of Natural Resources, Madison, Wisconsin. Available at: www.wicci.wisc.edu/report/Wildlife.pdf.

Winkler, J. A., G. S. Guentchev, . Perdinan [*sic*], P. -N. Tan, S. Zhong, M. Liszewska, Z. Abraham, T. Niedźwiedź, Z. Ustrnul. 2011. Climate scenario development and applications for local/regional climate change impact assessments: An overview for the non-climate scientist. Part I: Scenario development using downscaling methods. Geography Compass 5(6):275–300. Available at: https://doi.org/10.1111/j.1749-8198.2011.00425.x.

Wisconsin Department of Natural Resources. 2015. The ecological landscapes of Wisconsin: An assessment of ecological resources and a guide to planning sustainable management. Wisconsin Department of Natural Resources, Madison, Wisconsin. Available at: https://dnr.wi.gov/topic/landscapes/index.asp.

Wisconsin Department of Natural Resources. 2019. Chronic wasting disease. Available at: https://dnr.wi.gov/topic/wildlifehabitat/regulations.html (accessed 11 February 2019).

Wisconsin Department of Natural Resources. 2019. Oak wilt. Available at: https://dnr.wi.gov/topic/foresthealth/oakwilt.HTML (accessed 11 February 2019).

WICCI (Wisconsin Initiative on Climate Change Impacts). 2011. Wisconsin's changing climate: Impacts and adaptation. Nelson Institute for Environmental Studies, University of Wisconsin-Madison, and the Wisconsin Department of Natural Resources, Madison, Wisconsin.

Wuebbles, D., G. Meehl, K. Hayhoe, T. R. Karl, K. Kunkel, B. Santer, M. Wehner, B. Colle, E. M. Fischer, R. Fu, A. Goodman, E. Janssen, V. Kharin, H. Lee, W. Li, L. N. Long, S. C. Olsen, Z. Pan, A. Seth, J. Sheffield, and L. Sun. 2014. CMIP5 climate model analyses: Climate extremes in the United States. Bulletin of the American Meteorological Society 95(4):571–583.

Zobel, Z., J. Wang, D. J. Wuebbles, and V. R. Kotamarthi. 2017. High-resolution dynamical downscaling ensemble projections of future extreme temperature distributions for the United States. Earth's Future 5(12):1234–1251.

Appendix 1: Glossary

Adaptive Capacity
The general ability of systems, institutions, and individuals to moderate the risks of climate change, or to realize benefits, through changes in their characteristics or behavior. Adaptive capacity can be an inherent property, or it could have been developed as a result of previous policy, planning, or design decisions.

Agreement
The extent to which evidence is consistent in support of a vulnerability statement or rating. (See also *confidence*, *evidence*.)

Boreal
A species or ecosystem characteristic of the climatic zone south of the Arctic, especially the cold temperate region dominated by taiga and forests of birch, poplar, and conifers.

Climate Change
A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural factors, or to persistent anthropogenic changes in the composition of the atmosphere.

Confidence
A qualitative assessment of uncertainty as determined through evaluation of evidence and agreement. (See also *evidence*, *agreement*.)

Disturbance
Stresses and destructive agents such as invasive species, diseases, and fire; changes in climate and serious weather events such as hurricanes and ice storms; pollution of the air, water, and soil; real estate development of forest lands; and timber harvest. Some of these are caused by humans, in part or entirely; others are not.

Downscaling
Methods for obtaining high-resolution climate or climate change information from coarse-resolution general circulation models.

Driver
Any natural or human-induced factor that directly or indirectly determines the identity of an ecosystem.

Dynamical Downscaling
A method for obtaining high-resolution climate or climate change information from relatively coarse-resolution general circulation models (GCMs) by using a limited-area, high-resolution model (a regional climate model, or RCM) driven by boundary conditions from a GCM to derive smaller-scale information.

Emissions Scenario
A plausible representation of the future development of emissions of greenhouse gases, based on demographic, technological, or environmental developments. Sometimes referred to as an emissions pathway. (See *representative concentration pathway (RCP)*.)

Evapotranspiration
The sum of evaporation from the soil and transpiration from plants.

Evidence
Mechanistic understanding, theory, data, models, or expert judgment used to determine the level of confidence in a vulnerability statement or rating. (See also *agreement*, *confidence*.)

Exposure
The nature and degree to which a system is exposed to significant climate variations.

General Circulation Model (GCM)

Numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and their feedback processes, and accounting for all or some of its known properties (also called global climate model).

Greenhouse Gas (GHG)

Certain gases in the atmosphere (e.g., water vapor, carbon dioxide, nitrous oxide, and methane) that absorb and emit energy from the sun.

Impact

Direct and indirect consequences of climate change on systems, particularly those that would occur without adaptation.

Importance Value

In the Climate Change Tree Atlas model, an index of the relative abundance of a species in a given location or pixel cell (0 = least abundant, 100 = most abundant).

Invasive Species

Any species that is nonnative to the ecosystem under consideration and whose introduction causes or is likely to cause damage, injury, or disruption to ecosystem processes or other species within that ecosystem.

Krummholz

A type of stunted, deformed vegetation encountered in subarctic and subalpine tree line landscapes, shaped by continual wind exposure.

Modifying Factor

In the Climate Change Tree Atlas model, environmental variables (e.g., site conditions, interspecies competition, disturbance, dispersal ability) that influence the way a tree may respond to climate change.

Old-growth

A forest that has attained great age without significant disturbance from fire, harvest, or other means, and thereby exhibits unique ecological features.

Phenology

The timing of natural events such as the date that migrating birds return, the first flower dates for plants, and the date on which a lake freezes in the autumn or opens in the spring.

Projection

A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized, and are therefore subject to substantial uncertainty.

Radiative Forcing

The difference between incoming energy (sunlight) absorbed by the Earth and the energy radiated back to space, measured in watts per square meter. Higher numbers mean that there is more energy being absorbed than being released, which increases the amount of energy in the Earth's radiation budget and the climate system. For example, RCP 4.5 indicates a long-term stabilization of 4.5 watts per square meter. (See also *representative concentration pathway (RCP)*.)

Refugia, Refugium

Locations and habitats that support populations of organisms that are limited to small fragments of their previous geographic range.

Representative Concentration Pathway (RCP)

Scenarios of future radiative forcing that provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. RCPs are distinguished according to a specific long-term GHG concentration or radiative forcing outcome as well as the trajectory that is taken over time to reach that outcome. (See also *radiative forcing*.)

Resilience
Capacity of a system to absorb a disturbance and continue to develop with similar fundamental function, structure, identity, and feedbacks.

Sandscape
A landscape that consists mostly of sand. For example, beaches, dunes, tombolos, sand spits, and other similar formations are all considered sandscapes.

Scenario
A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline. (See also *emissions scenario*.)

Sensitivity
The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.

Statistical Downscaling
A method for obtaining high-resolution climate or climate change information from relatively coarse-resolution general circulation models (GCMs) by deriving statistical relationships between observed small-scale (often station-level) variables and larger-scale (GCM-scale) variables. Future values of the large-scale variables obtained from GCM projections of future climate are then used to drive the statistical relationships and so estimate the smaller-scale details of future climate.

Stressor
An agent, condition, change in condition, or other stimulus that causes stress to an organism.

Suitable Habitat
In the Climate Change Tree Atlas model, the area-weighted importance value, or the product of tree species abundance and the number of cells with projected occupancy.

Terrestrial Ecosystem
An ecosystem that exists wholly or partially on land, as opposed to in the water. For the purposes of this assessment, we are using the term “ecosystem” to describe a particular natural community, or assemblage of vegetation, including many factors such as disturbance processes, soils and landform, characteristic plant species, and interactions between living organisms and the physical environment.

Uncertainty
An expression of the degree to which a value (such as the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can be described by using quantitative measures or by qualitative statements.

Vulnerability
The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. For this assessment, a system may be considered to be vulnerable if it is at risk of a decline in health, a decline in extent, a substantial change in identity, or a decline in crucial ecosystem functions.

Weather
The state of the atmosphere at a given time and place, with respect to variables such as temperature, moisture, wind velocity, and barometric pressure.

Appendix 2: Species Names

Appendix 2-1. Common names, Latin names, and Ojibwe names (Anishinaabemowin) for plant species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Latin Name	Ojibwe Name (Anishinaabemowin)
American basswood	*Tilia americana*	wiigobaatig
American beech	*Fagus grandifolia*	gawe'mik
American elm	*Ulmus americana*	aniib
American hornbeam	*Carpinus caroliniana*	maananoons
American mountain-ash	*Sorbus americana*	makominagaawanzh
baby's breath	*Gypsophila* spp.	*
balsam fir	*Abies balsamea*	zhingob
balsam poplar	*Populus balsamifera*	maanazaadi
beach grass	*Ammophila breviligulata*	*
beach pea	*Lathyrus japonicus*	*
beach rose	*Rosa rugosa*	
beach wormwood	*Artemisia stelleriana*	*
bearberry or kinnikinnick	*Arctostaphylos uvaursi*	apaakozigan
bigleaf aster	*Eurybia macrophylla*	migizibag
bigtooth aspen	*Populus grandidentata*	azaadi
bird's-eye primrose	*Primula mistassinica*	*
bird's-foot trefoil	*Lotus corniculatus*	*
bitternut hickory	*Carya cordiformis*	mitigwaabaak
black ash	*Fraxinus nigra*	baapaagimaak
black cherry	*Prunus serotina*	ookwemin
black locust	*Robinia pseudoacacia*	*
black oak	*Quercus velutina*	mitigomizh
black spruce	*Picea mariana*	zesegaandag
black walnut	*Juglans nigra*	*
black willow	*Salix nigra*	zasgogmizh
blackgum	*Nyssa sylvatica*	*
bladderworts	*Utricularia* spp.	*
bluebead lily	*Clintonia borealis*	odotaagaans
blueberry	*Vaccinium angustifolium* and *V. myrtilloides*	miinagaawanzh
bluegrass spp	*Poa* spp.	ozhaawashkwa-mashkosiwan
bluejoint grass	*Calamagrostis canadensis*	*
bog laurel	*Kalmia polifolia*	*
bog rosemary	*Andromeda polifolia* var. *glaucophylla*	binemiiki

Appendix 2-1 (continued). Common names, Latin names, and Ojibwe names (Anishinaabemowin) for plant species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Latin Name	Ojibwe Name (Anishinaabemowin)
boxelder	*Acer negundo*	ajigobi'mak
bracken fern	*Pteridium aquilinum*	waagaan
broad-leaved twayblade	*Listera convallarioides*	*
bulblet fern	*Cystopteris bulbifera*	*
bur oak	*Quercus macrocarpa*	mitigomizh
butterwort	*Pinguicula vulgaris*	*
Canada bluegrass	*Poa compressa*	*
Canada mayflower	*Maianthemum canadense*	agongosminaan
Canada wild rye	*Elymus canadensis*	*
Canada yew	*Taxus canadensis*	niibaayaandag
cattails	*Typha* spp.	Apakweshk
cattail (hybrid)	*Typha* x *glauca*	*
chestnut oak	*Quercus prinus*	*
Chilean sweetcicely	*Osmorhiza berteroi*	*
chokecherry	*Prunus virginiana*	asasaweminagaawanzh
clover	*Trifolium spp.*	*
coast sedge	*Carex exilis*	*
common reed	*Phragmites australis*	aaboojigan
cranberry	*Vaccinium macrocarpon* and *V. oxycoccos*	mashkiigimin
crown vetch	*Coronilla varia*	*
dandelion	*Taraxacum officinale*	doodooshaaboojiibik
dragon's mouth orchid	*Arethusa bulbosa*	*
drooping sedge	*Carex prasina*	*
dwarf ginseng	*Panax trifolius*	*
dwarf juniper	*Juniperus communis*	gaagaagiwaandag
dwarf scouring rush	*Equisetum scirpoides*	anaakanashk or giji'binusk
dwarf trout lily	*Erythronium propullans*	*
eastern cottonwood	*Populus deltoides*	*
eastern hemlock	*Tsuga canadensis*	gagaagi wanzh
eastern redcedar	*Juniperus virginiana*	miskwaawaak
eastern white pine	*Pinus strobus*	biisaandago-zhingwaak or zhingwaak
elegant groundsel	*Packera indecora*	*
Eurasian buckthorn	*Rhamnus cathartica*	*
evening primrose	*Oenothera biennis*	*
fewseed sedge	*Carex oligosperma*	*
fire cherry	*Prunus pensylvanicum*	*
fireweed	*Chamerion angustifolium*	*

Appendix 2-1 (continued). Common names, Latin names, and Ojibwe names (Anishinaabemowin) for plant species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Latin Name	Ojibwe Name (Anishinaabemowin)
flat-leaved willow	*Salix planifolia*	oziisigobiminzh
grass-of-Parnassus	*Parnassia palustris*	*
green alder	*Alnus viridis*	*
green ash	*Fraxinus pennsylvanica*	*
green bog orchid	*Platanthera huronensis*	*
hackberry	*Celtis occidentalis*	*
hair-like sedge	*Carex capillaris*	*
hairgrass	*Avenella flexuosa*	*
harebell	*Campanula rotundifolia*	*
harlequin blueflag	*Iris versicolor*	*
hazelnut	*Corylus cornuta*	bagaanimizh
heart-leaved birch	*Betula cordiformis*	*
honeysuckle	*Lonicera* spp.	*
huckleberry	*Gaylussacia baccata*	miinan
ironwood	*Ostrya virginiana*	maananoons
jack pine	*Pinus banksiana*	akikaandag
Labrador tea	*Ledum groenlandicum*	mashkiigobag
lake sedge	*Carex lacustris*	*
large-leaved lupine	*Lupinus polyphyllus*	*
leatherleaf	*Chamaedaphne calyculata*	*
lenticular sedge	*Carex lenticularis*	*
lichens	*Usnea* sp.	*
marsh cinquefoil	*Comarum palustre*	*
Michaux's sedge	*Carex michauxiana*	*
mountain maple	*Acer spicatum*	*
narrow false oats	*Trisetum spicatum*	*
narrowleaf cowwheat	*Melampyrum lineare*	*
ninebark	*Physocarpus opulifolius*	*
nodding trillium	*Trillium cernuum*	ininiwin dibige'gun
northern pin oak	*Quercus ellipsoidalis*	mitigomizh
northern red oak	*Quercus rubra*	wiisagi-mitigomizh
northern white-cedar	*Thuja occidentalis*	giizhikaatig
Norway spruce	*Picea abies*	*
ox-eye daisy	*Leucanthemum vulgare*	*
paper birch	*Betula papyrifera*	wiigwaasaatig
Pawpaw	*Asimina triloba*	*
peachleaf willow	*Salix amygdaloides*	*
pearly everlasting	*Anaphalis margaritacea*	waabigwan

Appendix 2-1 (continued). Common names, Latin names, and Ojibwe names (Anishinaabemowin) for plant species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Latin Name	Ojibwe Name (Anishinaabemowin)
pignut hickory	*Carya glabra*	*
pin cherry	*Prunus pensylvanica*	bawa'iminaan
pin oak	*Quercus palustris*	*
pink lady's slipper	*Cypripedium acaule*	*
pitcher plant	*Sarracenia purpurea*	*
pod-grass	*Scheuchzeria palustris*	*
poison ivy	*Toxicodendron rydbergii*	maji-aniibiish
purple loosetrife	*Lythrum salicaria*	*
quaking aspen	*Populus tremuloides*	azaadi
quack grass	*Elymus repens*	*
raspberry	*Rubus idaeus*	miskomin
rattlesnake plantain	*Goodyera oblongifolia*	*
red currant	*Ribes triste*	*
red maple	*Acer rubrum*	zhiishiigimiiwanzh
red-osier dogwood	*Cornus sericea*	miskwaabiimizh
red pine	*Pinus resinosa*	bapakwanagemag or wenda-zhingwaak
red spruce	*Picea rubens*	*
reed canarygrass	*Phalaris arundinacea*	*
reindeer moss	*Cladina subtenuis*	aasaakamig
rock elm	*Ulmus thomasii*	*
roughleaf ricegrass	*Oryzopsis asperifolia*	*
sand cherry	*Prunus pumila*	*
sassafras	*Sassafras albidum*	*
scarlet oak	*Quercus coccinea*	*
Scotch pine	*Pinus sylvestris*	*
sedges	*Carex* spp.	*
serviceberry	*Amelanchier* spp.	Gozigwaakomin
Schreber's big red stem moss	*Pleurozium schreberi*	*
shagbark hickory	*Carya ovata*	mitigwaabaak
shaved sedge	*Carex tonsa*	*
showy mountain ash	*Sorbus decora*	makominagaawanzh
silver maple	*Acer saccharinum*	*
skunk currant	*Ribes glandulosum*	*
slippery elm	*Ulmus rubra*	ozhaashigob
smooth sawgrass	*Cladium mariscoides*	*
sow thistle	*Sonchus arvensis*	*
speckled alder	*Alnus incana*	wadoop

Appendix 2-1 (continued). Common names, Latin names, and Ojibwe names (Anishinaabemowin) for plant species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Latin Name	Ojibwe Name (Anishinaabemowin)
spike trisetum	*Trisetum spicatum*	*
sphagnum moss	*Sphagnum* spp.	Mashkiigwakamig
spotted knapweed	*Centaurea stoebe* ssp. *micranthos*	*
starflower	*Trientalis borealis*	*
strawberry	*Fragaria virginiana*	ode'iminijiibik
sundews	*Drosera spp.*	*
sugarberry	*Celtis laevigata*	*
sugar maple	*Acer saccharum*	ziinzibaakwadwaatig or aninaatig
swamp white oak	*Quercus bicolor*	*
sweet birch	*Betula lenta*	*
sweet gale	*Myrica gale*	wa'sawasni'mike
sycamore	*Platanus occidentalis*	*
tamarack	*Larix laricina*	mashkiigwaatig
tansy	*Tanacetum vulgare*	oshkiniikwebagoons
thistle species	*Cirsium* spp.	mazaanaatig
touch-me-not	*Impatiens capensis*	omakakiibag
tuberous grass pink orchid	*Calopogon tuberosus*	*
water horsetail	*Equisetum fluviatile*	*
white ash	*Fraxinus americana*	aagimaak
white-beak rush	*Rhyncospora alba*	*
white mandarin	*Streptopus amplexifolius*	*
white oak	*Quercus alba*	wiishkobi-mitigomizh
white spruce	*Picea glauca*	gaawaandag
wild sarsaparilla	*Aralia nudicaulis*	waaboozojiibik
willow spp	*Salix* spp.	*
wintergreen	*Gaultheria procumbens*	*
wood ferns	*Dryopteris* spp.	*
woolyfruit sedge	*Carex lasiocarpa*	*
yarrow	*Achillea millefolium*	nookwezigan
yellow birch	*Betula alleghaniensis*	wiinizik
yellow poplar	*Liriodendron tulipifera*	*
valerian	*Valeriana officinalis*	*
variegated horsetail	*Equisetum variegatum*	*

Appendix 2-2. Common names, Latin names, and Ojibwe names (Anishinaabemowin) for animals and other species mentioned in this assessment. Ojibwe names are provided from the Great Lakes Indian Fish and Wildlife Commission and local speakers as primary resources to reflect the local dialect. Names from the Inter-Tribal Council of Michigan and the online Ojibwe People's Dictionary (https://ojibwe.lib.umn.edu/) are also supplemental sources. Asterisks (*) indicate that the Ojibwe name of the species was unknown by the authors at the time of publication. Species are listed in alphabetical order according to common names as referenced in the text.

Common Name	Scientific Name	Ojibwe Name (Anishinaabemowin)
American marten	*Martes americana*	waabizheshi
beaver	*Castor canadensis*	amik
coyote	*Canis latrans*	wiisagi-ma' iingan
earthworms (non-native)	*Dendrobaena octaedra*, *Lumbricus rubellus*, and *L. terrestris*	moose
eastern larch beetle	*Dendroctonus simplex*	*
emerald ash borer	*Agrilus planipennis*	*
forest tent caterpillar	*Malacosoma disstria*	*
four-toed salamanders	*Hemidactylium scutatum*	*
gypsy moth	*Lymantria dispar dispar*	*
hemlock wooly adelgid	*Adelges tsugae*	*
oak wilt	*Bretziella fagacearum*	*
pale juniper webworm	*Aethes rutilana*	*
piping plover	*Charadrius melodus*	*
spruce budworm	*Choristoneura fumiferana*	*
tamarack sawfly	*Pristiphora erichsonii*	*
two-lined chestnut borer	*Agrilus bilineatus*	*
white pine blister rust	*Cronartium ribicola*	*
white-tailed deer	*Odocoileus virginianus*	waawaashkeshi
wolf	*Canis lupus*	ma'iingan

Appendix 3: Supplemental Information on Climate Data

This appendix provides a brief background on models that simulate future climate change, as well as downscaling methods used to achieve greater spatial resolution. See Chapter 2 for more information.

Climate Models

Global climate models (also called general circulation models, GCMs) simulate important physical processes involving the land, atmosphere, ocean, ice, and additional components over the entire Earth. Global climate models use widely accepted mathematical equations that represent physical processes to simulate how energy, mass, and momentum move through a system with time. Climate models separate global space into a 3-dimensional grid. The exchange of energy, mass, and momentum occurs among the neighboring grid cells, so that these values are transferred through space and time. The grid cell size is related to the resolution of the data—if the grid cell is smaller, the resolution is higher. Therefore, there is more detail within the model. As resolution increases, however, so does the requirement for additional computational capacity and processing time.

Dozens of GCMs exist, as different research groups around the world work to improve model simulations. The worldwide set of the current best GCMs whose outputs were available at the time of preparation of this report have been assembled into the Fifth Phase of the Climate Model Intercomparison Study (CMIP5) (Taylor et al. 2012). These models are used in the Intergovernmental Panel on Climate Change Fifth Assessment Report (www.ipcc.ch/report/ar5/, IPCC AR5), and they allow for a wide range of model parameters to be used and compared in order to better examine plausible future conditions.

Computing limitations restrict GCMs to relatively coarse spatial resolution—meaning the models divide the Earth's surface into relatively large areas for performing simulations and averaging. Pixels in the grid are usually between 2° and 3° latitude and longitude. This makes GCMs an insufficient source of information for dynamics that occur at relatively small spatial scales (between two and three times the model's grid sizing or smaller), like extreme precipitation or wind, because these events are not physically simulated in the models. In addition, most GCMs do not include a representation of the Great Lakes or they are too simplistic to accurately represent lake-land-atmosphere interactions (e.g., lake-effect precipitation), which are important in the Great Lakes region. This, along with the exclusion of other smaller scale climate processes, makes GCMs best suited for large-scale climate studies of national or global projections.

Downscaling Methods

Since GCMs like the CMIP5 models represent the entire globe, their spatial resolution is often too coarse to be useful for local planning. Two primary "downscaling" methods are used to increase the spatial resolution of climate projections: statistical and dynamical downscaling. Each method has advantages and disadvantages (Winkler et al. 2011, Janowiak et al. 2014). It is important to understand underlying assumptions, benefits, and drawbacks of each downscaling procedure before using them in practice.

Statistical downscaling is a technique that relies on observations from the past to create statistical relationships between large- and small-scale climate features. These statistical relationships based on observed data are used to refine large-scale GCM simulations of the future for much smaller spatial scales. In statistical downscaling, one of the major underlying assumptions is stationarity. Stationarity refers to the assumption that current physical climate relationships will remain the same in the future. The local observed (historical) spatial pattern of a variable is used to define statistical relationships between the large-

scale model output and the downscaled data. In regions where lakes have a large impact on local climate, as is the case for the Apostle Islands, assumptions of stationarity do not hold (Briley et al. 2017). For example, the historic patterns of lake-effect snow downwind of the Great Lakes are dependent on lake temperature and ice cover conditions. Because lake temperatures and ice cover have already been changing and are expected to continue changing through the next century, projections of lake-effect precipitation downscaled using historical statistics may not be accurate. Furthermore, some statistical downscaling techniques are based on the observed means of climate parameters, so projections of extremes (e.g., high temperatures or heavy precipitation) may not be reliable. Therefore, for areas such as the Apostle Islands, where local conditions are highly dependent on interactions with Lake Superior and extreme conditions can lead to important ecosystem impacts, climate projections using statistical downscaling should be used with caution.

Statistical downscaling also has some benefits. It is significantly cheaper to perform than dynamical downscaling because it requires less computational effort. This means that research teams can afford to downscale larger datasets, covering a full array of multiple GCMs, time periods, and future pathways of greenhouse gas (GHG) concentrations. Additionally, data can be downscaled in both time and space. In other words, a small region can be examined on a seasonal or monthly timescale, as opposed to annually.

The other downscaling method that is commonly used by climate modelers is dynamical downscaling. Dynamical downscaling relies on a nested Regional Climate Model (RCM) to translate coarse GCM output to smaller scales by physically (as opposed to statistically) representing local climate processes over specific regions. When addressing smaller areas of interest, like the Great Lakes Region, the details of the landscape become crucially important. Landscape features such as topography and large water bodies can be better represented in RCMs. Because an RCM relies on the coarse-scale input from a GCM to provide the initial conditions and recurring boundary conditions for the simulation, it ensures that overarching physical equations are balanced and that the climate system as a whole is accurately represented. RCMs work at finer spatial resolution, ranging from 5–20 kilometers all the way down to hundreds of meters. This means that RCMs provide a much more detailed picture of the future climate prediction. They also aim to represent important climate processes for that region, such as lake-effect processes, thereby improving the quality of the prediction.

These enhancements make RCMs much more computationally and technically expensive compared to GCMs, so they are primarily designed for and limited to specific regions. Because of the effort involved in creating RCMs and dynamically downscaling GCM projections, researchers have not completed the full array of projections covering multiple GCMs, time periods, and GHG concentration pathways. Additionally, not all of the dynamically downscaled datasets are publicly available, further limiting the use of this method.

Bias correction, which is used in both statistical and dynamical downscaling, is another statistical technique used to adjust for differences between a model's historical simulation and observations. This method helps reduce model bias and make the model represent observations more accurately, in hopes that this will result in better future projections. There are several techniques, but in general, the model's historical simulation is compared to observations from an overlapping time period in order to determine the magnitude of difference between the two, or the bias. This difference is considered the correction and is applied to the model so that the model better represents the observations. It is important to remember that this correction does not improve the representation of physical processes in the models; it is solely a statistical correction. Additionally, this correction may not be constant over time, so

bias correction can be problematic. When it is used, it is important to retain information about the underlying model's bias in order to evaluate the model's projections accurately.

Uncertainty

Global climate models allow us to explore future climate conditions, but they require assumptions about how Earth's climate will be influenced by GHGs in the future. In the IPCC AR5, four GHG concentration pathways were developed in order to examine a range of possible futures (Cubasch et al. 2013, Moss et al. 2008). These scenarios, called Representative Concentration Pathways (RCPs), are based on estimates of radiative forcing in 2100. Radiative forcing is the difference between incoming energy (sunlight) absorbed by the Earth and the energy radiated back to space, measured in watts/m^2. Higher numbers mean that there is more energy being absorbed than being released, which increases the amount of energy in the Earth's radiation budget and the climate system. The RCPs are 2.6, 4.5, 6.0, and 8.5 W/m^2 in 2100 (Figure A3-1), and are hereafter referred to as RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. Using different RCPs allows modelers to explore a major source of uncertainty in future climate projections by illustrating the effects of different levels of greenhouse gas concentrations that result from a range of plausible future global decisions regarding development, energy use, population growth, and more. We do not know how the future will play out, but these RCPs provide a platform for exploring possible future climates.

Model projections should not be considered exact predictions of the future. There are three distinct sources of uncertainty—variability among different models, a range of plausible GHG concentrations, and internal variability of the climate (Hawkins and Sutton 2009). Different GCMs produce different results because some climate or meteorological processes are omitted or greatly simplified in some models. This occurs because scientists either do not completely understand them or they occur on spatial scales that are smaller than the GCMs operate. As scientists aim to include or better resolve important processes in models, dozens of GCMs have emerged as possible resources. A common approach in adaptation planning is to consider outputs from multiple GCMs to better explore the range of model uncertainty.

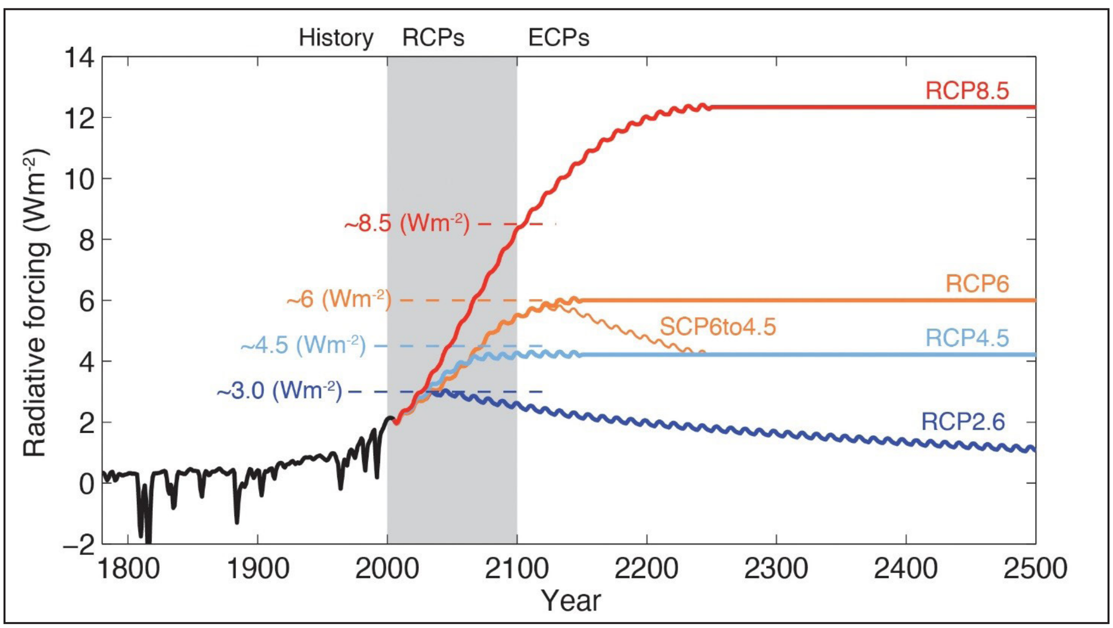


Figure A3-1. Total radiative forcing (anthropogenic plus natural) for RCPs and extended concentration pathways (ECPs) for RCP 2.6, RCP 4.5, and RCP 6, RCP 8.5, as well as a supplementary extension RCP 6 to 4.5 with an adjustment after 2100 to reach RCP 4.5 concentration levels in 2250 and thereafter (Cubasch et al. 2013).

Additionally, projected climate changes in GCMs are driven by prescribed changes in the future global energy balance, which cannot be predicted with 100% accuracy. Uncertainty in future conditions such as the magnitude of greenhouse gas forcing, the implementation of climate policy, and the development of new technology is explored using RCPs. In reality, the future is unlikely to unfold exactly as any RCP-GCM combination might suggest. This is why comparing a range of potential futures is helpful.

Uncertainty in future projections also arises from the internal variability of the climate system—how our climate naturally fluctuates. Examples of sources of variability include recurring pressure and circulation patterns like El Niño Southern Oscillation (ENSO), the Arctic Oscillation (AO), and the Pacific Decadal Oscillation (PDO). These patterns have the ability to exacerbate or partially negate the magnitude of climate change that occurs in the future (Kretschmer et al. 2018, Fei et al. 2018, Screen and Francis 2016).

While each of these sources contribute to uncertainty, the magnitude of contribution varies through time (Hawkins and Sutton 2009). When looking only one to two decades into the future, model uncertainty and internal variability are larger concerns. By contrast, when looking multiple decades into the future, model and concentration pathway uncertainty have a larger influence in the range of potential outcomes. This assessment is designed to address climate change impacts and vulnerability at the end of the century, and therefore the uncertainty between different concentration pathways (RCP 4.5 and RCP 8.5, for example) becomes quite important.

Supplemental Climate Information

Chapter 2 contains information on observed and projected climate trends in the Apostle Islands and the surrounding region. One data source used by the panel of authors is a nationwide statistically downscaled dataset, called Multivariate Adaptive Constructed Analogs (MACA, www.climatologylab.org/maca.html). This dataset from the University of Idaho Climatology Lab includes 20 General Circulation Models (GCMs) that have been downscaled and run under two representative concentration pathways (RCPs), RCP 4.5 and RCP 8.5 (Abatzoglou and Brown 2012). At the expert panel workshop, participants considered the ensemble average of 20 GCMs, using both RCP 4.5 and RCP 8.5 to represent a range of futures. This dataset was used to describe the broad trends in temperature, precipitation, growing season length, and other variables.

In Chapter 2, we also provide additional information about the range of values among the 20 GCMs for temperature and precipitation values. Figure A3-2 (annual mean temperature) and Figure A3-3 (annual precipitation) further illustrate the outcomes of the 20 different GCM projections in the MACA dataset, highlighting the overlap between end-of-century projections between RCP 4.5 and RCP 8.5. Comparing the multi-model mean from each RCP is useful to get a broad sense of the divergence between the GHG concentration pathways. This more detailed view allows a comparison of the multi-model mean as well as the model spread, which can indicate the uncertainty in these projections. In this appendix we show example figures for annual temperature and precipitation, but it is possible to generate similar figures for each season, multiple time periods, and for different variables at: https://climate.northwestknowledge.net/MACA/index.php.

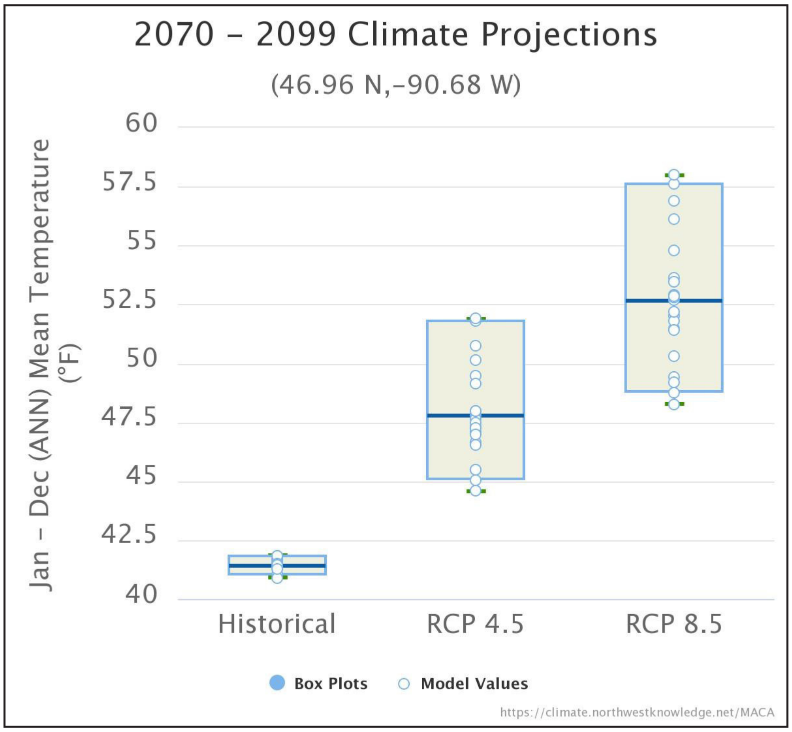


Figure A3-2. Boxplot illustrating projected annual mean temperature for 2070–2099 for a location in the Apostle Islands. White dots represent the 20 individual GCM model averages. Boxplots are constructed to show the 5th and 95th percentile values, as well as the low and high values among the 20 GCMs. Historical values are the GCM average values from 1971–2000.

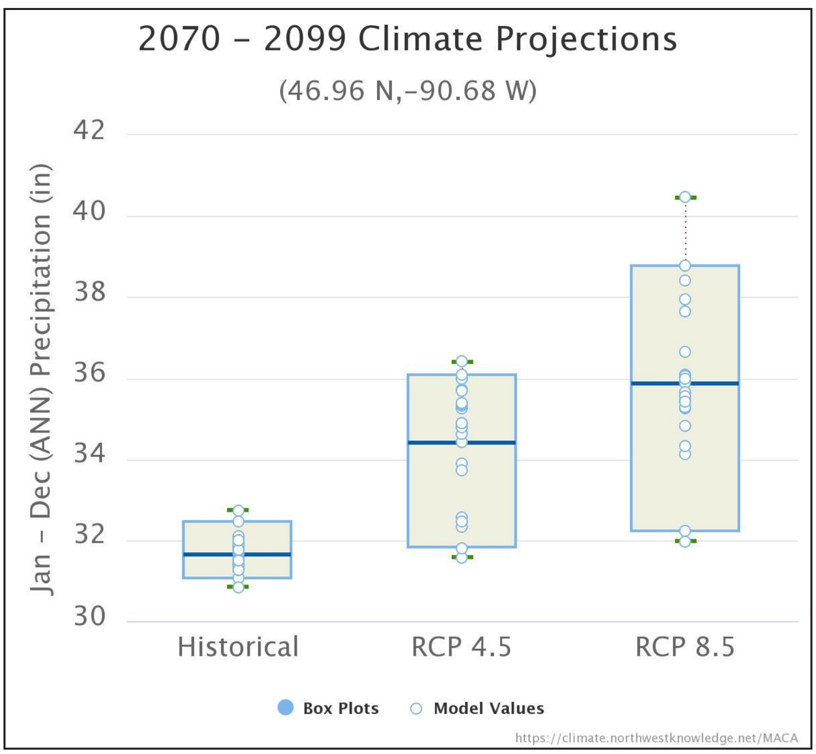


Figure A3-3. Boxplot illustrating projected annual mean precipitation for 2070–2099 for a location in the Apostle Islands. White dots represent the 20 individual GCM model averages. Boxplots are constructed to show the 5th and 95th percentile values, as well as the low and high values among the 20 GCMs. Historical values are the GCM average values from 1971–2000.

Appendix 4: Supplemental Information on the Climate Change Tree Atlas

The Climate Change Tree Atlas (Prasad et al. 2014) provides projections of how climate change will influence the available suitable habitat for individual tree species. Chapter 3 contains localized Tree Atlas projections for the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. This appendix contains supplemental information to help provide context to the results displayed in Table 4 in Chapter 3.

Changes in Suitable Habitat

For this assessment, current area-weighted importance values (IVs) were derived from Forest Inventory and Analysis (FIA) data. These were used to develop modeled current (1961–1990) IVs, as well as future IVs for the end of the century (2070 through 2099). Future habitat suitability is projected for two future greenhouse gas concentration pathways that bracket a wide range of possible futures for the year 2100. The “low” scenario is based on RCP 4.5 and the “high” scenario is based on RCP 8.5 (see Chapter 2 and Appendix 3 for a discussion of RCPs). Results presented in this assessment are averages from three general circulation models (CCSM4, HadGEM2, and GFDL CM3) (Moss et al. 2008, Jones et al. 2011, Donner et al. 2011).

Across the eastern United States, 134 tree species were initially modeled. If a species never had an area-weighted IV greater than 3 (FIA, current modeled, or future) across the assessment area, it was deleted from the list because the species has either no current or no future suitable habitat in the region, or there were not enough data. This step resulted in the list of 62 tree species for which complete data are shown in Table A4-2. For most species, Table A4-1 displays the rules applied to categorize each species into a Change Class, based on the ratio of future IVs to current modeled IVs.

A few exceptions applied to these general rules. When there was a zero in the numerator or denominator, a ratio could not be calculated. Instead, a species was classified as gaining new habitat if its FIA value was 0 and the future IV was greater than 3. A species’ habitat was considered to be extirpated if the future IV was 0 and FIA values were greater than 3. When the modelled future IV was >0 for <10% of the cells within the 1×1 degree zone, the species was categorized as ‘rare’ and the change classes were expanded, so that NoChange=ratio 0.6–4.0; Sm. inc.=ratio 4.0–8.0; Lg. inc.=ratio >8.0; Sm. dec.=ratio 0.2–0.6; Lg. dec.=ratio <0.2.

Table A4-1. Explanation of criteria used to assign change classes to each tree species according to model outputs from the Climate Change Tree Atlas. Ratios refer to the ratio of projected importance value at the end of the century to modeled current importance value.

Class	Criteria	Description
NoChange	Ratio of 0.8–1.2	No Change to very little change in habitat suitability
Sm. inc.	Ratio of 1.2–2.0	Small increase in habitat suitability
Lg. inc.	Ratio >2.0	Large increase in habitat suitability
Sm. dec.	Ratio of 0.5–0.8	Small decrease in habitat suitability
Lg. dec.	Ratio <0.5	Large decrease in habitat suitability
Very Lg. dec.	FIAi >0.5 and GCM45i = 0	Very large decrease in habitat suitability
Unknown	ModRel = unacceptable	Not enough information to assign a class due to very low model reliability or species is extremely rare either now or potentially in future.
New Habitat	MODi = 0 and GCM45i >0	Species is not currently reported by FIA and has not been modeled under current conditions to have suitable habitat, but could gain suitable habitat under future climate conditions.

Table A4-2. Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area. **Mod Rel**: the model reliability of the species' model predicting current and future suitable habitat (High, Medium, Low), based on several statistical parameters. **Pct Area**: the percentage of cells within the 1×1 degree of Lat/Lon (or other area) zone that currently have the species present according to the FIA data. It does not mean the species actually covers that amount of ground within the sample area. Also, if the 1×1 is only a partial rectangle because of coast or water, or because of the region of interest, there may be pieces without FIA plots or missing environmental predictors, therefore some fraction of the 1×1 without certain common species. Also, the region could be selecting only a small fraction of a cell with the species present. **FIAi**: the average importance value (IV) according to FIA records for the species, where it occurs, within the 10×10-km and/or 20×20-km cells of the area of interest. The 0–100 score is based on number of stems and basal area of tree species recorded during the FIA inventory cycle (FIA data used across the eastern U.S. range from 2001–2016). IVs are averaged at the cell level to indicate the average abundance of a species. Note that this IV is for the species only within the cells where it now occurs, not averaged over the entire region of interest. **MODi**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells. Includes cells that have modeled suitable habitat for the species, so that FIA plots need not be present for the model to predict species presence in the smaller cells. **GCM45i or GCM85i**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells, under the Representative Concentration Pathway (RCP) 4.5 (relatively low concentration future) or 8.5 (high concentration pathway) average of three general circulation models (GCMs) by 2100. **GCM45r or GCM85r**: the ratio of future (2070–2099) suitable habitat (=G45i/G85i) to current (1981–2010) habitat (=MODi), so that a ratio of 1 indicates no change in suitable habitat, <1 indicates a potential loss in habitat, and >1 indicates a potential gain in habitat by 2100 according to the lower (or higher) concentration scenario, average of three GCMs. **ChngCl4.5/8.5**: class of change in suitable habitat by 2100. Classes are based on ratios of future suitable habitat for common species. ***No Change*** = ratio 0.8–1.2; ***Small increase*** = ratio 1.2–2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5–0.8; ***Large decrease*** = ratio <0.5; ***Very Large decrease*** = future importance value of 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adapt**: Adaptability score for the species, according to a literature review of 12 disturbance and nine biological characteristics, or modification factors (Iverson et al. 2011, Matthews et al. 2011). Scores range from 1.7 (very low adaptability to a changing climate) to 8.5 (very high adaptability), with color class breaks at 3.4 and 5.2. Thus Low adaptability is 1.7–3.4, Moderate is 3.5–5.2, and High is >5.2.

Common Name	Scientific Name	Mod Rel	PctArea	FIAi	MODi	GCM45i	GCM85i	GCM45r	GCM85r	ChngCl45	ChngCl85	Adapt
sugar maple	*Acer saccharum*	High	87.3	15.18	1259.39	785.77	782.7	0.58	0.58	Sm. dec.	Sm. dec.	5.8
quaking aspen	*Populus tremuloides*	High	94	11.22	1049.37	800.98	706.82	0.8	0.71	Sm. dec.	Sm. dec.	4.7
red maple	*Acer rubrum*	High	97.2	9.6	841.08	1042.8	903.31	1.18	1.02	No change	No change	8.5
balsam fir	*Abies balsamea*	High	92.7	8.46	760.73	361.13	378.08	0.47	0.5	Lg. dec.	Sm. dec.	2.7
northern white-cedar	*Thuja occidentalis*	High	70.8	7.32	425.45	380.28	435.1	0.87	0.99	No change	No change	4.2
black ash	*Fraxinus nigra*	Medium	84.2	4.63	349.45	313.93	285.43	0.85	0.78	No change	Sm. dec.	1.7
paper birch	*Betula papyrifera*	High	63.9	4.08	286.52	337.91	300.79	1.11	0.98	No change	No change	3.4
yellow birch	*Betula alleghaniensis*	High	82.1	3.53	266.87	174.41	168.37	0.63	0.61	Sm. dec.	Sm. dec.	3.4
American basswood	*Tilia americana*	Medium	64.2	3.86	219.06	298.72	270.11	1.21	1.09	Sm. inc.	No change	4.6
tamarack (native)	*Larix laricina*	High	42.6	4.9	245.46	282.86	283.93	1.15	1.16	No change	No change	3.1
black spruce	*Picea mariana*	High	50.4	3.64	222.14	145.91	146.39	0.68	0.68	Sm. dec.	Sm. dec.	4.3
eastern hemlock	*Tsuga canadensis*	High	66.3	3.38	197.75	225.25	188.69	1.19	1	No change	No change	2.7
red pine	*Pinus resinosa*	Medium	31.7	5.51	153.55	254.59	265.14	1.37	1.42	Sm. inc.	Sm. inc.	3
eastern white pine	*Pinus strobus*	High	41.8	3.73	150.95	407.9	352.44	2.33	2.01	Lg. inc.	Lg. inc.	3.3
white spruce	*Picea glauca*	Medium	73.8	1.95	170.84	159.16	174.17	1.02	1.12	No change	No change	3.9
northern red oak	*Quercus rubra*	Medium	45.2	3.03	104.52	491.27	453.21	3.87	3.57	Lg. inc.	Lg. inc.	5.4
bigtooth aspen	*Populus grandidentata*	Medium	41.2	2.05	97.46	212.78	184.2	1.92	1.66	Sm. inc.	Sm. inc.	5.1

Table A4-2 (continued). Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area. **Mod Rel**: the model reliability of the species' model predicting current and future suitable habitat (High, Medium, Low), based on several statistical parameters. **Pct Area**: the percentage of cells within the 1×1 degree of Lat/Lon (or other area) zone that currently have the species present according to the FIA data. It does not mean the species actually covers that amount of ground within the sample area. Also, if the 1×1 is only a partial rectangle because of coast or water, or because of the region of interest, there may be pieces without FIA plots or missing environmental predictors; therefore some fraction of the 1×1 without certain common species. Also, the region could be selecting only a small fraction of a cell with the species present. **FIAi**: the average importance value (IV) according to FIA records for the species, where it occurs, within the 10×10-km and/or 20×20-km cells of the area of interest. The 0–100 score is based on number of stems and basal area of tree species recorded during the FIA inventory cycle (FIA data used across the eastern U.S. range from 2001–2016). IVs are averaged at the cell level to indicate the average abundance of a species. Note that this IV is for the species only within the cells where it now occurs, not averaged over the entire region of interest. **MODi**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells. Includes cells that have modeled suitable habitat for the species, so that FIA plots need not be present for the model to predict species presence in the smaller cells. **GCM45i** or **GCM85i**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells, under the Representative Concentration Pathway (RCP) 4.5 (relatively low concentration future) or 8.5 (high concentration pathway) average of three general circulation models (GCMs) by 2100. **GCM45r** or **GCM85r**: the ratio of future (2070–2099) suitable habitat (=G45i/G85i) to current (1981–2010) habitat (=MODi), so that a ratio of 1 indicates no change in suitable habitat, <1 indicates a potential loss in habitat, and >1 indicates a potential gain in habitat by 2100 according to the lower (or higher) concentration scenario, average of three GCMs. **ChngCl4.5/8.5**: class of change in suitable habitat by 2100. Classes are based on ratios of future suitable habitat for common species. ***No Change*** = ratio 0.8–1.2; ***Small increase*** = ratio 1.2–2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5–0.8; ***Large decrease*** = ratio <0.5; ***Very Large decrease*** = future importance value of 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adapt**: Adaptability score for the species, according to a literature review of 12 disturbance and nine biological characteristics, or modification factors (Iverson et al. 2011, Matthews et al. 2011). Scores range from 1.7 (very low adaptability to a changing climate) to 8.5 (very high adaptability), with color class breaks at 3.4 and 5.2. Thus Low adaptability is 1.7–3.4, Moderate is 3.5–5.2, and High is >5.2.

Common Name	Scientific Name	Mod Rel	PctArea	FIAi	MODi	GCM45i	GCM85i	GCM45r	GCM85r	ChngCl45	ChngCl85	Adapt
black cherry	*Prunus serotina*	Medium	70.3	1.75	82.06	373.03	422.31	3.85	4.36	Lg. inc.	Lg. inc.	3
eastern hophornbeam; ironwood	*Ostrya virginiana*	Low	65.9	1.44	67.97	139	147.87	1.53	1.63	Sm. inc.	Sm. inc.	6.4
American elm	*Ulmus americana*	Medium	41.3	1.83	40.51	256.93	285.79	4.29	4.77	Lg. inc.	Lg. inc.	4
white ash	*Fraxinus americana*	Medium	41.1	1.48	52.38	211.32	269.15	3.6	4.59	Lg. inc.	Lg. inc.	2.7
green ash	*Fraxinus pennsylvanica*	Low	28.5	0.9	13.09	198.35	282.31	8.19	11.66	Lg. inc.	Lg. inc.	4
serviceberry	*Amelanchier* spp.	Low	15	1.03	0.92	0.15	0	0.01	NA	Lg. dec.	Very Lg. dec.	4.8
American hornbeam; musclewood	*Carpinus caroliniana*	Low	8.5	1.65	4.94	12.32	16.51	1.03	1.38	No change	No change	5.1
jack pine	*Pinus banksiana*	Medium	6	2.27	9.48	18.56	20.65	1.99	2.21	No change	No change	5.2
chokecherry	*Prunus virginiana*	FIA	18.7	0.32	NA	NA	NA	NA	NA	Unknown	Unknown	3.8
northern pin oak	*Quercus ellipsoidalis*	Medium	6.6	0.69	1.05	189.38	134.44	39.59	28.1	Lg. inc.	Lg. inc.	6
Norway spruce	*Picea abies*	FIA	1.7	4.37	NA	NA	NA	NA	NA	Unknown	Unknown	NA
pin cherry	*Prunus pensylvanica*	Low	3.4	1.46	1.3	0.26	0	0.09	0	Lg. dec.	Very Lg. dec.	4.2
mountain maple	*Acer spicatum*	Low	5.5	0.29	0.95	0.02	0.01	0.01	0	Lg. dec.	Lg. dec.	5.9
black willow	*Salix nigra*	Low	3.4	1.07	0.57	6.13	13.1	2.87	6.13	No change	Sm. inc.	2.8
bur oak	*Quercus macrocarpa*	Medium	1.7	1.28	0.55	178.95	187.38	139.81	146.39	Lg. inc.	Lg. inc.	6.4

Table A4-2 (continued). Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area. **Mod Rel**: the model reliability of the species' model predicting current and future suitable habitat (High, Medium, Low), based on several statistical parameters. **Pct Area**: the percentage of cells within the 1×1 degree of Lat/Lon (or other area) zone that currently have the species present according to the FIA data. It does not mean the species actually covers that amount of ground within the sample area. Also, if the 1×1 is only a partial rectangle because of coast or water, or because of the region of interest, there may be pieces without FIA plots or missing environmental predictors; therefore some fraction of the 1×1 without certain common species. Also, the region could be selecting only a small fraction of a cell with the species present. **FIAi**: the average importance value (IV) according to FIA records for the species, where it occurs, within the 10×10-km and/or 20×20-km cells of the area of interest. The 0–100 score is based on number of stems and basal area of tree species recorded during the FIA inventory cycle (FIA data used across the eastern U.S. range from 2001–2016). IVs are averaged at the cell level to indicate the average abundance of a species. Note that this IV is for the species only within the cells where it now occurs, not averaged over the entire region of interest. **MODi**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells. Includes cells that have modeled suitable habitat for the species, so that FIA plots need not be present for the model to predict species presence in the smaller cells. **GCM45i** or **GCM85i**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells, under the Representative Concentration Pathway (RCP) 4.5 (relatively low concentration future) or 8.5 (high concentration pathway) average of three general circulation models (GCMs) by 2100. **GCM45r** or **GCM85r**: the ratio of future (2070–2099) suitable habitat (=G45i/G85i) to current (1981–2010) habitat (=MODi), so that a ratio of 1 indicates no change in suitable habitat, <1 indicates a potential loss in habitat, and >1 indicates a potential gain in habitat by 2100 according to the lower (or higher) concentration scenario, average of three GCMs. **ChngCl4.5/8.5**: class of change in suitable habitat by 2100. Classes are based on ratios of future suitable habitat for common species. ***No Change*** = ratio 0.8–1.2; ***Small increase*** = ratio 1.2–2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5–0.8; ***Large decrease*** = ratio <0.5; ***Very Large decrease*** = future importance value of 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adapt**: Adaptability score for the species, according to a literature review of 12 disturbance and nine biological characteristics, or modification factors (Iverson et al. 2011, Matthews et al. 2011). Scores range from 1.7 (very low adaptability to a changing climate) to 8.5 (very high adaptability), with color class breaks at 3.4 and 5.2. Thus Low adaptability is 1.7–3.4, Moderate is 3.5–5.2, and High is >5.2.

Common Name	Scientific Name	Mod Rel	PctArea	FIAi	MODi	GCM45i	GCM85i	GCM45r	GCM85r	ChngCl45	ChngCl85	Adapt
peachleaf willow	*Salix amygdaloides*	FIA	3.4	0.31	NA	NA	NA	NA	NA	Unknown	Unknown	3.4
Scotch pine	*Pinus sylvestris*	FIA	0.1	0.03	NA	NA	NA	NA	NA	Unknown	Unknown	NA
silver maple	*Acer saccharinum*	Low	1.7	0.3	0	60.45	96.53	201.49	321.78	Lg. inc.	Lg. inc.	5.6
eastern redcedar	*Juniperus virginiana*	Medium	0	0	0	180.42	434.88	NA	NA	New Habitat	New Habitat	3.9
red spruce	*Picea rubens*	High	0	0	0	1.39	7.47	NA	NA	New Habitat	New Habitat	2.9
boxelder	*Acer negundo*	Low	0	0	0	46.44	58.54	NA	NA	New Habitat	New Habitat	7.4
pawpaw	*Asimina triloba*	Low	0	0	0.01	0	0	NA	NA	Unknown	Unknown	3.7
sweet birch	*Betula lenta*	High	0	0	0	0.95	7.97	NA	NA	New Habitat	New Habitat	3.2
bitternut hickory	*Carya cordiformis*	Low	0	0	0	25.12	31.69	NA	NA	New Habitat	New Habitat	5.6
pignut hickory	*Carya glabra*	Medium	0	0	0	11.28	66.32	NA	NA	New Habitat	New Habitat	4.7
shagbark hickory	*Carya ovata*	Medium	0	0	0	74.69	94.46	NA	NA	New Habitat	New Habitat	4.4
sugarberry	*Celtis laevigata*	Medium	0	0	0	0.01	3.62	NA	NA	Unknown	New Habitat	4.6
hackberry	*Celtis occidentalis*	Medium	0	0	0.01	2.6	15.26	NA	NA	New Habitat	New Habitat	5.7
American beech	*Fagus grandifolia*	High	0	0	0	121.37	187.34	NA	NA	New Habitat	New Habitat	3.6
black walnut	*Juglans nigra*	Low	0	0	0	89.67	174.05	NA	NA	New Habitat	New Habitat	4
yellow-poplar	*Liriodendron tulipifera*	High	0	0	0	5.93	81.88	NA	NA	New Habitat	New Habitat	5.3

Table A4-2 (continued). Tree Atlas results for 62 tree species in the area bounded by 46° to 47° north latitude and 90° to 91° west longitude. Tree species are presented in order of highest to lowest abundance within the analysis area. **Mod Rel**: the model reliability of the species' model predicting current and future suitable habitat (High, Medium, Low), based on several statistical parameters. **Pct Area**: the percentage of cells within the 1×1 degree of Lat/Lon (or other area) zone that currently have the species present according to the FIA data. It does not mean the species actually covers that amount of ground within the sample area. Also, if the 1×1 is only a partial rectangle because of coast or water, or because of the region of interest, there may be pieces without FIA plots or missing environmental predictors; therefore some fraction of the 1×1 without certain common species. Also, the region could be selecting only a small fraction of a cell with the species present. **FIAi**: the average importance value (IV) according to FIA records for the species, where it occurs, within the 10×10-km and/or 20×20-km cells of the area of interest. The 0–100 score is based on number of stems and basal area of tree species recorded during the FIA inventory cycle (FIA data used across the eastern U.S. range from 2001–2016). IVs are averaged at the cell level to indicate the average abundance of a species. Note that this IV is for the species only within the cells where it now occurs, not averaged over the entire region of interest. **MODi**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells. Includes cells that have modeled suitable habitat for the species, so that FIA plots need not be present for the model to predict species presence in the smaller cells. **GCM45i** or **GCM85i**: the area-weighted average importance value (IV) according to a Random Forest model for the species within cells, under the Representative Concentration Pathway (RCP) 4.5 (relatively low concentration future) or 8.5 (high concentration pathway) average of three general circulation models (GCMs) by 2100. **GCM45r** or **GCM85r**: the ratio of future (2070–2099) suitable habitat (=G45i/G85i) to current (1981–2010) habitat (=MODi), so that a ratio of 1 indicates no change in suitable habitat, <1 indicates a potential loss in habitat, and >1 indicates a potential gain in habitat by 2100 according to the lower (or higher) concentration scenario, average of three GCMs. **ChngCl4.5/8.5**: class of change in suitable habitat by 2100. Classes are based on ratios of future suitable habitat for common species. ***No Change*** = ratio 0.8–1.2; ***Small increase*** = ratio 1.2–2.0; ***Large increase*** = ratio >2.0; ***Small decrease*** = ratio 0.5–0.8; ***Large decrease*** = ratio <0.5; ***Very Large decrease*** = future importance value of 0. ***New Habitat*** = FIA data currently does not show this species in the analysis area, but future importance value >0. **Adapt**: Adaptability score for the species, according to a literature review of 12 disturbance and nine biological characteristics, or modification factors (Iverson et al. 2011, Matthews et al. 2011). Scores range from 1.7 (very low adaptability to a changing climate) to 8.5 (very high adaptability), with color class breaks at 3.4 and 5.2. Thus Low adaptability is 1.7–3.4, Moderate is 3.5–5.2, and High is >5.2.

Common Name	Scientific Name	Mod Rel	PctArea	FIAi	MODi	GCM45i	GCM85i	GCM45r	GCM85r	ChngCl45	ChngCl85	Adapt
blackgum	*Nyssa sylvatica*	Medium	0	0	0	2.78	41.98	NA	NA	New Habitat	New Habitat	5.9
sycamore	*Platanus occidentalis*	Low	0	0	0	4.72	84.26	NA	NA	New Habitat	New Habitat	4.8
balsam poplar	*Populus balsamifera*	Medium	0	0	2.71	0	0	NA	NA	Unknown	Unknown	4
eastern cottonwood	*Populus deltoides*	Low	0	0	0	44.23	87.1	NA	NA	New Habitat	New Habitat	3.9
white oak	*Quercus alba*	Medium	0	0	0	322.74	420.95	NA	NA	New Habitat	New Habitat	6.1
swamp white oak	*Quercus bicolor*	Low	0	0	0	20.18	50.96	NA	NA	New Habitat	New Habitat	4.9
scarlet oak	*Quercus coccinea*	Medium	0	0	0	2.2	12.39	NA	NA	New Habitat	New Habitat	4.6
pin oak	*Quercus palustris*	Low	0	0	0	0.52	11.7	NA	NA	New Habitat	New Habitat	2.8
chestnut oak	*Quercus prinus*	High	0	0	0	4.1	11.83	NA	NA	New Habitat	New Habitat	6.1
black oak	*Quercus velutina*	High	0	0	0	258.85	382.06	NA	NA	New Habitat	New Habitat	4.9
black locust	*Robinia pseudoacacia*	Low	0	0	0	103.2	194.3	NA	NA	New Habitat	New Habitat	3.8
sassafras	*Sassafras albidum*	Low	0	0	0	0.71	68.86	NA	NA	New Habitat	New Habitat	4.2
American mountain-ash	*Sorbus americana*	Low	0	0	0.01	0.01	0	NA	NA	Unknown	Unknown	3.1
slippery elm	*Ulmus rubra*	Low	0	0	0	6.82	17.48	NA	NA	New Habitat	New Habitat	4.8

Modifying Factors and Adaptability Scores

Table A4-2 also shows information on the adaptability scores used in the Tree Atlas. These scores were developed based on a review of modifying factors, using a literature based scoring system to capture the potential adaptability of species to changes in climate that cannot be adequately captured by the DISTRIB model (Matthews et al. 2011). This approach was used to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics like competition ability for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pests, and fire.

This information distinguishes among species likely to be more tolerant (or sensitive) to environmental changes than the habitat models alone suggest. For each biological and disturbance factor, a species was scored on a scale from −3 to +3. A score of −3 indicated a very negative response of that species to that factor. A score of +3 indicated a very positive response to that factor. To account for confidence in the literature about these factors, each of these scores was then multiplied by 0.5, 0.75, or 1, with 0.5 indicating low confidence and 1 indicating high confidence. Finally, the score was further weighted by its relevance to future projected climate change by multiplying it by a relevance factor. A 4 indicated highly relevant and a 1 indicated not highly relevant to climate change. Means for individual biological scores and disturbance scores were then calculated to arrive at an overall biological and disturbance score for the species. To arrive at an overall adaptability score for the species that could be compared across all modeled tree species, the mean, rescaled (0–6) values for biological and disturbance characteristics were plotted to form two sides of a right triangle; the hypotenuse was then a combination (disturbance and biological characteristics) metric, ranging from 0 to 8.5 (Figure A4-1). For this assessment, adaptability scores 3.2 and less are considered low, and scores of 5.3 and greater are considered high. In Chapter 3, adaptability is presented categorically (Low, Moderate, and High) to avoid overstating the certainty and precision of the numerical values.

Note that modifying factors and adaptability scores are calculated for a species across its entire range. Many species may have higher or lower adaptability in certain areas. For example, a species with a low flooding tolerance may have higher adaptability in areas not subject to flooding. Likewise, local impacts of insects and disease may reduce the adaptability of a species in that area.

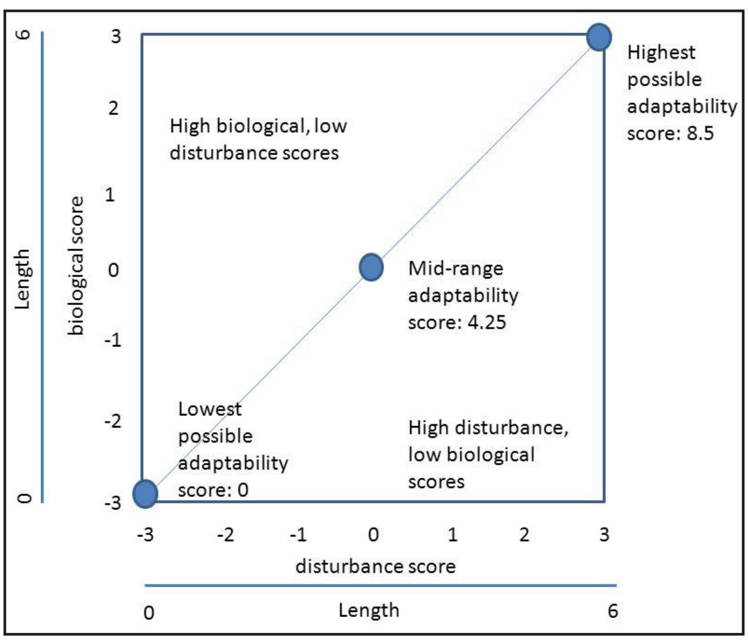


Figure A4-1. Schematic showing how adaptability was determined for information for the 62 tree species in the assessment area modeled using the Climate Change Tree Atlas. Adaptability scores are described in the appendix text.

Appendix 5: Vulnerability and Confidence Determination Process

To assess the climate change vulnerability of each terrestrial ecosystem in the Apostle Islands, we elicited input from a panel of 17 experts from a variety of land management and research organizations across the Great Lakes region (Table A5-1). We sought a team of panelists who would be able to contribute a diversity of subject area expertise, management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology of the Apostle Islands. This panel was assembled at an in-person workshop in Ashland, Wisconsin, in March 2018. Here we describe the structured discussion process that the panel used.

USDA Forest Service/S. Handler

Ecosystems Assessed

The authors of this assessment used the ecosystem classification described in Chapter 1. Prior to the workshop, a sub-group of authors collected information related to the major system drivers, dominant species, and stressors that characterize that community from the relevant ecological literature. The panel members had the opportunity to review and amend the community descriptions on a webinar prior to the workshop, and those suggestions were incorporated into the descriptions.

Table A5-1. Names and affiliations of the participants in the March 2018 expert panel workshop. Asterisks (*) indicate workshop facilitators.

Name	Affiliation
Peggy Burkman	National Park Service, Apostle Islands National Lakeshore
Julie Van Stappen	National Park Service, Apostle Islands National Lakeshore
Bob Krumenaker	National Park Service, Apostle Islands National Lakeshore (now Big Bend National Park)
Dave Cooper	National Park Service, Apostle Islands National Lakeshore
Ulf Gafvert	National Park Service, Great Lakes Inventory and Monitoring Network (retired)
Damen Panek	National Park Service, Apostle Islands National Lakeshore
Sarah Johnson	Northland College
Matt Cooper	Northland College
Ryan O'Connor	Wisconsin Department of Natural Resources
Eric Epstein	Wisconsin Department of Natural Resources (retired)
Linda Parker	U.S. Forest Service
Christopher Swanston	U.S. Forest Service Northern Research Station and Northern Institute of Applied Climate Science
Alexia Prosperi	Great Lakes Integrated Sciences and Assessments (now U.S. Forest Service Eastern Region)
Brent Lofgren	National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory
Nisogaabo Ikwe Melonee Montano	Great Lakes Indian Fish and Wildlife Commission
Hannah Panci	Great Lakes Indian Fish and Wildlife Commission
Naomi Tillison	Bad River Band of Lake Superior Chippewa
Stephen Handler*	U.S. Forest Service Northern Research Station and Northern Institute of Applied Climate Science
Kristen Schmitt*	Michigan Technological University and Northern Institute of Applied Climate Science

Potential Impacts

To examine potential impacts, the panel was given several sources of background information on past and future climate change in the region (summarized in Chapter 2) and projected impacts on dominant tree species, Lake Superior dynamics, and other relevant topics (summarized in Chapter 3). The panel was directed to focus on impacts to each ecosystem from the present through the end of the century, but more weight was given to the end-of-century period. The panel assessed impacts by considering a range of climate futures bracketed by two scenarios: RCP 4.5 and RCP 8.5. Panelists were then led through a structured discussion process to consider this information for each ecosystem considered in the assessment. Potential impacts on ecosystem drivers and stressors were summarized based on climate model projections, published literature, and insights from the panelists. Impacts on drivers were rated based on whether they would be supportive or disruptive to the ecosystem in question. Impacts on stressors were considered negative if they increased the influence of that stressor or positive if they decreased the influence of that stressor. Panelists were also asked to consider the potential for climate change to facilitate new stressors in the Apostle Islands over the next century. To assess potential impacts on dominant tree species, the panelists examined results from Tree Atlas and were asked to consider those results in addition to their knowledge of life history traits and ecology of those species. Panel members also contributed their own knowledge on the particular characteristics and key species for each ecosystem. Finally, panelists were asked to consider the potential for interactions among anticipated climate trends, species impacts, and stressors. Input on these future ecosystem interactions relied primarily on the panelists' expertise and judgment because there are not many examples of published literature on complex interactions, nor are future interactions accurately represented by ecosystem models.

Adaptive Capacity

Panelists discussed the adaptive capacity of each ecosystem based on their ecological knowledge and experience with the Apostle Islands and the surrounding region. Panelists were told to focus on community characteristics that would increase or decrease the adaptive capacity of that ecosystem. Factors that the panel considered included characteristics of dominant species within each ecosystem (e.g., dispersal ability, genetic diversity, range limits) and comprehensive characteristics (e.g., functional and species diversity or species richness, tolerance to a variety of disturbances, distribution across the landscape). The panelists were directed to base their considerations on the current condition of the system given past and current management regimes, with no consideration of potential adaptation actions that could take place in the future.

Vulnerability

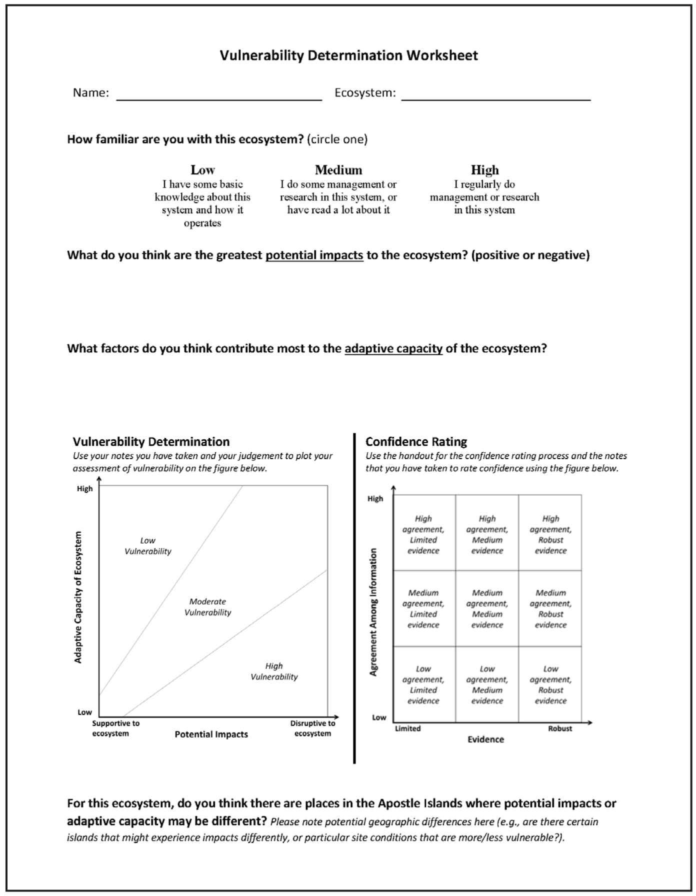
As explained in Chapter 4, we consider an ecosystem to be vulnerable if it is at risk of changes leading to a new ecological state; if it may have reduced ability to fulfill key ecosystem functions; or if the system is anticipated to suffer substantial declines in health, productivity, or geographic extent. Expert panel members discussed this broad definition of vulnerability on a webinar prior to the workshop and again at the workshop, so that everyone had a common understanding.

Following extensive group discussion, each panelist evaluated the potential impacts and adaptive capacity of each ecosystem to arrive at a vulnerability rating. Participants were provided with individual worksheets and asked to list which impacts they felt were most important to that system in addition to the major factors that would contribute to the adaptive capacity of that system (Figure A5-1). Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Figure A5-2). This vulnerability figure required the participants to evaluate the degree of potential impacts related to climate change as well as the adaptive

capacity of the system to tolerate those impacts. Individual ratings were compared and discussed and used to arrive at a group determination. In many cases, the group determination was at or near the centroid of all individual determinations. Sometimes the group determination deviated from the centroid because further discussion convinced some group members to alter their original response.

Confidence

Panelists were also directed to give a confidence rating to each of their individual vulnerability determinations (Figure A5-3). Panelists were asked to evaluate the amount of evidence they felt was available to support their vulnerability determination and the level of agreement among the available evidence (Mastrandrea et al. 2010). Panelists evaluated confidence individually and as a group, in a similar fashion to the vulnerability determination. Vulnerability and Confidence figures appear in Chapter 4 for each ecosystem. We do not intend for direct comparison between these figures because the axes represent subjective, qualitative scales.


Vulnerability Determination Worksheet

Name: ________________ Ecosystem: ________________

How familiar are you with this ecosystem? (circle one)

Low	Medium	High
I have some basic knowledge about this system and how it operates	I do some management or research in this system, or have read a lot about it	I regularly do management or research in this system

What do you think are the greatest potential impacts to the ecosystem? (positive or negative)

What factors do you think contribute most to the adaptive capacity of the ecosystem?

Vulnerability Determination
Use your notes you have taken and your judgement to plot your assessment of vulnerability on the figure below.

Confidence Rating
Use the handout for the confidence rating process and the notes that you have taken to rate confidence using the figure below.

For this ecosystem, do you think there are places in the Apostle Islands where potential impacts or adaptive capacity may be different? *Please note potential geographic differences here (e.g., are there certain islands that might experience impacts differently, or particular site conditions that are more/less vulnerable?).*

Figure A5-1. The individual worksheet used by each expert panel member to take notes and assess vulnerability and confidence for each Apostle Islands ecosystem.

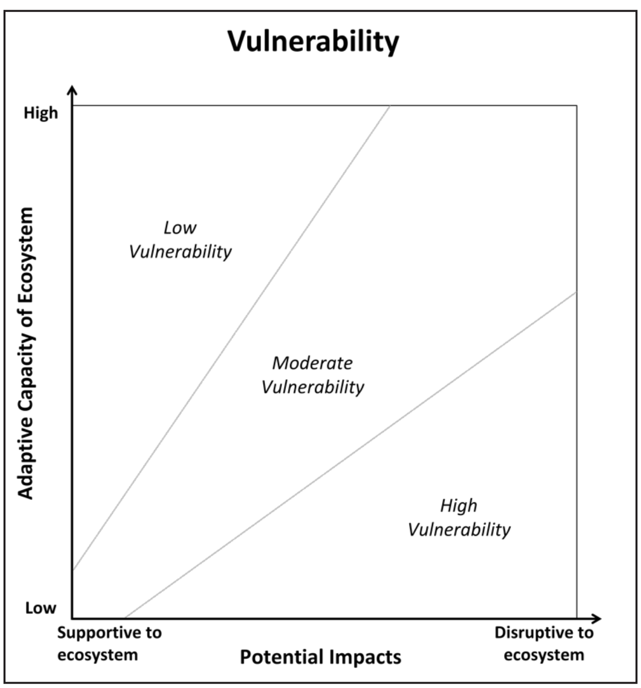


Figure A5-2. Chart used to rank climate change vulnerability of Apostle Islands terrestrial ecosystems, illustrating the relationship among potential impacts and adaptive capacity. Modified from Swanston et al. (2011).

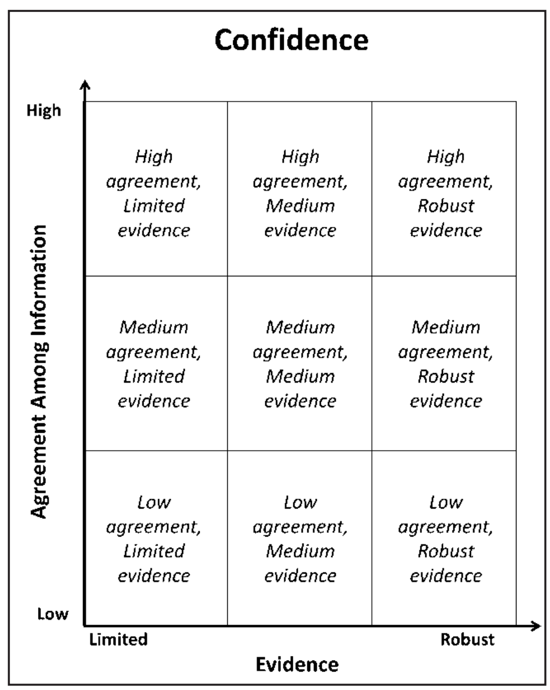


Figure A5-3. Confidence determination diagram used in the assessment workshop. Adapted from Mastrandrea et al. (2010).

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