Effects of Climate Change on Midwestern Ecosystems: North American Bog and Fen

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Table of Contents

Foreword 5
Series Overview 5
Process 5
Habitat Selection 5
Climate Exposure 5
Habitat Prioritization 6
Focal Wildlife Species 7
Focal Aquatic Systems 8
Literature Review 8
Taxonomic Conventions 8
Chapter Organization 8
Executive Summary 10
North American Bog and Fen 11
Key Climate Change Stressors 11
Water Deficits 11
Warming 11
Key Climate Change Impacts 14
Habitat Structure 14
Community Composition 16
Invasive Species 18
Pests and Pathogens 18
Microbial Communities 19
Climate Change Impacts by Habitat 20
Midwest Prairie Alkaline Fen 20
Overview of Climate Projections 23
Key Climate Change Stressors 23
Key Climate Change Impacts 26
Focal Wildlife Species: Eastern Massasauga 30
Focal Aquatic System: Saul Lake Bog 31
Eastern North American Boreal-Subboreal Bog and Acidic Fen 32
Overview of Climate Projections 34
Key Climate Change Stressors 35
Key Climate Change Impacts 38

Focal Wildlife Species: Four-toed Salamander 43
Work Cited 44
Appendix 1 64
Appendix 2 69

Foreword

Series Overview

The following is the third chapter of a multi-part series examining the vulnerability of natural habitats in the Midwest region to the impacts of climate change. This work was conceived as part of an interagency effort to facilitate the inclusion of climate change considerations into 2025 revisions of State Wildlife Action Plans (SWAPs). Although tailored to the needs of state agencies within the Midwest region, these assessments focus on habitats and species found throughout North America and are thus broadly relevant to regions and considerations beyond that of the Midwest.

This work was developed as a collaboration between the U.S. Geological Survey (USGS) Midwest Climate Adaptation Science Center (MW CASC) and natural resource agencies from Minnesota, Wisconsin, Michigan, Ohio, Indiana, Illinois, Iowa, and Missouri. During discussions on the needs and challenges of the 2025 SWAP revision process, collaborators identified habitat climate vulnerability as a key area requiring further exploration and deeper understanding.

Process

To assess the impact of climate change on habitats in the Midwest, the MW CASC developed a process comprised of the following steps: 1) potential habitat identification and delineation; 2) summarizing exposure to key climate change stressors; and 3) reviewing and synthesizing relevant scientific literature into qualitative summaries of climate change impacts to habitats.

Habitat Selection

We identified and defined habitats using the U.S. National Vegetation Classification database (USNVC, 2020), which provides a common lexicon of hierarchically classified and spatially referenced vegetation communities throughout the United States. Within this hierarchy, the Group level represents the finest resolution classification tier that is coupled with spatially referenced distributions. Hereafter, discrete “habitats” are synonymous with USNVC Groups and their corresponding lower-level community classifications (Alliance and Association). To enhance relevancy for the Midwest region, the lowest-level classifications for each group (Association) not occurring within the Midwest were excluded from this assessment.

Climate Exposure

To summarize climate exposure, we utilized a combination of Level II and Level III ecoregions (U.S. Environmental Protection Agency, 2013) to identify 12 ecologically relevant subregions of the Midwest that served as the spatial basis for summarizing climate exposure (Figure i). Climate projections are derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and were statistically downscaled using the MACAv2-METDATA dataset, which applies the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou, 2013; van Vuuren and others, 2011). Projections are presented under two greenhouse gas concentration pathways: RCP4.5, an emissions scenario assuming global mitigation efforts that lead to greenhouse gas emissions peaking mid-century and stabilizing by 2100, and RCP8.5, a high-emissions scenario that assumes continued growth in greenhouse gas emissions with

limited mitigation. These scenarios represent a range of plausible future climate conditions and are commonly used to bracket moderate and high-end climate change trajectories. In-text references to climate projections primarily detail RCP8.5 estimates to highlight particularly severe outcomes, although all tables and figures report both RCP4.5 and RCP8.5 estimates. To capture variation across CMIP5 climate models, models with the lowest (minimum model) and highest (maximum model) projected values under the RCP8.5 scenario are presented in addition to the mean of all models. Appendix 2 includes a list of all climate models as well as the minimum and maximum model selected for each region and climate variable.

Figure i. Distribution and names of 12 ecoregions within the larger Midwest region. Ecoregions represent a mixture of Level II and Level III EPA ecoregions (U.S. Environmental Protection Agency, 2013) and have been renamed following the Midwest Conservation Blueprint Ecoregions (Wright and others, 2022).

Habitat Prioritization

Seventy-seven natural Groups (i.e., habitats) occur in states comprising the Midwest region (Minnesota, Wisconsin, Michigan, Ohio, Indiana, Illinois, Iowa, and Missouri). To focus this assessment on a subset of

these habitats, representatives from each state identified two or more habitats for each ecoregion present in their respective state. We reconciled conflicting priorities to identify two habitats per ecoregion (hereafter identified as "priority habitats") for a total of 22 priority habitats that served as the focus of our analysis (Table i).

Table i. Priority habitats for each ecoregion. Analogous Level III EPA ecoregion numbers (U.S. Environmental Protection Agency, 2013) and U.S. National Vegetation Classification database Group numbers (USNVC, 2020) are provided for each ecoregion and priority habitat.

Ecoregion	Priority habitat
Appalachian Forest (8.4.3)	Appalachian-Central Interior Mesic Forest (G020)
	Central Appalachian-Northeast Oak Forest and Woodland (G650)
Central Irregular Plains (9.2.4)	Central Midwest Oak Openings and Barrens (G181)
	South Central-Appalachian-Northeast Floodplain Forest Group (G673)
Central Plains (8.2.1–8.2.4)	Midwest Floodplain Forest (G652)
	Central Interior-Great Lakes Flatwoods and Swamp Forest (G917)
Driftless Area (8.1.5)	North-Central Beech- Maple- Basswood Forest (G021)
	North-Central Oak- Hickory Forest and Woodland (G649)
Erie Drift Plains (8.1.1, 8.1.10)	North-Central Beech- Maple- Basswood Forest (G021)
	Appalachian-Northeast Mesic Forest (G742)
Interior Plateau (8.3.2, 8.3.3, 8.3.6, 8.5.2)	Bald-cypress- Tupelo Floodplain Forest (G033)
	Interior Low Plateau Oak Forest, Woodland and Savanna (G950)
Mixed Wood Plains (8.1.4)	Laurentian-Acadian Alkaline Swamp (G046)
	Eastern North American Freshwater Marsh (G125)
Northern Hardwood Forest (5.2.1, 5.2.2)	Laurentian Subboreal Mesic Balsam Fir- Spruce- Hardwood Forest (G048)
	Eastern North American Boreal-Subboreal Bog and Acidic Fen (G1172)
Northern Plains (9.2.1, 9.2.2)	Northern Tallgrass Prairie (G075)
	Midwest Wet Prairie, Wet Meadow, and Shrub Swamp (G770)
Ozarks (8.4.5)	Central Midwest Oak Openings and Barrens (G178)
	Oak- Shortleaf Pine Ozark-Ouachita Forest, Woodland and Savanna (G949)
Temperate Prairie (9.2.3)	North-Central Oak-Hickory Forest and Woodland (G059)
	Interior Low Plateau Oak Woodland Forest (G333)
Great Lakes Plains (8.1.6)	Midwest Prairie Alkaline Fen (G183)

Focal Wildlife Species

We include focal wildlife species to demonstrate how habitat impacts may influence wildlife responses to climate change. For each priority habitat (Table i), we review climate change impacts on one focal wildlife species, with specific attention paid to habitat considerations. We selected focal wildlife species based on consultation with state agencies, with the aim of choosing species listed by one or more state agency as a Species of Greatest Conservation Need (SGCN).

Focal Aquatic Systems

Because the USNVC is predominantly focused on terrestrial habitat types, we also include sections summarizing the impact of climate change on select focal aquatic systems. Unlike the focal wildlife species sections, which are associated with specific priority habitats (Table i), we selected one focal aquatic system for each ecoregion (Figure i). These selections were based on consultation with state agencies, with the aim of discussing a diverse set of aquatic system types. While focused on specific geographic areas, each section includes climate change impacts that are relevant to the broader aquatic system type.

Literature Review

For each priority habitat, we reviewed and synthesized available scientific literature. We used USNVC habitat descriptions and lists of dominant plant species provided for each Group and relevant sub-level to characterize each habitat and focus our literature search (Appendix 1). We searched for relevant literature related to these habitat characteristics and dominant species that either explicitly mentioned climate change or indirectly discussed climate-related topics. Lastly, to narrow our focus, we identified two particularly relevant climate-related stressors for each habitat to hone our literature search.

Taxonomic Conventions

Wherever possible, we follow the Integrated Taxonomic Information System database (Integrated Taxonomic Information System (ITIS), 2025) for common names, Latin names, and taxonomic authorities. Because many species have multiple common names, we defer to the PLANTS Database (USDA, NRCS, 2025) to select a single, consistent common name for each plant species. In cases where taxonomic resolution is lacking, such as for certain pests or pathogens not included in ITIS, we use the most widely accepted names from the primary scientific literature. To enhance clarity and usability, especially for readers consulting individual sections as standalone references, we define Latin names at first mention for each common name in each chapter subsection.

Chapter Organization

Each chapter in this series focuses on a subset of ecologically related priority habitats (Table ii). Because climate change impacts are frequently shared between similar habitat types, we first provide an overview of climate impacts to the broader system type before summarizing climate impacts for each specific habitat. The higher-level USNVC classification that links ecologically similar habitats (typically at the Macrogroup level and hereafter referred to as “ecosystem”) determines each broader system type into which chapters are organized.

Table ii. Series chapters and priority habitats. Habitats are organized by the series chapter in which they occur, with their corresponding U.S. National Vegetation Classification database Group numbers (USNVC, 2020).

Series chapter	Priority habitat
1. Temperate Flooded and Swamp Forest	Midwest Floodplain Forest (G652)
	South Central-Appalachian-Northeast Floodplain Forest Group (G673)
	Bald-cypress- Tupelo Floodplain Forest (G033)
	Central Interior-Great Lakes Flatwoods and Swamp Forest (G917)
	Laurentian-Acadian Alkaline Swamp (G046)
2. Appalachian-Interior-Northeast Mesic Forest	Appalachian-Central Interior Mesic Forest (G020)
	Appalachian-Northeast Mesic Forest (G742)
	North-Central Beech- Maple- Basswood Forest (G021)
3. North American Bog and Fen	Midwest Prairie Alkaline Fen (G183)
	Eastern North American Boreal-Subboreal Bog and Acidic Fen (G1172)
4. Eastern North American Temperate Freshwater Marsh, Wet Meadow and Shrubland	Eastern North American Freshwater Marsh (G125)
	Midwest Wet Prairie, Wet Meadow and Shrub Swamp (G770)
5. Central and Eastern North American Grassland and Shrubland	Central Tallgrass Prairie (G333)
	Northern Tallgrass Prairie (G075)
	Central Interior Acidic Open Glade and Barrens (G178)
	Eastern North American Ruderal Meadow and Shrubland (G059)
6. Central Interior Oak Forest, Woodland and Savanna	Interior Low Plateau Oak Forest, Woodland and Savanna (G950)
	Oak- Shortleaf Pine Ozark-Ouachita Forest, Woodland and Savanna (G949)
	Central Midwest Oak Openings and Barrens (G181)
	North-Central Oak- Hickory Forest and Woodland (G649)
	Central Appalachian-Northeast Oak Forest and Woodland (G650)
7. Laurentian-Acadian Mesic Hardwood- Conifer Forest	Laurentian Subboreal Mesic Balsam Fir- Spruce- Hardwood Forest (G048)

Executive Summary

The North American Bog and Fen ecosystem is increasingly vulnerable to climate stressors, particularly water deficits and warming temperatures. These peat-forming wetlands, found at the southern extent of their range in the Midwest, depend on relatively stable hydrological and thermal conditions. Climate change may disrupt these conditions through projected declines in summer precipitation, increases in summer vapor pressure deficit and temperature, and longer periods of warmth throughout the year. These changes could lower water tables, accelerate aerobic decomposition, and alter peat-accumulating processes that define bogs and fens. Water deficits, compounded by warmer conditions, may reduce moss and sedge productivity and promote peat subsidence and compaction. Collectively, these impacts may compromise the structural integrity of this ecosystem and reduce its capacity to store carbon, maintain unique microhabitats, and support moisture-dependent species.

The two focal North American Bog and Fen habitats in the Midwest, the Midwest Prairie Alkaline Fen habitat and Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat, may experience distinct yet overlapping impacts from climate change. Midwest Prairie Alkaline Fen habitats, which depend on cool, calcareous groundwater, could be especially sensitive to increasingly irregular recharge, driven by altered precipitation patterns and rising evapotranspiration, potentially leading to lower water tables and peat desiccation. Eastern North American Boreal-Subboreal Bog and Acidic Fen habitats, though somewhat buffered by their more northern and cooler climates, may also be affected by water deficits and warming temperatures that favor relatively drought-tolerant shrubs and other vascular plants over moss-dominated communities. In both habitats, these stressors may contribute to long-term transitions from open, saturated peatlands to drier ecosystems with greater woody cover.

In addition to hydrological and thermal effects on habitat structure and community composition, biotic interactions may also be shaped by climate change. Declining water tables and elevated nutrient availability may relax environmental constraints and create opportunities for invasive species that thrive under warmer, drier, and more nutrient-rich conditions. These species may outcompete native sedges, mosses, and forbs, contributing to further declines in native bog and fen specialists. While less studied than in forested systems, pest and pathogen pressures in this ecosystem may intensify with warming, particularly for tree species vulnerable to insect outbreaks. Warming-driven shifts in microbial communities, including a decline in moss-associated fungi, increased decomposer activity, and greater carbon mobilization, may further alter nutrient cycling and peatland carbon dynamics.

Human activities have already reduced the historical extent of the North American Bog and Fen ecosystem, and climate change may further erode the environmental conditions that sustain them, threatening their continued presence in the Midwest. Conservation strategies may therefore benefit from prioritizing the protection of hydrological regimes and slowing the spread of both woody and invasive species, to help preserve ecosystem function and biodiversity.

North American Bog and Fen

Key Climate Change Stressors

Climate change is creating new challenges for the North American Bog and Fen ecosystem, especially through increasing water deficits and warming temperatures. These temperate peatlands, which are at the southern edge of their range in the Midwest, depend on a narrowly defined set of hydrological and thermal conditions (Burkman and others, 2023; Faber-Langendoen, 2005; Jaszczuk and others, 2024; Kost and others, 2007; Xu and others, 2018). Their historical extent has already been reduced by human activities (Campbell and others, 2021; Lamers and others, 2015; Ma and others, 2022), and, as a result, future shifts in water and temperature conditions may further jeopardize their persistence across the Midwest.

Water Deficits

Bogs and fens are peat-forming wetlands that depend on reliable water inputs throughout the year. Water balance is shaped by both inputs and losses, with evapotranspiration as the primary export. When evapotranspiration increases, especially during dry periods, water tables can drop, leading to moisture deficits (Didiano and others, 2018; Rochefort and others, 2012; Waddington and others, 2015). Bogs receive nearly all their water from precipitation, which creates acidic, nutrient-poor (i.e., ombrotrophic) conditions. Fens, by contrast, are fed mainly by groundwater, resulting in more nutrient-rich and less acidic (i.e., minerotrophic) environments (Bedford and Godwin, 2003; Kost and others, 2007). Because groundwater inputs are generally more stable than rainfall, fens are often more buffered from short-term drying than bogs (Rochefort and others, 2012).

While individual models vary, climate projections suggest that summer precipitation may decline in the coming century, with the majority indicating a net drying trend across much of the Midwest (Figure 1), and increasing evapotranspiration (Grady and others, 2021; Marvel and others, 2021; Marvel and others, 2023; Zhao and others, 2023). As a result, water deficits may become more frequent and intense. Bogs may be especially sensitive to reduced summer precipitation. Where climate change and agricultural use contribute to declines in groundwater recharge, fens could also be negatively affected (Anurag and Ng, 2022; Christie and Bostwick, 2012; Costa and others, 2021; Kløve and others, 2014; Wuebbles and others, 2021).

Warming

Temperatures are projected to rise across the Midwest, with longer growing seasons, more frequent temperature extremes, and consistently warmer summers across all climate models (Figure 2) (Ford and others, 2021; Marvel and others, 2023; Xue and others, 2022). Warming may increase evapotranspiration, reduce moisture availability, and alter key ecological processes, all threatening the sustainability of these peatlands (Bu and others, 2011; Essl and others, 2012; Ma and others, 2022; Salimi and others, 2021).

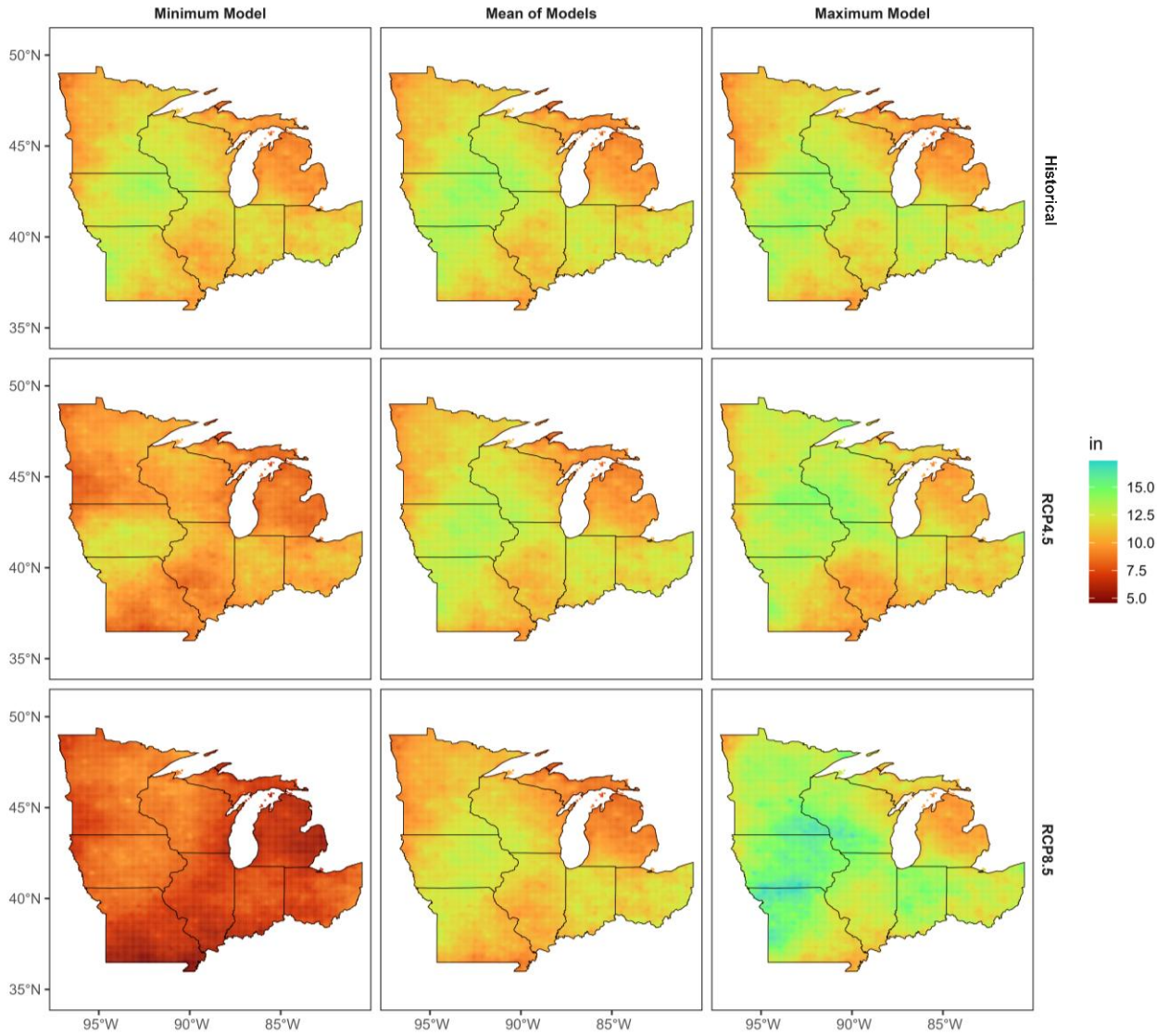

Figure 1. Projected changes in summer precipitation in the Midwest. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) total summer (June–August) precipitation (inches) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected summer precipitation under RCP 8.5 are presented in addition to the mean of all models (middle column).

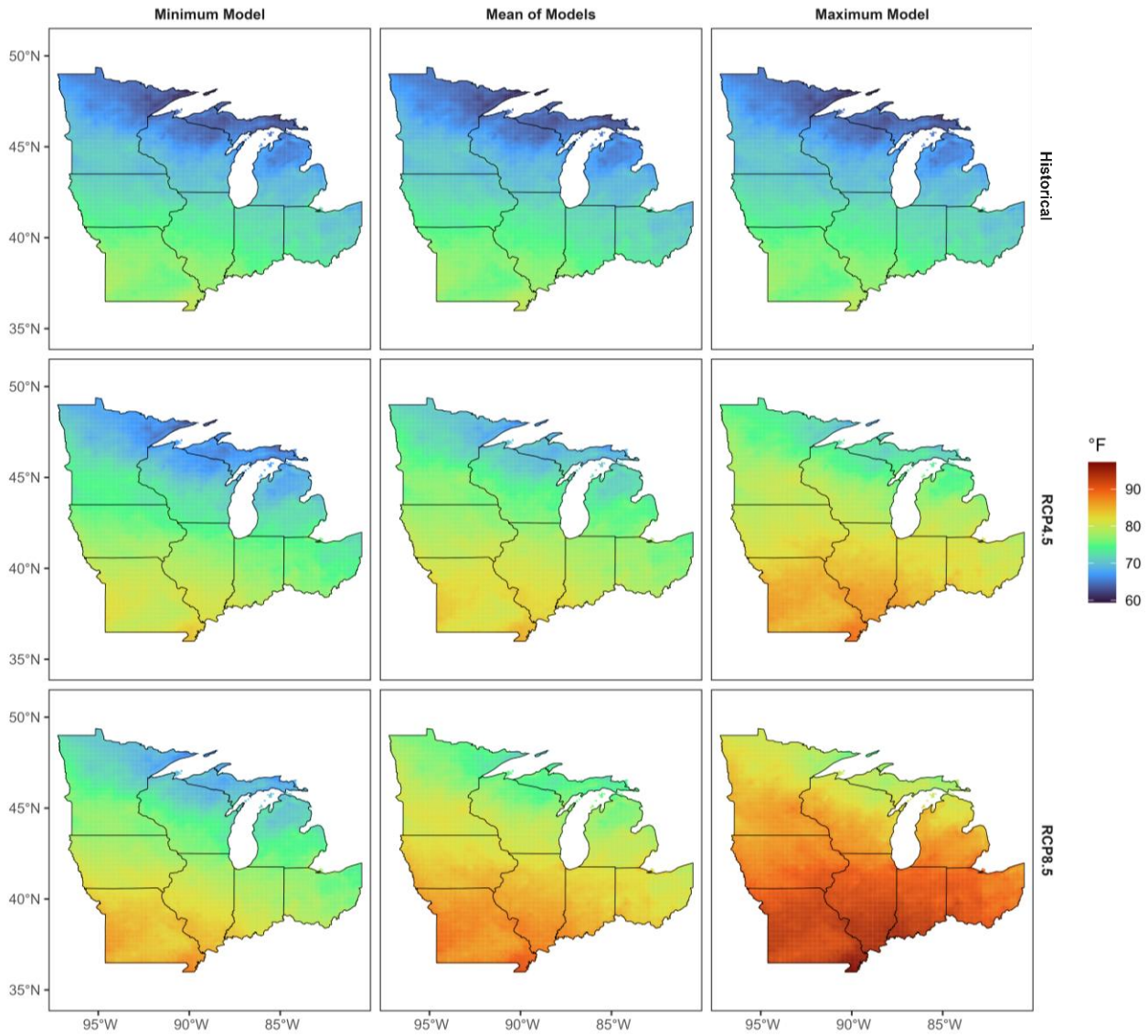

Figure 2. Projected changes in summer mean temperature in the Midwest. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) summer (June–August) mean temperature (°F) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected summer mean temperature under RCP 8.5 are presented in addition to the mean of all models (middle column).

Key Climate Change Impacts

Many species have evolved specialized strategies to thrive under the unique hydrological conditions of the North American Bog and Fen ecosystem. Water deficits and warming may impose substantial stress on this ecosystem, potentially altering habitat structure, community composition, and species interactions.

Habitat Structure

Abiotic responses to water deficits. Water deficits can change the structure and biogeochemistry of the North American Bog and Fen ecosystem. Peat forms when water-saturated soils slow decomposition, allowing organic material to accumulate over time. As water tables drop, oxygen is introduced into the peat layer, increasing aerobic respiration, promoting microbial activity, decomposition, and the release of stored nutrients (Breeuwer and others, 2009; Chapin and others, 1995; Jaatinen and others, 2007; Loisel and Gallego-Sala, 2022; Strack and others, 2006a; Trettin and others, 2019; Zhong and others, 2020). If nutrient levels rise enough, these changes may contribute to the eutrophication of otherwise nutrient-poor bogs and fens (Grootjans and others, 1996; Kost and others, 2007; Lamers and others, 2015; Middleton and others, 2006).

Peat naturally contracts during dry periods, reducing the small spaces between plant material that usually hold water. But with more severe or prolonged water deficits, peat can compact and subside, altering microtopography and potentially forming cracks that lead to further desiccation (Kost and others, 2007; Lamers and others, 2015; Potvin and others, 2015; Price and Schlotzhauer, 1999). Compacted peat may retain less water, intensify future drought impacts, and become more vulnerable to erosion during heavy rainfall (Loisel and Gallego-Sala, 2022; Price and Schlotzhauer, 1999). Drier, denser peat is also more flammable, increasing the risk of intense fires that can further shift nutrient dynamics and alter bog and fen hydrology (Kettridge and others, 2015; Kost and others, 2007; Rochefort and others, 2012; Staffen and others, 2019; Turetsky and others, 2015). Decomposition, desiccation, and fire may also contribute to carbon loss, increased acidity, and higher rates of iron and sulfate oxidation (Bourbonniere, 2009; Hughes and others, 1997; Lamers and others, 1998; Lamers and others, 2015). These changes may disrupt the delicate conditions that sustain bogs and fens, making them less suitable for historically dominant plant species and potentially promoting succession toward drier ecosystem types (Amon and others, 2002; Fiedler, 2010; Kost and others, 2007; Spieles and others, 1999).

Abiotic responses to warming. One of the most direct effects of warming on the North American Bog and Fen ecosystem is the increase in evapotranspiration, which contributes to lower water tables, drier surface conditions, and more aerobic soils (Heijmans and others, 2013; Wilson and others, 2016). Longer growing seasons may further reduce soil moisture, intensifying seasonal water deficits (Moore and Waddington, 2015; Zhong and others, 2020). Rising soil temperatures can also disrupt winter hydrological processes. For example, increased soil frost may reduce snowmelt infiltration, leading to greater spring runoff and water table fluctuations (Friesen and others, 2021).

Warming also accelerates biogeochemical processes, increasing the mineralization of nutrients like nitrogen and phosphorus (Hájek and others, 2020; Heijmans and others, 2013; Iversen and others, 2023; Middleton and others, 2006; Norby and others, 2019). This greater nutrient availability may reduce the environmental extremity of bogs and fens, diminishing the advantage held by species adapted to nutrient-poor conditions (Bu and others, 2011; Hájek and others, 2022; Norby and others, 2019). Higher

temperatures may also stimulate microbial activity and decomposition (Bu and others, 2011; Clymo and others, 1998; Trettin and others, 2019). As microbial respiration outpaces plant growth, peatlands may shift from carbon sinks to carbon sources, reducing their long-term carbon storage potential (Bu and others, 2011; Janowiak and others, 2014).

Biotic habitat responses to water deficits. While the North American Bog and Fen ecosystem is adapted to withstand some variation in water levels, prolonged or severe deficits may introduce physiological stress that reduces plant productivity and alters habitat structure. Many bog and fen species, particularly mosses and shallow-rooted forbs, are adapted to persist in saturated conditions, which limits their ability to tolerate dry soils and falling water tables (Antala and others, 2022; Luo and others, 2008; McPartland and others, 2020; Niinemets and Valladares, 2006; Ormshaw and Duval, 2020). When moisture availability drops below what these species can store, primary productivity tends to decline, as has been observed in many sphagnum mosses (*Sphagnum* spp.) and other hydrophilic plants (Jassey and Signarbieux, 2019; McPartland and others, 2019b; Olefeldt and others, 2017; Salimi and others, 2021; Zhong and others, 2020). In many cases, productivity losses during drought may outweigh gains that occur in warmer, wetter conditions (Jassey and Signarbieux, 2019). If deficits are prolonged or severe, they may even lead to mortality (Luo and others, 2008; Nelson, 2017; Strack and others, 2006a; Warren and others, 2021). These impacts can arise even during relatively short dry periods, regardless of total annual precipitation (Ballantyne and others, 2014; Didiano and others, 2018).

However, plant responses vary widely across species and functional groups. Microtopography creates a range of moisture conditions within bogs and fens, with elevated hummocks tending to be drier and less connected to the water table (Moore and Waddington, 2015; Rochefort and others, 2012; Werner and Zedler, 2002), and species in these zones often more drought-tolerant (Moore and Waddington, 2015; Potvin and others, 2015; Robroek and others, 2007). Shrubs, for example, may maintain or even increase productivity during dry periods by drawing on deeper water sources (Potvin and others, 2015; Sulman and others, 2009; Weltzin and others, 2000; Weltzin and others, 2003; Zhong and others, 2020). Sedges occupy diverse ecological niches and show a wide range of responses to water table declines, depending on the species (Churchill and others, 2015; Jaszczuk and others, 2024; Strack and others, 2006b; Talbot and others, 2014; Weltzin and others, 2000; Zhong and others, 2020). In contrast, many sphagnum mosses rely on capillary water movement to stay hydrated and are especially vulnerable to drying, particularly those growing in lower-lying, typically wetter, microhabitats (Antala and others, 2022; Breeuwer and others, 2009; Zhong and others, 2020). As a result, moisture deficits may reduce sphagnum-dependent peat formation processes, contributing to long-term ecological change.

Biotic habitat responses to warming. Rising average temperatures and more frequent seasonal extremes may also reshape habitat structure in the North American Bog and Fen ecosystem. Plant productivity responses to warming are highly variable and depend on habitat type, species composition, and water availability. In some bogs and fens, warming has been shown to increase both above- and belowground productivity, especially in forbs, graminoids, and some sedges (Bu and others, 2011; Dieleman and others, 2015; Gunnarsson, 2005; Heijmans and others, 2008; McCollum and Ibáñez, 2020; Moore and others, 2006; Weltzin and others, 2003). In other cases, however, warming does not appear to enhance productivity (Breeuwer and others, 2009; Mäkiranta and others, 2018). These differences likely depend on water availability during warm periods, as productivity gains often depend on whether plants can access enough water to support growth under warmer conditions (Oke and Hager, 2017). For many species, productivity may increase with warming up to a certain threshold, beyond which thermal stress and water limitation begin to suppress growth, as has been observed for sphagnum mosses (*Sphagnum* spp.) (Bu and others, 2011; Iversen and others, 2023; Jassey and Signarbieux, 2019; Lyons and others,

2020; McCollum and Ibáñez, 2020; Norby and others, 2019). Warming during winter and spring may also lead to earlier biomass accumulation, particularly in forbs and graminoids, which could amplify late-season water stress (Aerts and others, 2006; Antala and others, 2022; Bu and others, 2011; Kross and others, 2014). Conversely, extreme summer heat may exceed the thermal tolerance of some bog and fen species, reducing productivity and increasing mortality (Iversen and others, 2023; Norby and others, 2019; Pasiche-Lisboa and others, 2018; Petro and others, 2023; Warren and others, 2021).

Community Composition

Community responses to water deficits. Soil moisture deficits and lowered water tables are among the most influential drivers of vegetation change in the North American Bog and Fen ecosystem. Because species vary in their hydrological tolerance, drought tends to shift competitive dynamics and influence succession, often reducing the dominance of shallow-rooted, low-nutrient specialists in favor of more drought-tolerant vascular plants (Breeuwer and others, 2009; Fraser and Miletti, 2008; Hájek and others, 2020; Zhong and others, 2020). Forbs, for example, often decline in abundance under dry conditions, likely due to low drought tolerance and sensitivity in photosynthetic function (Antala and others, 2022; Didiano and others, 2018; Mäkiranta and others, 2018; Ormshaw and Duval, 2020). Moisture variability along gradients in microtopography means even modest water table declines can reduce sphagnum moss cover and abundance, especially in hollow- or lawn-forming species (e.g., *Sphagnum rubellum*, *S. magellanicum*) (Buttler and others, 2015; Potvin and others, 2015; Strack and others, 2006a). Species-level restructuring is common, however, and drought-tolerant, hummock-forming species (e.g., *S. fuscum*) may become more dominant during prolonged dry periods (Dieleman and others, 2015; Moore and Waddington, 2015; Robroek and others, 2007; Zhong and others, 2020).

Many vascular plants tend to increase in abundance as water levels decline, often outcompeting sphagnum mosses and other moisture-dependent species (Dieleman and others, 2015; Eppinga and others, 2009a; Malmer and others, 1994; Mauquoy and Yeloff, 2008; Weltzin and others, 2000). Water deficits may promote root growth and photosynthesis in vascular plants, particularly shrubs and sedges (Olefeldt and others, 2017; Warren and others, 2021). Ericaceous and deciduous shrubs, such as leatherleaf (*Chamaedaphne calyculata*) and small cranberry (*Vaccinium oxycoccos*), often benefit from lower water tables and higher nutrient availability, showing increased cover and productivity under these conditions. Sedges (e.g., *Carex* spp., *Eriophorum* spp.) exhibit more mixed responses. Some species increase in abundance initially following water table drawdown or in restoration contexts with low woody competition (Buttler and others, 2015; Murphy and others, 2009; Strack and others, 2006a; Zhong and others, 2020), but many decline under prolonged drought or when shrub cover becomes dominant (Antala and others, 2022; Breeuwer and others, 2009; Mauquoy and Yeloff, 2008; Santelmann, 1991; Schwarzer and others, 2013; Weltzin and others, 2003; Yuan and others, 2017). Shifts in water levels may also favor taller, nutrient-responsive, and drought-tolerant sedges that invest more in aboveground growth (Jaszczuk and others, 2024; Kercher and Zedler, 2004; Kotowski and van Diggelen, 2004).

Because low nutrient conditions and prolonged periods of water saturation suppress woody upland species, water deficits may act as catalysts for woody encroachment into peatland interiors where tree and shrub cover is often less dense (Buttler and others, 2023; Fiedler, 2010; Hedwall and others, 2017; Heijmans and others, 2013; Holmgren and others, 2015; Pellerin and others, 2021; Ratcliffe and others, 2017; Rochefort and others, 2012). These changing vegetation patterns will thus shift competitive dynamics within fen and bog systems, threatening to cause lasting ecological change (Buttler and others, 2023; Czerepko, 2008; Favreau and others, 2019; Hedwall and others, 2017; Heijmans and others, 2013;

Holmgren and others, 2015; Pellerin and others, 2021; Ratcliffe and others, 2017). Once established, dense shrub canopies can reinforce their own persistence by moderating soil temperatures – further lowering water tables and reducing light availability and evapotranspiration through shading – creating favorable conditions for tree seedlings and other woody species (Heijmans and others, 2013; Holmgren and others, 2015; Stelling and others, 2023). It therefore remains unclear whether the return of wet conditions following water deficits will be enough to limit the continued persistence and spread of flood-intolerant species (Hedwall and others, 2017; Olefeldt and others, 2017). As a result, the frequency and intensity of drought events, along with the timing and duration of wet season flooding, are likely important in determining encroachment outcomes.

Low-intensity fires also help limit woody encroachment and maintain biodiversity in bog and fen ecosystems (Fiedler, 2010; Gibson and others, 2023; Kost and others, 2007; Middleton and others, 2006). However, reduced water tables and existing shrub cover may shift fire behavior in ways that damage the peat layer and further promote encroachment of woody species, as has been observed with red-oiser dogwood (*Cornus sericea*) (Davies and others, 2023; Francis, 2004; Kettridge and others, 2015; Noble and others, 2019; Turetsky and others, 2015). Without the regulating effects of wet years or targeted management, tree and shrub encroachment into open peatland systems may contribute to long-term ecological transformation and a continued decline in the extent of bog and fen communities across the Midwest.

Community responses to warming. Numerous dominant species in the North American Bog and Fen ecosystem likely already occur near the southern limit of their thermal tolerances (Biota of North America Program (BONAP), 2025; Faber-Langendoen, 2005; Iverson and Taft, 2022; Kebtieneh, 2017). As a result, warming is expected to drive northward shifts in peatland extent, threatening the existing temperate ecosystems in this region (Burkett and Kusler, 2000; Ma and others, 2022; Wróblewska and Mirski, 2018).

Warming may also alter competitive balances among functional groups, favoring species better adapted to warmer temperatures and nutrient-rich conditions (Bu and others, 2011; Hájek and others, 2022; Mäkiranta and others, 2018; McPartland and others, 2019b; Turetsky and others, 2012). While the direction and magnitude of these shifts vary across habitat types and locations, warming-related increases in nitrogen and phosphorus availability consistently support a rise in vascular species, particularly shrubs and graminoids, often at the expense of forbs and mosses (Bu and others, 2011; Dieleman and others, 2015; Mauquoy and Yeloff, 2008; Weltzin and others, 2003). Forbs are often among the first vascular plants to decline under warming, likely due to low heat tolerance and reduced photosynthetic efficiency at higher temperatures (Hanson and others, 2025; McPartland and others, 2019b; McPartland and others, 2019a; McPartland and others, 2020; Rastogi and others, 2019). Sphagnum mosses (*Sphagnum* spp.) also tend to decline, affected both by direct thermal stress and increased competition (Antala and others, 2022; Dieleman and others, 2015; Lyons and others, 2020; Norby and others, 2019), as prolonged growing seasons may intensify interspecific competition and narrow niche space for sphagnum specialists (Hájek and others, 2022). However, some evidence suggests that phenotypic plasticity in dominant sphagnum species may support resilience under moderate warming (Jassey and Signarbieux, 2019).

In contrast, ericaceous and deciduous shrubs, such as bog rosemary (*Andromeda polifolia*) or small cranberry (*Vaccinium oxycoccos*), often respond positively to warming, with studies reporting increases of up to 50% in cover and productivity over just a few years (Hanson and others, 2025; McPartland and others, 2019b; Warren and others, 2021; Weltzin and others, 2003). Shrubs benefit from longer growing

seasons and increased foliar density in warmer conditions (Hanson and others, 2025; Hufnagel, 2014; Lyons and others, 2020; Weltzin and others, 2003; Wiedermann and others, 2007). Like shrubs, sedges (e.g., *Carex* spp., *Eriophorum* spp.) also frequently increase in abundance with warming (Dieleman and others, 2015; Łuców and others, 2017; Weltzin and others, 2003).

While woody encroachment is commonly associated with water deficits, temperature increases alone may also be enough to trigger persistent shifts from moss-dominated bogs and fens to shrubby or forested peatlands (Hedwall and others, 2017; Heijmans and others, 2013; Holmgren and others, 2015; Langdon and others, 2020). Once established, shrubs can facilitate further woody recruitment by buffering soil and air temperatures and enhancing nutrient availability, setting up a positive feedback loop that accelerates forest development (Holmgren and others, 2015; Mäkiranta and others, 2018). Tree establishment has been observed in response to relatively small increases in mean temperature, suggesting that warming may drive broad-scale successional change, altering community composition, biodiversity, nutrient cycling, soil acidity, and carbon storage in the North American Bog and Fen ecosystem (Bu and others, 2011; Heijmans and others, 2013; Iversen and others, 2023; Ratcliffe and others, 2017).

Invasive Species

Invasive species responses to water deficits and warming. Altered hydrologic conditions and rising temperatures can ease environmental constraints that typically limit invasive species, creating more favorable conditions for their colonization, persistence, and spread (Fiedler, 2010; Kost and others, 2007; Langdon and others, 2020). This is particularly relevant in the North American Bog and Fen near its southern range limit in the Midwest. As precipitation declines, evapotranspiration increases, and water tables drop, fluctuating hydrology can weaken the competitive resistance of native specialists and open ecological space for invasive species to establish (Faber-Langendoen, 2005; Zedler and Kercher, 2004). Drier and warmer conditions facilitate more nutrient-rich and less acidic environments, which may favor fast-growing, rhizomatous invaders. These species often outcompete native sedges and forbs, rapidly converting species-rich peatlands into low-diversity monocultures (Bornette and Puijalon, 2011; He and others, 2011; Kost and others, 2007; Werner and Zedler, 2002). Small, isolated peatland remnants, especially those near agricultural or urban areas, may be especially vulnerable (Christie and Bostwick, 2012; Kost and others, 2007; Langdon and others, 2020; Middleton and others, 2006; Schuette, 2022).

Reed canarygrass (*Phalaris arundinacea*) and glossy buckthorn (*Frangula alnus*) are among the most prominent and competitive invaders under warming and water-limited conditions. Reed canarygrass grows rapidly across a wide temperature range, thrives in drained or seasonally moist soils, and may displace native sedges such as upright sedge (*Carex stricta*) (DeRoy and MacIsaac, 2020; He and others, 2011; Kercher and Zedler, 2004). Glossy buckthorn is tolerant of dry conditions and is well suited to colonize peatlands with lowered water tables (Fiedler and Landis, 2012; Gibson and others, 2023; Godwin, 1943). Once established, it may change habitat structure and reinforce drying, making conditions less favorable for native specialists (Fiedler and Landis, 2012).

Pests and Pathogens

Pest and pathogen responses to water deficits and warming. Compared to forested ecosystems, pest and pathogen dynamics in the North American Bog and Fen ecosystem remain relatively understudied. Warming may reduce certain pathogen pressures, such as the incidence of parasitic fungi in ericaceous

shrubs such as bog rosemary (*Andromeda polifolia*) and small cranberry (*Vaccinium oxycoccos*), though these effects appear variable and species-specific (Wiedermann and others, 2007). While bogs and fens typically have limited tree cover, the few tree species that persist may be particularly vulnerable to pest and pathogen outbreaks. For example, eastern larch beetle (*Dendroctonus simplex*) and larch sawfly (*Pristiphora erichsonii*) have caused widespread tamarack (*Larix laricina*) mortality in the Great Lakes region, and these impacts are expected to intensify under warming (McKee and others, 2022). Similarly, amplified parasitism of black spruce (*Picea mariana*) by eastern dwarf mistletoe (*Arceuthobium pusillum*) exacerbates its vulnerability to water deficits (Kost and others, 2007; Lesven and others, 2024; Swanston and others, 2011).

Microbial Communities

Microbial response to warming. Warming can also drive shifts in microbial communities within the North American Bog and Fen ecosystem, with effects that vary by soil depth and plant-microbe interactions (Binet and others, 2017; Peltoniemi and others, 2015; Petro and others, 2023; Seward and others, 2020). These shifts may include a decline in moss-associated and aquatic fungi, increased dominance of root-associated and decomposer microbes, and a general homogenization of microbial communities (Asemaninejad and others, 2018; Buttler and others, 2023). Enhanced microbial activity may also raise levels of dissolved organic carbon, increasing the amount of carbon moving through nearby ecosystems (Bourbonniere, 2009; Clair and others, 2002).

Climate Change Impacts by Habitat

Midwest Prairie Alkaline Fen

The Midwest Prairie Alkaline Fen habitat is a rare and distinctive wetland habitat sustained by continuous discharge of cold, calcareous groundwater. These fens occur primarily south of the climatic tension zone in the upper Midwest, including southern Michigan, northern Indiana and Illinois, eastern Iowa, and central Minnesota (Figure 3), representing the southernmost extent of this habitat type (Faber-Langendoen and others, 2020; USNVC, 2025; Xu and others, 2018). While some regional variation exists, these fens are occasionally found near lakes and streams, but are more often located in depressional or gently sloping landscapes, where mineral-rich groundwater reaches the surface through seepage slopes or springs (Faber-Langendoen and others, 2020; Gawler and others, 2014; Kost and others, 2007; USNVC, 2025). Hydrologically, these systems are primarily groundwater-fed. Surface flows and flooding are uncommon, and water tables show only slight seasonal fluctuations, although they may drop during extended droughts (Amon and others, 2002; Bijkerk and others, 2022; Faber-Langendoen, 2005; Kost and others, 2007; Rochefort and others, 2012). The incoming groundwater is typically neutral to alkaline, mineral-rich but nutrient-poor, and remains cool throughout the summer, slowing decomposition and promoting peat accumulation (Bijkerk and others, 2022; Faber-Langendoen, 2005; Kost and others, 2007; Spieles and others, 1999). In warmer regions, faster decomposition limits peat development and restricts the distribution of this habitat. Peat depth varies from less than half a meter in small, shallow fens, to several meters deep in long-established sites (Gawler and others, 2014; Kost and others, 2007). Structurally, these fens support a mosaic of microhabitats, including sedge flats, spring runs, marl pools, and hummocks, which are organized along moisture and elevation gradients and support a diverse array of plant communities, including many habitat specialists (Faber-Langendoen, 2005; Gawler and others, 2014).

Intact Midwest Prairie Alkaline Fen habitat is typically comprised of 45 key species (Table 1). The ground layer is often dominated by sedges, rushes, and grasses, with forbs commonly interspersed. Dwarf shrubs may occur in scattered patches, particularly on slightly elevated and less saturated ground. Trees are generally absent due to persistent soil saturation, although stunted tamarack (*Larix laricina*) and arborvitae (*Thuja occidentalis*) may occur on moss hummocks or near fen margins where saturation is less consistent (Faber-Langendoen, 2005; Faber-Langendoen and others, 2020; Gawler and others, 2014; Kost and others, 2007; Rochefort and others, 2012). When fen hydrology is disrupted, shrub and tree encroachment can occur rapidly, transforming the habitat and reducing suitability for specialist species (Barry and others, 2008; Favreau and others, 2019; Langdon and others, 2020). Human activities, especially agricultural drainage, have therefore greatly reduced the extent of this habitat across the Midwest, with losses as high as 98% in Ohio and 40% in Iowa (Andreas and Knoop, 1992; Barry and others, 2008; Campbell and others, 2021; Kost and others, 2007; Pearson and Leoschke, 1992). Fire suppression has also allowed woody species to expand, further altering fen structure (Fiedler, 2010; Kost and others, 2007). In addition, fens face threats from a range of invasive species, including marsh thistle *(Cirsium palustre*), autumn olive (*Elaeagnus umbellata*), purple loosestrife (*Lythrum salicaria*), reed canarygrass (*Phalaris arundinacea*), common reed (*Phragmites australis*), common buckthorn (*Rhamnus cathartica*), glossy buckthorn (*Frangula alnus*), multiflora rose (*Rosa multiflora*), and cattails (*Typha* spp.) (Bowles and Jones, 2007; Faber-Langendoen and others, 2020; Kost and others, 2007; Werner and Zedler, 2002).

Table 1. Plant species common to the Midwest Prairie Alkaline Fen habitat. Asterisks (*) denote species introduced to the region. Daggers (†) denote some species within the genus may be introduced to the region, though most are native. Taxonomic authority, common name, growth habit, and native status are determined according to the PLANTS Database (USDA, NRCS, 2025).

Species	Common name	Growth habit
Betula pumila L.	Bog birch	Shrub
Cornus amomum Mill.	Silky dogwood	Shrub
Cornus sericea L.	Redosier dogwood	Shrub, tree
Dasiphora fruticose (L.) Rydb.	Shrubby cinquefoil	Shrub
**Frangula alnus* Mill.	Glossy buckthorn	Shrub, tree
Rhamnus lanceolata Pursh	Lanceleaf buckthorn	Shrub, tree
Salix candida Flueggé ex Willd.	Sageleaf willow	Shrub
Salix discolor Muhl.	Pussy willow	Shrub, tree
Salix petiolaris Sm.	Meadow willow	Shrub, tree
Salix sericea Marshall	Silky willow	Shrub, tree
Toxicodendron vernix (L.) Kuntze	Poison sumac	Shrub, tree
Viburnum lentago L.	Nannyberry	Shrub, tree
Andropogon gerardii Vitman	Big bluestem	Graminoid
Arnoglossum plantagineum Raf.	Groovestem Indian plantain	Forb/herb
Calamagrostis canadensis (Michx.) P. Beauv.	Bluejoint	Graminoid
Calamagrostis stricta (Timm) Koeler	Slimstem reedgrass	Graminoid
Carex aquatilis Wahlenb.	Water sedge	Graminoid
Carex cryptolepis Mack.	Northeastern sedge	Graminoid
Carex haydenii Dewey	Hayden's sedge	Graminoid
Carex hystericina Muhl. ex Willd.	Bottlebrush sedge	Graminoid
Carex lasiocarpa Ehrh.	Woollyfruit sedge	Graminoid
Carex leptalea Wahlenb.	Bristlystalked sedge	Graminoid
Carex pellita Muhl. ex Willd.	Woolly sedge	Graminoid
Carex prairea Dewey ex Alph. Wood	Prairie sedge	Graminoid
Carex sartwellii Dewey	Sartwell's sedge	Graminoid
Carex sterilis Willd.	Dioecious sedge	Graminoid
Carex stricta Lam.	Upright sedge	Graminoid
Cladium mariscoides (Muhl.) Torr.	Smooth sawgrass	Graminoid
†*Eleocharis* spp. R. Br.	Spikerush	Graminoid
Eriophorum angustifolium Honck.	Tall cottongrass	Graminoid
Eutrochium maculatum (L.) E.E. Lamont	Spotted joe pye weed	Forb/herb
Filipendula rubra (Hill) B.L. Rob.	Queen of the prairie	Forb/herb
Juncus canadensis J. Gay ex Laharpe	Canadian rush	Graminoid
Liatris spicata (L.) Willd.	Dense blazing star	Forb/herb

Species	Common name	Growth habit
Lobelia kalmia L.	Ontario lobelia	Forb/herb
Muhlenbergia glomerata (Willd.) Trin.	Spiked muhly	Graminoid
Muhlenbergia richardsonis (Trin.) Rydb.	Mat muhly	Graminoid
Oligoneuron ohioense (Frank ex Riddell) G.N. Jones	Ohio goldenrod	Forb/herb
Parnassia glauca Raf.	Fen grass of Parnassus	Forb/herb
Rhynchospora alba (L.) Vahl	White beaksedge	Graminoid
Rhynchospora capillacea Torr.	Needle beaksedge	Graminoid
Schoenoplectus pungens (Vahl) Palla	Common threesquare	Graminoid
Silphium terebinthinaceum Jacq.	Prairie rosinweed	Forb/herb
Spartina pectinata Bosc ex Link	Prairie cordgrass	Graminoid
Triglochin maritima L.	Seaside arrowgrass	Graminoid

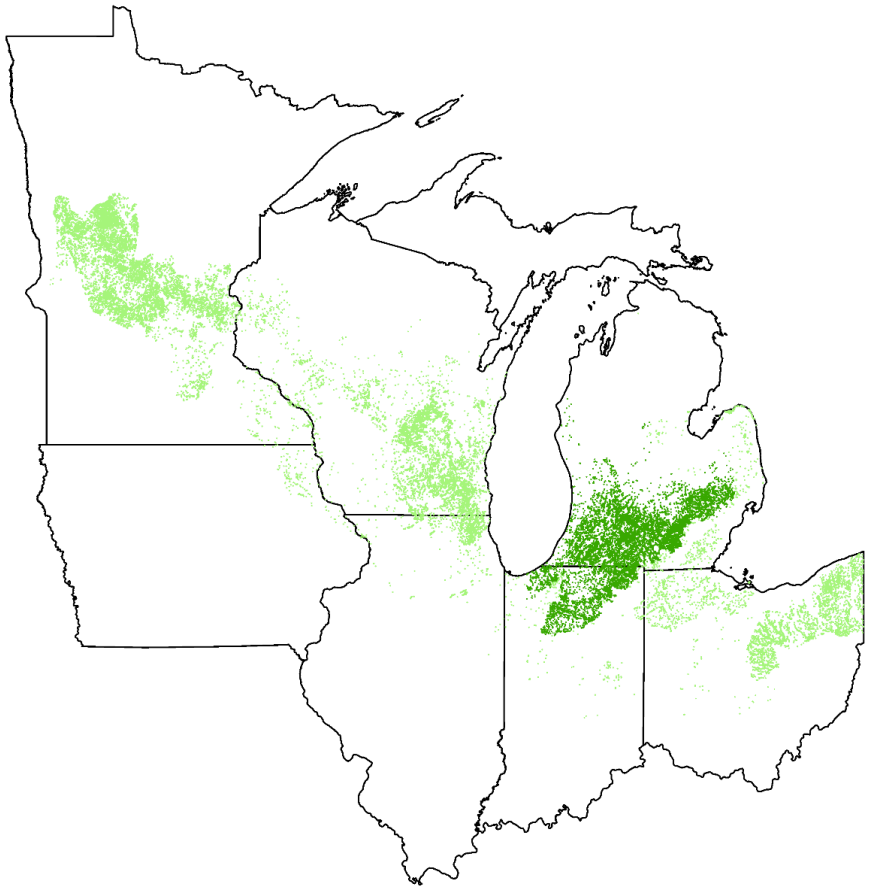

Figure 3. Midwest Prairie Alkaline Fen habitat distribution. Geographic distribution of the Midwest Prairie Alkaline Fen habitat (Group Code: G183) in the Midwest (USNVC, 2025). Dark green areas indicate Midwest Prairie Alkaline Fen habitat in the Great Lakes Plains ecoregion, while light green areas mark additional locations throughout the Midwest. Habitat boundaries have been enlarged to enhance visibility and do not reflect true proportions.

Overview of Climate Projections

The Midwest Prairie Alkaline Fen habitat is prioritized for the Great Lakes Plains ecoregion, and climate projections for this area largely reflect regional trends. Both average and extreme temperatures are expected to rise throughout the coming century (RCP 8.5; Table 2) (Clarke and others, 2022; Marvel and others, 2023; Masson-Delmotte and others, 2021; Polasky and others, 2022; Xue and others, 2022). Most models also project an increase in precipitation, although a few indicate a slight decrease (Table 3) (Marvel and others, 2023). Additionally, precipitation patterns are anticipated to shift toward more extreme events and greater seasonal variability, with notably drier summers (Chen and Ford, 2023; Dollan and others, 2022; Marvel and others, 2023; Na and Najafi, 2024; Zhao and others, 2023).

Table 2. Projected changes in annual temperature in the Great Lakes Plains ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual mean temperature (°F) by mid- (2040–2069) and end of the century (2070–2099), as well as the absolute change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected temperature under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	48.3°F	51.0°F (2.7)	52.1°F (3.7)	51.7°F (3.4)	54.7°F (6.4)
Mean of models	48.5°F	53.2°F (4.8)	54.8°F (6.4)	54.3°F (5.8)	58.6°F (10.2)
Maximum model	48.3°F	54.6°F (6.4)	56.8°F (8.5)	57.0°F (8.7)	63.0°F (14.7)

Table 3. Projected changes in annual precipitation in the Great Lakes Plains ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual precipitation (inches) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected precipitation under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	35.6 in	35.1 in (-1%)	35.4 in (-1%)	38.2 in (7%)	34.0 in (-4%)
Mean of models	35.8 in	38.2 in (7%)	38.3 in (7%)	38.1 in (6%)	39.2 in (9%)
Maximum model	35.5 in	42.0 in (18%)	39.1 in (10%)	42.3 in (19%)	44.4 in (25%)

Key Climate Change Stressors

Water deficits and warming. Across the Great Lakes Plains ecoregion, summer vapor pressure deficit (VPD) is projected to increase by approximately 72% compared to historical conditions by the end of the century (Table 4), with the potential for even greater increases near the Michigan-Indiana border (Figure 4). Higher VPD means more rapid evaporation and water loss from plants and soils, which can intensify

water deficits during summer months. The annual number of warm days is also projected to increase by approximately 278% by the end of the century, translating to more than two additional months of days exceeding 86°F (Table 5). These increases are expected to be most pronounced just south of the Michigan-Indiana border, while areas along the eastern shore of Lake Michigan may experience a slightly smaller increase (Figure 5). Longer periods of extreme heat can further dry out soils, stress vegetation, and reduce water availability.

Table 4. Projected changes in summer vapor pressure deficit in the Great Lakes Plains ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected summer (June–August) vapor pressure deficit (VPD; kilopascals) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected VPD under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	0.96 kPa	1.03 kPa (7%)	1.08 kPa (13%)	1.07 kPa (11%)	1.17 kPa (22%)
Mean of models	0.98 kPa	1.22 kPa (24%)	1.36 kPa (39%)	1.31 kPa (33%)	1.69 kPa (72%)
Maximum model	0.99 kPa	1.47 kPa (49%)	1.66 kPa (68%)	1.83 kPa (85%)	2.80 kPa (184%)

Table 5. Projected changes in annual number of warm days in the Great Lakes Plains ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual number of warm days (days with a maximum temperature greater than or equal to 86°F) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. This temperature threshold is used to calculate American Horticultural Society Plant Heat-Tolerance Zones and is a common proxy for physiological temperature stress (Cathey, 1997). To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected annual number of warm days under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	27.1	39.3 (45%)	56.4 (108%)	49.7 (83%)	62.4 (130%)
Mean of models	26.1	59.4 (128%)	72.9 (180%)	68.1 (161%)	98.6 (278%)
Maximum model	25.5	73.2 (187%)	83.8 (229%)	90.5 (255%)	122.6 (382%)

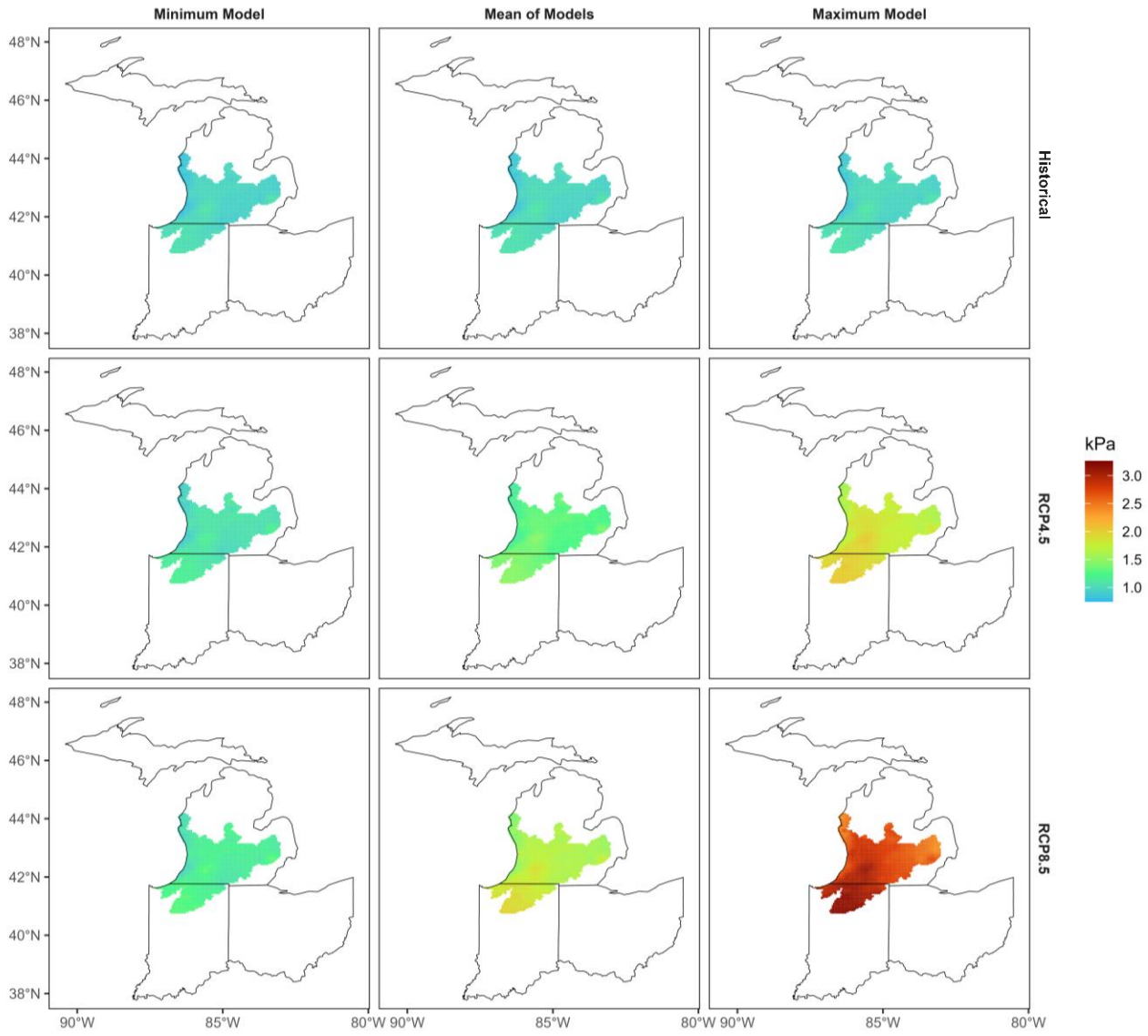

Figure 4. Projected changes in summer vapor pressure deficit in the Great Lakes Plains ecoregion. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) summer (June–August) vapor pressure deficit (VPD; kilopascals) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected VPD under RCP 8.5 are presented in addition to the mean of all models (middle column).

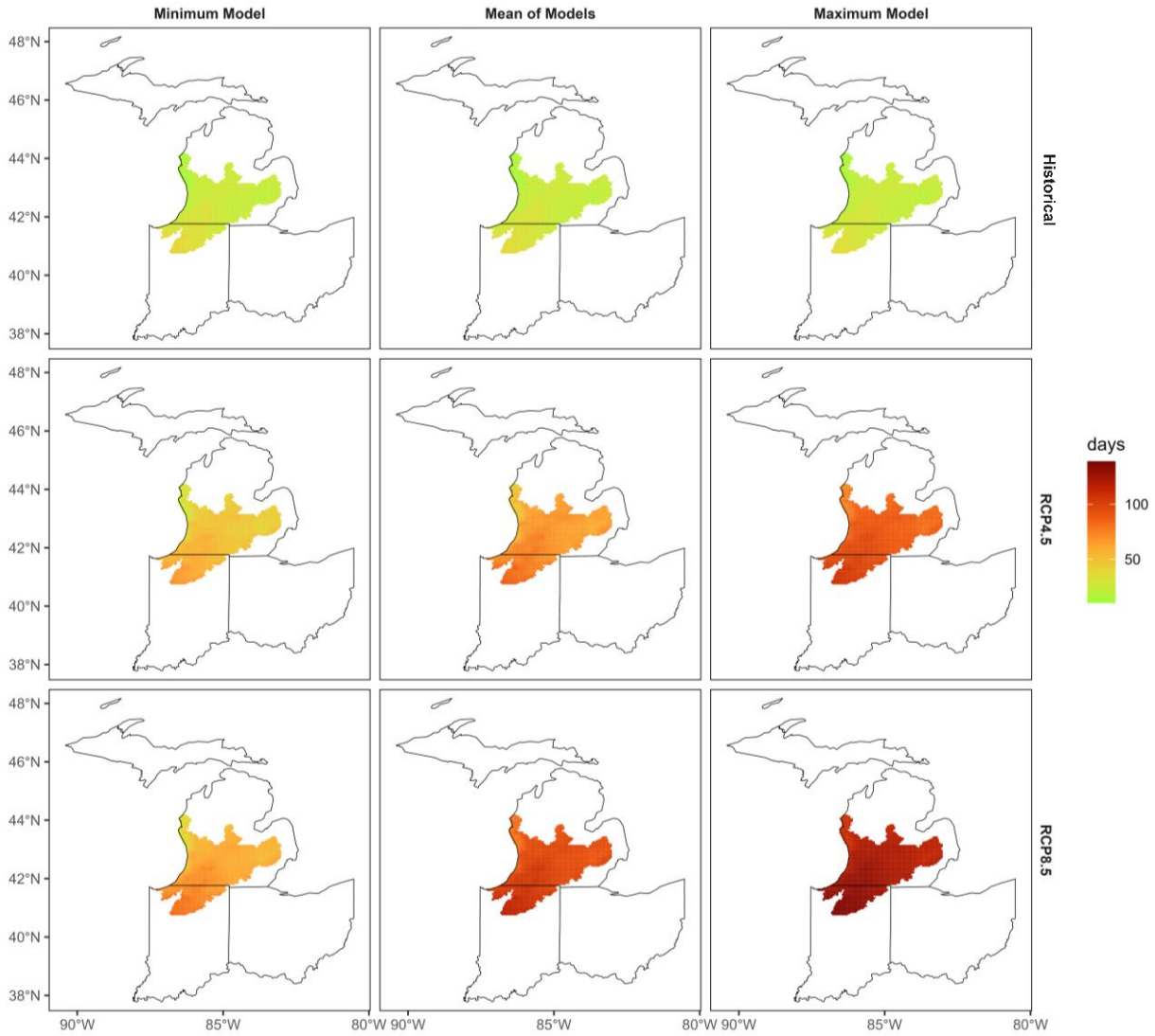

Figure 5. Projected changes in annual number of warm days in the Great Lakes Plains ecoregion. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) annual number of warm days (days with a maximum temperature greater than or equal to 86°F) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). This temperature threshold is used to calculate American Horticultural Society Plant Heat-Tolerance Zones and is a common proxy for physiological temperature stress (Cathey, 1997). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected annual number of warm days under RCP 8.5 are presented in addition to the mean of all models (middle column).

Key Climate Change Impacts

This section summarizes how climate change is impacting the Midwest Prairie Alkaline Fen habitat. It covers both the overall influence on species distributions, adaptive capacity, and vulnerability (Table 6) and the specific effects of water deficits and warming (Table 7). The bullet points below provide a concise overview of these impacts on habitat structure, community composition, invasive species, pests and pathogens, and microbial communities.

Habitat structure:

- Water deficits can lower water tables and expose peat to oxygen, accelerating aerobic decomposition and nutrient release and weakening the conditions that support saturated, low-nutrient habitats (Breeuwer and others, 2009; Jaatinen and others, 2007; Loisel and Gallego-Sala, 2022; Trettin and others, 2019; Zhong and others, 2020).
- Warming may increase evapotranspiration and extend the growing season, resulting in lower water tables and aerobic surface conditions (Heijmans and others, 2013; Moore and Waddington, 2015; Wilson and others, 2016; Zhong and others, 2020).
- Water deficits and warming can cause peat subsidence, compaction, and cracking, reducing microtopographic variation, limiting hydraulic conductivity, and heightening susceptibility to drought, surface erosion, and fire (Kettridge and others, 2015; Kost and others, 2007; Potvin and others, 2015; Price and Schlotzhauer, 1999; Rochefort and others, 2012; Turetsky and others, 2015).
- Decomposition, desiccation, and fire may increase acidity, nutrient availability, and carbon loss, disrupting the biogeochemical conditions that maintain fens and potentially initiating transitions toward drier upland habitats (Bourbonniere, 2009; Faber-Langendoen, 2005; Lamers and others, 2015).
- Water deficits may reduce productivity in shallow-rooted fen specialists, such as mosses and sedges, particularly in low-lying areas that depend on persistent saturation (Jassey and Signarbieux, 2019; Zhong and others, 2020).
- Warming may initially increase productivity of some vascular plants, including forbs and graminoids, but sustained heat and moisture stress can reduce long-term productivity and shift vegetation structure in favor of drought-tolerant species at the expense of fen-adapted specialists (Bu and others, 2011; Iversen and others, 2023; Norby and others, 2019).

Community composition:

- Several key species may lose suitable habitat under future climate scenarios, while limited adaptive capacity and heightened vulnerability may hinder the persistence of others (Table 6).
- Water deficits may reduce the abundance of moisture-dependent species and favor plants that can access deeper moisture but are otherwise sensitive to flooding, especially ericaceous and deciduous shrubs and trees such as red-osier dogwood (*Cornus sericea*) (Table 7) (Buttler and others, 2015; Dieleman and others, 2015; Potvin and others, 2015; Robroek and others, 2007; Weltzin and others, 2003; Zhong and others, 2020).
- Water deficits and associated nutrient enrichment may promote shrub and tree encroachment, particularly at drier habitat margins, which may lead to long-term ecological shifts (Breeuwer and others, 2009; Heijmans and others, 2013; Holmgren and others, 2015; Ratcliffe and others, 2017; Rochefort and others, 2012; Stelling and others, 2023).
- Warming enhances nutrient availability and extends growing seasons, potentially shifting competitive dynamics away from fen specialists, such as forbs and mosses, and increasing the abundance of vascular plants, particularly ericaceous shrubs and graminoids such as big bluestem (*Andropogon gerardii*) (Table 7) (Bu and others, 2011; Dieleman and others, 2015; Hanson and others, 2025; McPartland and others, 2019a; Weltzin and others, 2000; Weltzin and others, 2003).

Invasive species:

- Water deficits and warming may increase nutrient availability and relax environmental constraints that typically limit invasion, creating favorable conditions for species such as glossy buckthorn (*Frangula alnus*), reed canarygrass (*Phalaris arundinacea*), common reed (*Phragmites australis*), and cattails (*Typha* spp.) (Bornette and Puijalon, 2011; Fiedler, 2010; Fiedler and Landis, 2012; He and others, 2011; Kost and others, 2007; Langdon and others, 2020; Werner and Zedler, 2002).
- Some invasive species, such as glossy buckthorn (*Frangula alnus*), may facilitate their own spread by drawing down local water tables through evapotranspiration and reducing suitability for native fen specialists (Fiedler and Landis, 2012; Gibson and others, 2023).

Pests and pathogens:

- Climate change is expected to amplify pest and pathogen pressure by directly increasing pest and pathogen populations and indirectly by heightening host susceptibility (Dukes and others, 2009; Stanturf and others, 2024; Sturrock and others, 2011; Teshome and others, 2020; Vose and others, 2013).
- Introduced pests and pathogens may become more prevalent as climate change facilitates their spread into the Midwest (Cooke and Roland, 2018; Dukes and others, 2009; Fraver and others, 2022; Kasson and Livingston, 2012; Liang and Fei, 2014; Tobin and others, 2014; Ward and Aukema, 2019).
- Warming may reduce the incidence of certain parasitic fungi on ericaceous shrubs such as bog rosemary (*Andromeda polifolia*) and small cranberry (*Vaccinium oxycoccos*), though effects are likely to be variable and species-specific (Wiedermann and others, 2007).

Microbial communities:

- Warming may increase microbial activity and drive shifts in microbial communities, likely influencing key plant-microbe interactions (Asemaninejad and others, 2018; Binet and others, 2017; Peltoniemi and others, 2015; Petro and others, 2023; Seward and others, 2020).
- Increased microbial activity may accelerate peat decomposition, potentially shifting fens from carbon sinks to carbon sources (Bu and others, 2011; Janowiak and others, 2014; Trettin and others, 2019).

Table 6. Summary of the expected general influence of climate change on Midwest Prairie Alkaline Fen habitat species. Asterisks (*) denote species introduced to the region. Daggers (†) denote some species within the genus may be introduced to the region, though most are native.

Expected influence of climate change on species distributions		Hypothesized adaptive capacity and/or vulnerability to climate change	
Reduced extent or amount (–)	Increased extent or amount (+)	Low adaptive capacity/ high vulnerability (–)	High adaptive capacity/ low vulnerability (+)
†*Eleocharis* spp.[1]		*Carex cryptolepis*[3]	*Cornus sericea*[5,6]
Parnassia glauca[1]		*Carex lasiocarpa*[4]	**Frangula alnus*[4]
Phragmites australis[2]		*Carex stricta*[4]	*Salix petiolaris*[4]
		Filipendula rubra[3]	*Viburnum lentago*[4]

[1]Schuette (2022); [2]Tuck (2006); [3]Molano-Flores and others (2019); [4]Mortsch and others (2006); [5]GLIFWC (2023); [6]Inter-Tribal Council of Michigan (2016)

Table 7. Summary of impacts from key climate change stressors on Midwest Prairie Alkaline Fen habitat species. Some species appear in contradictory impacts (e.g., showing both high and low tolerance of droughts and/or lowered water tables), reflecting conflicting findings in the literature.

Stressor	Impact	Affected species
Warming	When thermal tolerance is high, increased performance, growth, and/or abundance	*Andropogon gerardii*[1]
		Carex lasiocarpa[2]
		Rhynchospora alba[2,3]
Water deficits	When tolerance of droughts and/or lowered water tables is high, competitive advantage and/or increased abundance	*Andropogon gerardii*[1,4,5]
		Carex pellita[6]
		Carex stricta[7,8]
		Cornus sericea[9,10]
		Muhlenbergia richardsonis[11]
	When tolerance of droughts and/or lowered water tables is low, reduced growth and/or abundance	*Betula pumila*[5]
		Calamagrostis canadensis[5]
		Calamagrostis stricta[5]
		Carex aquatilis[5]
		Carex lasiocarpa[12–16]
		Carex stricta[5]
		Cornus amomum[5]
		Cornus sericea[5]
		Muhlenbergia glomerata[5]
		Muhlenbergia richardsonis[5]
		Rhynchospora alba[14]
		Salix candida[5]
		Salix discolor[5]

Stressor	Impact	Affected species
		Salix sericea[5]
		Schoenoplectus pungens[5,17]
		Spartina pectinata[5]
		Viburnum lentago[5]

[1]Baty and others (2015); [2]LaPlante (2021); [3]Breeuwer and others (2009); [4]Slette and others (2023); [5]USDA, NRCS (2025); [6]Sueltenfuss and others (2020); [7]Budelsky and Galatowitsch (2004); [8]Kercher and Zedler (2004); [9]Francis (2004); [10]Ormshaw and Duval (2020); [11]Sedivec and Barker (2002) ; [12]Antala and others (2022); [13]Luo and others (2008); [14]Weltzin and others (2000); [15]Weltzin and others (2003); [16]Yuan and others (2017); [17]Tuchman (2013)

Focal Wildlife Species: Eastern Massasauga

The eastern massasauga (*Sistrurus catenatus*) is a small pit viper listed as threatened under the Endangered Species Act in 2016. Historically, the eastern massasauga ranged across much of the Midwest and northeastern North America, including New York, Pennsylvania, Ontario, Michigan, Ohio, Indiana, Illinois, Wisconsin, Minnesota, Missouri, and Iowa, but today, only Michigan and Ontario are considered to be population strongholds (U.S. Fish and Wildlife Service, 2024). While habitat loss and degradation remain the primary drivers of decline (Symanski and others, 2016), climate change and associated extreme events have contributed to local extirpations and further range contraction (Pomara and others, 2013).

Extreme flood events can directly increase mortality and alter population structure (Seigel and others, 1998). The eastern massasauga occupies thermally challenging environments (Harvey and Weatherhead, 2011) and may have limited tolerance for extreme or prolonged temperature fluctuations (Markle and others, 2020). Subterranean overwintering habitats with stable temperatures and low flood risk are essential for survival, but these areas are increasingly threatened by heavy rainfall and rain-on-snow events (Markle and others, 2020), both of which are expected to become more frequent under projected climate trends in the Midwest (Chen and Ford, 2023; Grady and others, 2021; Marvel and others, 2023; Myers and others, 2023; Wachowicz and others, 2020).

The northeastern portion of the eastern massasauga's range, where drought and flood risks remain relatively low, may serve as a long-term climate refugium (Pomara and others, 2013). To reduce the negative impacts of flooding, drought, and thermal stress, management strategies may include restoring wetland hydrology (Johnson and others, 2020), controlling invasive species and woody encroachment via vegetation management (Hilerman and others, 2018), or providing suitable microclimatic habitat (Moore and Gillingham, 2006).

Climate change may also influence the emergence and severity of fungal pathogens in wildlife (Fisher and others, 2020; Gallana and others, 2013), such as snake fungal disease (*Ophidiomyces ophiodiicola*), which may threaten the viability of eastern massasauga populations in Michigan (Allender and others, 2016; Jassey and Signarbieux, 2019; Lorch and others, 2016). Ongoing surveillance and early detection may be critical to slowing its spread and mitigating further population impacts.

Focal Aquatic System: Saul Lake Bog

Located in Grattan Township, Michigan, Saul Lake Bog Nature Preserve spans 22.1 hectares and exemplifies the resilience and ecological stability of northern bog ecosystems at their southern range boundary (Jolman and others, 2019). Defined by the Michigan Natural Features Inventory program as low-nutrient, acidic, peat-accumulating wetlands isolated from mineral-rich water sources, these lake bogs form in low-lying areas where water accumulates primarily from rainfall (Cohen, 2015). Despite surrounding urbanization and agricultural development, the Saul Lake Bog has maintained many of its pre-settlement conditions, supporting a diverse array of plant communities, from open water zones with American white waterlily (*Nymphaea odorata*) and yellow pond-lily (*Nuphar advena*), to floating mats of sedges, and to woody zones dominated by tamarack (*Larix laricina*) and black spruce (*Picea mariana*) (Jolman and others, 2019).

Situated at 43° latitude, Saul Lake Bog lies within a critical transition zone for peat-accumulating wetlands and is particularly vulnerable to climate change, with projections indicating significant losses in sphagnum moss (*Sphagnum* spp.) richness under future climate scenarios (Ma and others, 2022). Prolonged drought, rising temperatures, and extended growing seasons may intensify evapotranspiration, lowering the water table and threatening the bog's specialized flora (Langdon and others, 2020; Ma and others, 2022). Intense summer droughts can also sharply reduce sphagnum carbon uptake, though occasional rapid rainfall events may provide temporary relief (Jassey and Signarbieux, 2019; Ma and others, 2022). However, rapid transitions between wet and dry periods can reverse sphagnum responses, as low soil moisture not only suppresses productivity, but also limit potential gains from warmer, wetter intervals (Jassey and Signarbieux, 2019). As water levels decline, peat oxidation may increase, creating opportunities for more drought-tolerant vascular plants to encroach, potentially transforming the habitat from a moss-dominated community into one that is increasingly structured by shrubs and trees (Dieleman and others, 2015; Langdon and others, 2020; Ma and others, 2022; Warren and others, 2021).

Eastern North American Boreal-Subboreal Bog and Acidic Fen

The Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat is an extensive peat-forming wetland habitat found primarily across the northern Great Lakes region and into central and eastern Canada, with the Midwest representing its southern extent (Figure 6) (USNVC, 2025; Xu and others, 2018). These systems span a range of hydrologic and geomorphic conditions, from fully ombrotrophic bogs that rely solely on precipitation to weakly minerotrophic poor fens that receive moderate groundwater inputs (Faber-Langendoen and others, 2020; Faber-Langendoen and Gawler, 2024; Kost and others, 2007). These wetlands are maintained by consistent saturation and periodic flooding, which contribute to low decomposition rates (Amon and others, 2002; Faber-Langendoen, 2005). Human disturbances, especially agriculture, ditching, roads, urban drainage, and nutrient pollution, have reduced and degraded bogs and poor fens across the Midwest (Andreas and Knoop, 1992; Johnston, 1989; Kost and others, 2007; Moore, 2002; Pearson and Leoschke, 1992). Cool climates, low evapotranspiration, and the structural and functional dominance of Sphagnum mosses (*Sphagnum* spp.) help sustain these saturated, acidic conditions (Antala and others, 2022; van Breemen, 1995; Handler and others, 2020; Loisel and Gallego-Sala, 2022; Rydin and others, 2013). Bogs are typically more acidic and nutrient-poor, dominated by sphagnum mosses, ericaceous shrubs, and stunted black spruce (*Picea mariana*), while poor fens tend to support greater cover of sedges and graminoids and may include scattered tamarack (*Larix laricina*) and low-stature shrubs in response to weak minerotrophic conditions (Faber-Langendoen and others, 2020; Faber-Langendoen and Gawler, 2024; Kost and others, 2007; Rydin and others, 2013). Microtopography created by sphagnum hummocks and hollows contributes to fine-scale variation in soil moisture and nutrient availability, supporting diverse and spatially heterogeneous plant communities (Couwenberg and Joosten, 2005; Eppinga and others, 2009b; Van der Ploeg and others, 2012).

Intact Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat is typically comprised of 39 key species (Table 8). However, both natural and anthropogenic disturbances can alter the structure and dynamics of this habitat (Kost and others, 2007; Langdon and others, 2020; Page and Baird, 2016; Turetsky and St. Louis, 2006). Superficial fires can limit woody encroachment and regenerate sphagnum mats (Kost and others, 2007). While the high acidity and low nutrient content of these systems provide some natural resistance to invasive species, eutrophication or hydrologic disturbance may allow species like glossy buckthorn (*Frangula alnus*), reed canarygrass (*Phalaris arundinacea*), common reed (*Phragmites australis*), and cattails (*Typha* spp.) to establish and spread, displacing native species and altering microhabitat structure (Faber-Langendoen and others, 2020; Kost and others, 2007).

Table 8. Plant species common to the Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat. Taxonomic authority, common name, and growth habit are determined according to the PLANTS Database (USDA, NRCS, 2025).

Species	Common name	Growth habit
Andromeda polifolia L.	Bog rosemary	Shrub
Betula pumila L.	Bog birch	Shrub
Chamaedaphne calyculata (L.) Moench	Leatherleaf	Shrub
Gaultheria hispidula (L.) Muhl. ex Bigelow	Creeping snowberry	Shrub
Gaylussacia baccata (Wangenh.) K. Koch	Black huckleberry	Shrub
Ilex mucronate (L.) Powell, Savolainen & Andrews	Catberry	Shrub, tree

Species	Common name	Growth habit
Kalmia polifolia Wangenh.	Bog laurel	Shrub
Larix laricina (Du Roi) K. Koch	Tamarack	Tree
Ledum groenlandicum Oeder	Bog Labrador tea	Shrub
Picea mariana (Mill.) Britton, Sterns & Poggenb.	Black spruce	Tree
Salix discolor Muhl.	Pussy willow	Shrub, tree
Salix pedicellaris Pursh	Bog willow	Shrub
Vaccinium corymbosum L.	Highbush blueberry	Shrub
Vaccinium macrocarpon Aiton	Cranberry	Shrub
Vaccinium myrtilloides Michx.	Velvetleaf huckleberry	Shrub
Vaccinium oxycoccos L.	Small cranberry	Shrub
Carex chordorrhiza Ehrh. ex L. f.	Creeping sedge	Graminoid
Carex exilis Dewey	Coastal sedge	Graminoid
Carex haydenii Dewey	Hayden's sedge	Graminoid
Carex lasiocarpa Ehrh.	Woollyfruit sedge	Graminoid
Carex limosa L.	Mud sedge	Graminoid
Carex oligosperma Michx.	Fewseed sedge	Graminoid
Carex pauciflora Lightf.	Fewflower sedge	Graminoid
Carex utriculate Boott	Northwest Territory sedge	Graminoid
Eriophorum vaginatum L.	Tussock cottongrass	Graminoid
Eriophorum virginicum L.	Tawny cottongrass	Graminoid
Pleurozium schreberi (Brid.) Mitt.	Schreber's big red stem moss	Nonvascular
Rhynchospora alba (L.) Vahl.	White beaksedge	Graminoid
Scheuchzeria palustris L.	Rannoch-rush	Forb/herb
Sphagnum angustifolium (C.E.O. Jensen ex Russow) C.E.O. Jensen	Sphagnum	Nonvascular
Sphagnum capillifolium (Ehrh.) Hedw.	Sphagnum	Nonvascular
Sphagnum centrale C.E.O. Jensen	Sphagnum	Nonvascular
Sphagnum fimbriatum Wilson	Sphagnum	Nonvascular
Sphagnum fuscum (Schimp.) Klinggr.	Sphagnum	Nonvascular
Sphagnum magellanicum Brid.	Magellan's sphagnum	Nonvascular
Sphagnum recurvum P. Beauv.	Recurved sphagnum	Nonvascular
Sphagnum rubellum Wilson	Sphagnum	Nonvascular
Sphagnum spp. L.	Sphagnum	Nonvascular
Trichophorum cespitosum (L.) Hartm.	Tufted bulrush	Graminoid

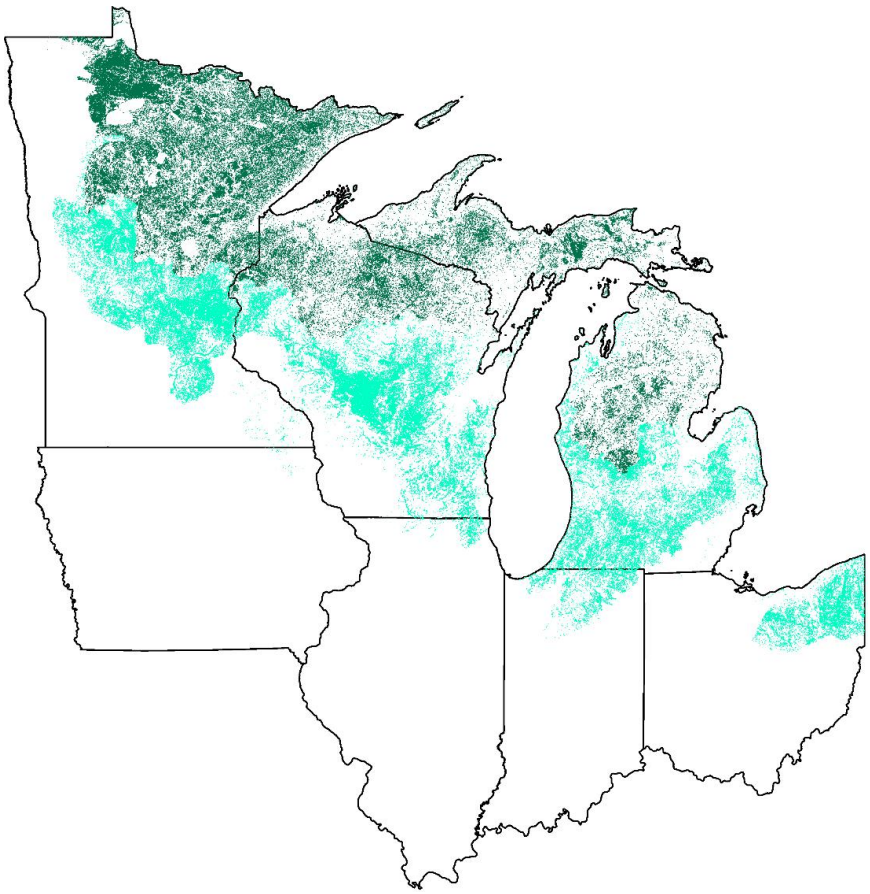

Figure 6. Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat distribution. Geographic distribution of the Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat (Group Code: G1172) in the Midwest (USNVC, 2025). Dark green areas indicate Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat in the Northern Hardwood Forest ecoregion, while light teal areas mark additional locations throughout the Midwest. Habitat boundaries have been enlarged to enhance visibility and do not reflect true proportions.

Overview of Climate Projections

The Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat is prioritized for the Northern Hardwood Forest ecoregion, and climate projections for this area largely reflect regional trends. Both average and extreme temperatures are expected to rise throughout the coming century (RCP 8.5; Table 9) (Clarke and others, 2022; Marvel and others, 2023; Masson-Delmotte and others, 2021; Polasky and others, 2022; Xue and others, 2022). Most models also project an increase in precipitation, although a few indicate a slight decrease (Table 10) (Marvel and others, 2023). Additionally, precipitation patterns are anticipated to shift toward more extreme events and greater seasonal variability, with notably drier summers (Chen and Ford, 2023; Dollan and others, 2022; Marvel and others, 2023; Na and Najafi, 2024; Zhao and others, 2023).

Table 9. Projected changes in annual temperature in the Northern Hardwood Forest ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual mean temperature (°F) by mid- (2040–2069) and end of the century (2070–2099), as well as the absolute change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected temperature under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	41.3°F	43.9°F (2.6)	45.5°F (4.2)	44.3°F (3.0)	47.9°F (6.6)
Mean of models	41.1°F	46.3°F (5.2)	47.9°F (6.8)	47.4°F (6.3)	52.2°F (11.0)
Maximum model	41.2°F	49.5°F (8.3)	51.2°F (10.0)	51.2°F (10.0)	57.2°F (15.9)

Table 10. Projected changes in annual precipitation in the Northern Hardwood Forest ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual precipitation (inches) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected precipitation under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	29.5 in	29.6 in (0%)	29.3 in (-1%)	30.7 in (4%)	28.7 in (-3%)
Mean of models	29.5 in	31.5 in (7%)	32.0 in (8%)	31.8 in (8%)	32.7 in (11%)
Maximum model	29.7 in	33.8 in (14%)	36.1 in (22%)	33.1 in (12%)	36.6 in (24%)

Key Climate Change Stressors

Water deficits and warming. Across the Northern Hardwood Forest ecoregion, summer vapor pressure deficit (VPD) is projected to increase by approximately 66% compared to historical conditions by the end of the century (Table 11), with even greater increases possible in the southernmost portion of the Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat in this ecoregion (Figure 7). Higher VPD means more rapid evaporation and water loss from plants and soils, which can intensify water deficits during summer months. The annual number of warm days is also projected to increase by approximately 450% by the end of the century, translating to nearly two additional months of days exceeding 86°F (Table 12). As with VPD, the most pronounced increases are again projected in the southern extent of this habitat type within the ecoregion (Figure 8). Longer periods of extreme heat can further dry out soils, stress vegetation, and reduce water availability.

Table 11. Projected changes in summer vapor pressure deficit in the Northern Hardwood Forest ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected summer (June–August) vapor pressure deficit (VPD; kilopascals) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected temperature under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	0.82 kPa	0.78 kPa (-5%)	0.81 kPa (-1%)	0.88 kPa (7%)	0.96 kPa (17%)
Mean of models	0.85 kPa	1.06 kPa (24%)	1.15 kPa (35%)	1.13 kPa (32%)	1.41 kPa (66%)
Maximum model	0.87 kPa	1.24 kPa (44%)	1.39 kPa (60%)	1.45 kPa (67%)	2.06 kPa (138%)

Table 12. Projected changes in warm days in the Northern Hardwood Forest ecoregion. Projections use data obtained via the Climate Toolbox Climate Mapper (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000) and projected annual number of warm days (days with a maximum temperature greater than or equal to 86°F) by mid- (2040–2069) and end of the century (2070–2099), as well as the percent change relative to the historical value (in parentheses), for each emissions scenario. This temperature threshold is used to calculate American Horticultural Society Plant Heat-Tolerance Zones and is a common proxy for physiological temperature stress (Cathey, 1997). To capture variation across climate models, models with the lowest (minimum model) and highest (maximum model) projected annual number of warm days under RCP 8.5 are presented in addition to the mean of all models.

	1971–2000	2040–2069		2070–2099	
	Historical	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum model	12.8	19.9 (55%)	26.2 (105%)	25.5 (99%)	31.8 (148%)
Mean of models	12.5	33.5 (169%)	43.6 (250%)	40.7 (227%)	68.5 (450%)
Maximum model	12.8	43.1 (236%)	55.9 (336%)	60.6 (372%)	93.7 (630%)

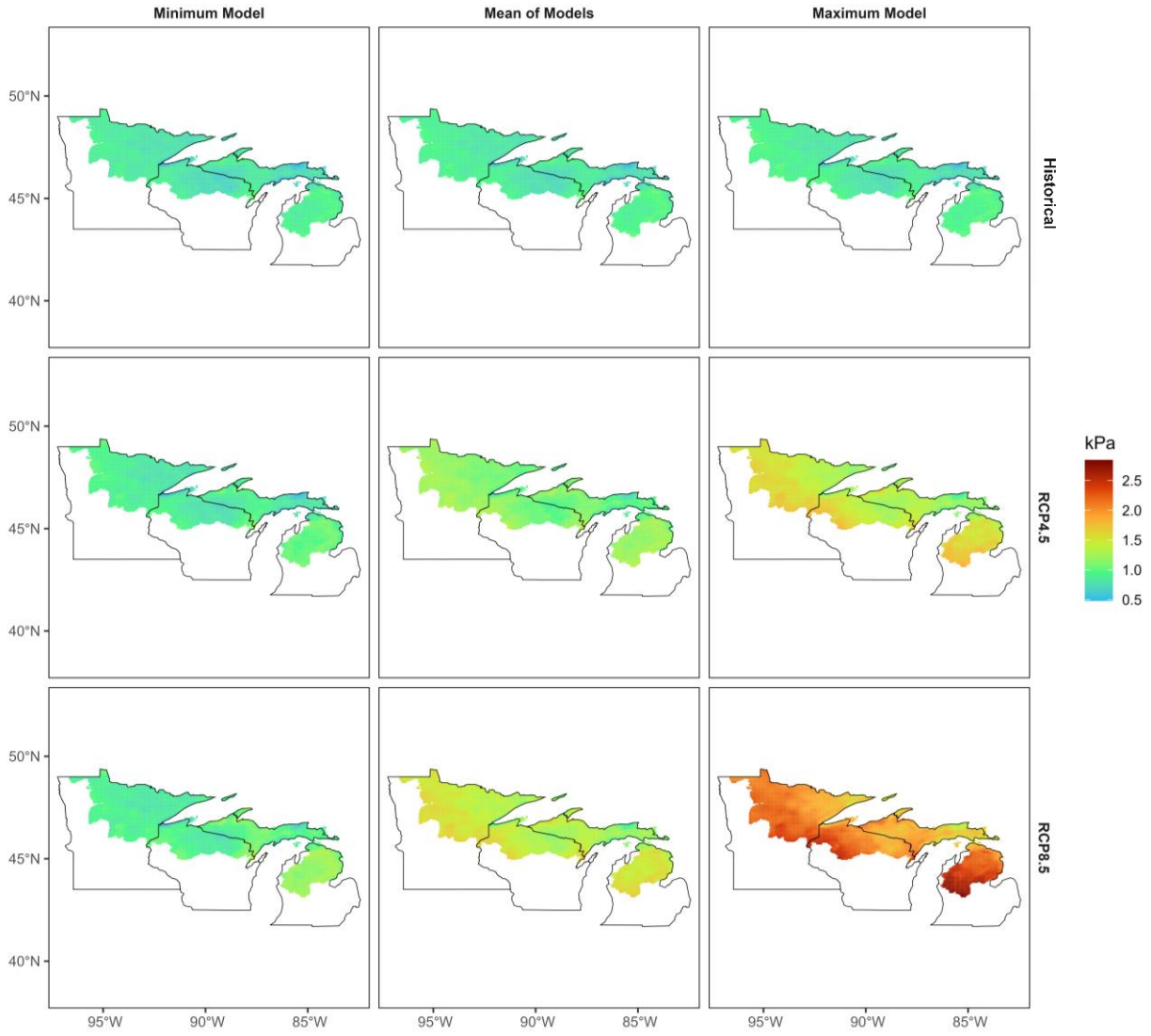

Figure 7. Projected changes in summer vapor pressure deficit in the Northern Hardwood Forest ecoregion. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) summer (June–August) vapor pressure deficit (VPD; kilopascals) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected VPD under RCP 8.5 are presented in addition to the mean of all models (middle column).

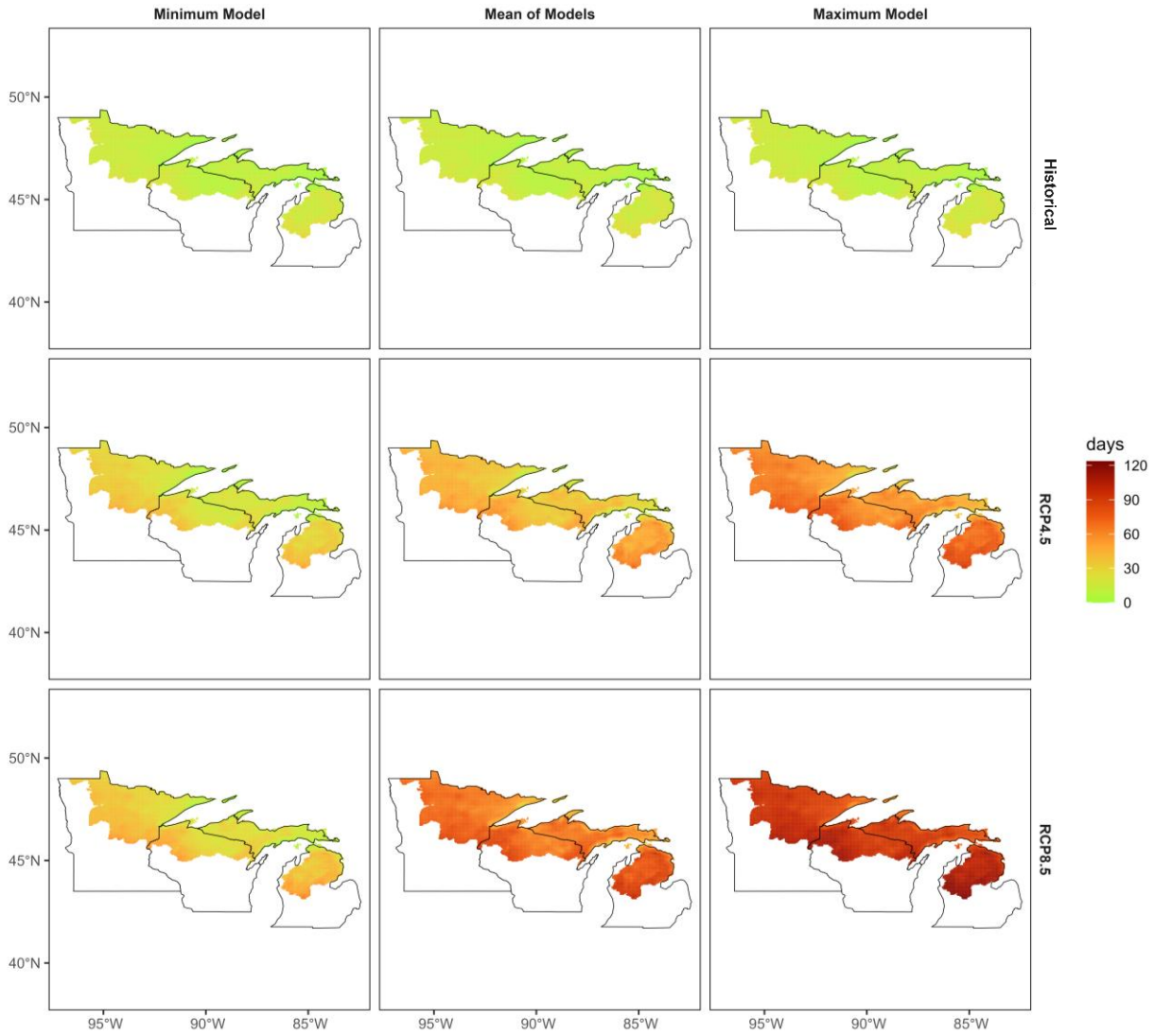

Figure 8. Projected changes in annual number of warm days in the Northern Hardwood Forest ecoregion. Projections use gridded climate data obtained via the Climate Toolbox Climate Mapper at a 4-km resolution (Hegewisch and Abatzoglou, 2024) based on 20 CMIP5 climate models downscaled using MACAv2-METDATA for moderate- and high-emissions (RCP 4.5 and 8.5) scenarios (Abatzoglou, 2013; Abatzoglou and Brown, 2012). Values show average historical (1971–2000, top row) and projected (2070–2099) annual number of warm days (days with a maximum temperature greater than or equal to 86°F) for each emissions scenario (RCP 4.5, middle row; RCP 8.5, bottom row). This temperature threshold is used to calculate American Horticultural Society Plant Heat-Tolerance Zones and is a common proxy for physiological temperature stress (Cathey, 1997). To capture variation across climate models, models with the lowest (minimum model, left column) and highest (maximum model, right column) projected annual number of warm days under RCP 8.5 are presented in addition to the mean of all models (middle column).

Key Climate Change Impacts

This section summarizes how climate change is impacting the Eastern North American Boreal-Subboreal Bog and Acidic Fen habtat. It covers both the overall influence on species distributions, adaptive capacity, and vulnerability (Table 13) and the specific effects of water deficits and warming (Table 14).

The bullet points below provide a concise overview of these impacts on habitat structure, community composition, invasive species, pests and pathogens, and microbial communities.

Habitat structure:

- Water deficits can lower water tables and expose peat to oxygen, accelerating aerobic decomposition and nutrient release, disrupting the slow peat accumulation processes that sustain ombrotrophic habitats (Breeuwer and others, 2009; Jaatinen and others, 2007; Loisel and Gallego-Sala, 2022; Trettin and others, 2019; Zhong and others, 2020).
- Warming may increase evapotranspiration and extend the growing season, resulting in lower water tables and aerobic surface conditions (Heijmans and others, 2013; Moore and Waddington, 2015; Wilson and others, 2016; Zhong and others, 2020).
- Water deficits and warming can cause peat subsidence, compaction, and cracking, reducing water retention, limiting hydraulic conductivity, and heightening susceptibility to fire (Kost and others, 2007; Loisel and Gallego-Sala, 2022; Potvin and others, 2015; Price and Schlotzhauer, 1999; Staffen and others, 2019).
- Decomposition, desiccation, and fire may increase acidity, nutrient availability, and carbon loss, disrupting the biogeochemical conditions that maintain peatlands (Bourbonniere, 2009; Kettridge and others, 2015; Kost and others, 2007; Lamers and others, 2015; Strack and others, 2006a).
- Water deficits may reduce productivity in shallow-rooted mosses (e.g., *Sphagnum magellanicum*), which are poorly adapted to dry conditions (Jassey and Signarbieux, 2019; Zhong and others, 2020).
- Warming may initially increase productivity of some vascular plants, including forbs and graminoids, but sustained heat and moisture stress can reduce long-term productivity and shift vegetation structure away from Sphagnum moss (*Sphagnum* spp.) dominance (Bu and others, 2011; Norby and others, 2019).

Community composition:

- Several key species may lose suitable habitat under future climate scenarios, while limited adaptive capacity and heightened vulnerability may hinder the persistence of others (Table 13).
- Water deficits may reduce the abundance and alter the composition of sphagnum mosses, with lawn and hollow species declining (e.g., *Sphagnum magellanicum, S. rubellum*), and drought-tolerant hummock species increasing (e.g., *S. fuscum*) (Table 14) (Lyons and others, 2020; Moore and Waddington, 2015; Potvin and others, 2015; Robroek and others, 2007; Strack and others, 2006b).
- Water deficits may reduce the abundance of moisture-dependent species and favor plants that can access deeper moisture, but are otherwise sensitive to flooding, especially ericaceous and deciduous shrubs and trees such as bog rosemary (*Andromeda polifolia*) and leatherleaf (*Chamaedaphne calyculata*) (Table 14) (Antala and others, 2022; Buttler and others, 2015; Dieleman and others, 2015; Potvin and others, 2015; Robroek and others, 2007; Weltzin and others, 2003; Zhong and others, 2020).
- Water deficits and associated nutrient enrichment may promote shrub and tree encroachment, particularly at drier habitat margins, which may lead to long-term ecological shifts (Breeuwer and

others, 2009; Heijmans and others, 2013; Holmgren and others, 2015; Ratcliffe and others, 2017; Rochefort and others, 2012; Stelling and others, 2023).

- Warming enhances nutrient availability and extends growing seasons, potentially shifting competitive dynamics away from bryophytes and other thermally sensitive species, and increasing the abundance of vascular plants, particularly ericaceous shrubs such as bog rosemary (*Andromeda polifolia*) and small cranberry (*Vaccinium oxycoccos*) (Table 14) (Bu and others, 2011; Buttler and others, 2015; Dieleman and others, 2015; Hanson and others, 2025; Hufnagel, 2014; Norby and others, 2019; Warren and others, 2021; Weltzin and others, 2003).

Invasive species:

- Water deficits and warming may increase nutrient availability and relax environmental constraints that typically limit invasion, creating favorable conditions for species such as glossy buckthorn (*Frangula alnus*), reed canarygrass (*Phalaris arundinacea*), common reed (*Phragmites australis*), and cattails (*Typha* spp.) (Bornette and Puijalon, 2011; Fiedler, 2010; Fiedler and Landis, 2012; He and others, 2011; Kost and others, 2007; Langdon and others, 2020; Werner and Zedler, 2002).
- Some invasive species, such as glossy buckthorn (*Frangula alnus*), may facilitate their own spread by drawing down local water tables through evapotranspiration and reducing suitability for native bog and poor fen specialists (Fiedler and Landis, 2012; Gibson and others, 2023).

Pests and pathogens:

- Climate change is expected to amplify pest and pathogen pressure by directly increasing pest and pathogen populations, and indirectly heightening host susceptibility (Dukes and others, 2009; Stanturf and others, 2024; Sturrock and others, 2011; Teshome and others, 2020; Vose and others, 2013).
- Introduced pests and pathogens may become more prevalent as climate change facilitates their spread into the Midwest (Cooke and Roland, 2018; Dukes and others, 2009; Fraver and others, 2022; Kasson and Livingston, 2012; Liang and Fei, 2014; Tobin and others, 2014; Ward and Aukema, 2019).
- Warming may exacerbate pest and pathogen outbreaks in tree species such as tamarack (*Larix laricina*) and black spruce (*Picea mariana*), which are vulnerable to pests like eastern larch beetle (*Dendroctonus simplex*) and spruce budworm (*Choristoneura fumiferana*) (Bellemin-Noël and others, 2021; McKee and others, 2022; Ren and others, 2020).
- Warming may reduce the incidence of certain parasitic fungi on ericaceous shrubs such as bog rosemary (*Andromeda polifolia*) and small cranberry (*Vaccinium oxycoccos*), though the effects are likely to be variable and species-specific (Wiedermann and others, 2007).

Microbial communities:

- Warming may increase microbial activity and drive shifts in microbial communities, likely influencing key plant-microbe interactions (Asemaninejad and others, 2018; Binet and others, 2017; Peltoniemi and others, 2015; Petro and others, 2023; Seward and others, 2020).

Table 13. Summary of the expected general influence of climate change on Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat species.

Expected influence of climate change on species distributions		Hypothesized adaptive capacity and/or vulnerability to climate change	
Reduced extent or amount (–)	Increased extent or amount (+)	Low adaptive capacity/ high vulnerability (–)	High adaptive capacity/ low vulnerability (+)
Larix laricina[1]		*Andromeda polifolia*[9]	*Vaccinium corymbosum*[10]
Phragmites australis[2]		*Carex chordorrhiza*[10]	
Picea mariana[3–6]		*Carex lasiocarpa*[11]	
Sphagnum angustifolium[7]		*Carex oligosperma*[10]	
Sphagnum magellanicum[7]		*Chamaedaphne calyculata*[10]	
Sphagnum rubellum[7]		*Eriophorum virginicum*[10]	
Vaccinium macrocarpon[8]		*Larix laricina*[4,10,12,13]	
		Ledum groenlandicum[9,12]	
		Picea mariana[9,13,14]	
		Trichophorum cespitosum[10]	
		Vaccinium macrocarpon[9,10]	
		Vaccinium oxycoccos[10]	

[1]Mamet and others (2019); [2]Tuck (2006); [3]Boisvert-Marsh and Blois (2021); [4]Peters and others (2020); [5]Joyce and Rehfeldt (2013); [6]Prasad and others (2020); [7]Oke and Hager (2017); [8]Hirabayashi (2022); [9]Inter-Tribal Council of Michigan (2016); [10]Molano-Flores and others (2019); [11]Mortsch and others (2006); [12]GLIFWC (2023); [13]Potter and others (2017); [14]Swanston and others (2011)

Table 14. Summary of impacts from key climate change stressors on Eastern North American Boreal-Subboreal Bog and Acidic Fen habitat species. Some species appear in contradictory impacts (e.g., showing both high and low tolerance of droughts and/or lowered water tables), reflecting conflicting findings in the literature.

Stressor	Impact	Affected species
Warming	When thermal tolerance is low, decreased performance, growth, and/or abundance	*Chamaedaphne calyculata*[1]
		Kalmia polifolia[2]
		Larix laricina[1]
		Picea mariana[3]
		Pleurozium schreberi[4]
		Sphagnum angustifolium[5]
		Sphagnum spp.[2,6,7]
		Vaccinium oxycoccos[8]

Stressor	Impact	Affected species
	When thermal tolerance is high, increased performance, growth, and/or abundance	*Andromeda polifolia*[9,10]
		Carex lasiocarpa[11]
		Carex limosa[12]
		Eriophorum vaginatum[2,9,10,13,14]
		Picea mariana[15]
		Rhynchospora alba[11,16]
		Scheuchzeria palustris[2,7,17]
		Sphagnum magellanicum[6,18]
		Vaccinium oxycoccos[9,10]
Water deficits	When tolerance of drought and/or lowered water tables is high, competitive advantage and/or increased abundance	*Andromeda polifolia*[9]
		Carex oligosperma[19]
		Chamaedaphne calyculata[19]
		Eriophorum vaginatum[13,20]
		Larix laricina[21,22]
		Picea mariana[21,22]
		Sphagnum fuscum[19,23]
		Trichophorum cespitosum[24]
	When tolerance of drought and/or lowered water tables is low, reduced growth and/or abundance	*Betula pumila*[25]
		Carex exilis[26]
		Carex lasiocarpa[2,17,24,27,28]
		Carex limosa[27]
		Carex utriculata[25]
		Chamaedaphne calyculata[2,25]
		Eriophorum vaginatum[24,29,30]
		Eriophorum virginicum[25]
		Kalmia polifolia[25]
		Larix laricina[25,31–35]
		Picea mariana[15,25,36,37]
		Rhynchospora alba[17]
		Salix discolor[25]
		Scheuchzeria palustris[2]
		Sphagnum magellanicum[18,23]
		Sphagnum rubellum[19,23]
		Sphagnum spp.[2,20]
		Vaccinium corymbosum[25]
		Vaccinium oxycoccos[9,19,38,39]

[1]Warren and others (2021); [2]Weltzin and others (2003); [3]Girardin and others (2016); [4]Pasiche-Lisboa and others (2018); [5]Lyons and others (2020); [6]Dieleman and others (2015); [7]Hedwall and others (2017); [8]McPartland (2020); [9]Buttler and others (2023); [10]Wiedermann and others (2007); [11]LaPlante (2021); [12]Łuców and others (2017); [13]Gignac and others (2004); [14]Mäkiranta and others (2018); [15]Wang and others (2023); [16]Breeuwer and others (2009); [17]Weltzin and others (2000); [18]Robroek and others (2007); [19]Potvin and others (2015); [20]Jassey and others (2018); [21]Gustafson and Sturtevant (2013); [22]Niinemets and Vallardares (2006); [23]Strack and others (2006a); [24]Antala and others (2022); [25]USDA, NRCS (2025); [26]Santelmann (1991); [27]Luo and others (2008); [28]Yuan and others (2017); [29]Bragazza and others (2016); [30]Schwarzer and others (2013); [31]Janowiak and others (2014); [32]Mamet and others (2019); [33]Olson and others (2021); [34]Stelling and others (2023); [35]Johnston (1990); [36]Luo and Chen (2015); [37]Peters and others (2015); [38]Jacquemart (1998); [39]Malmer and others (1994)

Focal Wildlife Species: Four-toed Salamander

Four-toed salamanders (*Hemidactylium scutatum*) are a secretive, widely distributed amphibian with a large but fragmented range spanning much of eastern United States and Canada. Its patchy distribution likely reflects both species-specific habitat needs and the effects of past habitat loss and degradation (Minnesota Department of Natural Resources, 2025). Four-toed salamanders depend on mature forest for adult and juvenile activity, foraging, and overwintering and fishless wetlands, such as bogs, swamps, marshes, and vernal pools, for breeding (Petranka, 2010). Preferred egg deposition sites include sphagnum moss (*Sphagnum* spp.) hummocks, although other mosses or similar substrates may also be used (Petranka, 2010).

While four-toed salamanders are unlikely to be directly affected by warming in the Midwest, given their broader distribution to the south, climate change may still affect their viability by altering habitat availability and increasing susceptibility to disease. Habitat loss and degradation remain the greatest threats and are likely to be compounded by changing climate conditions. The species rarely breeds in water bodies that support fish, due to high larval depredation. However, shifting precipitation patterns, increased evapotranspiration, and drought may reduce the hydroperiod of breeding sites like vernal pools (Cartwright and others, 2022), potentially causing them to dry before larvae can complete metamorphosis. Warming may also reduce the availability of sphagnum-dominated bogs (Norby and others, 2019), a key breeding habitat. Adaptive management for four-toed salamanders may include the construction or maintenance of fish-free surface waters, along with efforts to support moss hummock development and persistence (Petranka, 2010).

Chytrid fungal diseases such as *Batrachochytrium dendrobatidis* (Bd) and *B. salamandrivorans* (Bsal) represent an additional concern, with the potential to cause significant mortality in salamander populations. Climate change is likely to influence both the spread of these and other novel pathogens, and the susceptibility of amphibians like four-toed salamanders (Rollins-Smith, 2017). Although four-toed salamander susceptibility to Bsal remains unknown, members of their family (Plethodontidae) are considered at high risk of mortality (Gray and others, 2023). Interestingly, however, warmer temperatures appear to reduce Bsal-related mortality (Gray and others, 2023). Four-toed salamanders often use communal nest sites, and this behavior may provide some protection against fungal pathogens if some females carry antifungal skin bacteria (Banning and others, 2008).

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Appendix 1

Table i. Woody plant species common to the North American Bog and Fen ecosystem. Key species were identified using USNVC floristic descriptions (USNVC, 2020), filtered by habitats occurring within the Midwest that collectively comprise the North American Bog and Fen ecosystem. Asterisks (*) denote species introduced to the region. Taxonomic authority, common name, growth habit, and native status are determined according to the PLANTS Database (USDA, NRCS, 2025).

Species	Common name	Growth habit	North American Bog and Fen	Eastern North American Boreal-Subboreal Bog and Acidic Fen
Andromeda polifolia L.	Bog rosemary	Shrub		×
Betula pumila L.	Bog birch	Shrub	×	×
Chamaedaphne calyculata (L.) Moench	Leatherleaf	Shrub		×
Cornus amomum Mill.	Silky dogwood	Shrub	×	
Cornus sericea L.	Redosier dogwood	Shrub, tree	×	
Dasiphora fruticose (L.) Rydb.	Shrubby cinquefoil	Shrub	×	
**Frangula alnus* Mill.	Glossy buckthorn	Shrub, tree	×	
Gaultheria hispidula (L.) Muhl. ex Bigelow	Creeping snowberry	Shrub		×
Gaylussacia baccata (Wangenh.) K. Koch	Black huckleberry	Shrub		×
Ilex mucronate (L.) Powell, Savolainen & Andrews	Catberry	Shrub, tree		×
Kalmia polifolia Wangenh.	Bog laurel	Shrub		×
Larix laricina (Du Roi) K. Koch	Tamarack	Tree		×
Ledum groenlandicum Oeder	Bog Labrador tea	Shrub		×
Picea mariana (Mill.) Britton, Sterns & Poggenb.	Black spruce	Tree		×
Rhamnus lanceolata Pursh	Lanceleaf buckthorn	Shrub, tree	×	
Salix candida Flueggé ex Willd.	Sageleaf willow	Shrub	×	
Salix discolor Muhl.	Pussy willow	Shrub, tree	×	×
Salix pedicellaris Pursh	Bog willow	Shrub		×
Salix petiolaris Sm.	Meadow willow	Shrub, tree	×	

Species	Common name	Growth habit	North American Bog and Fen	Eastern North American Boreal-Subboreal Bog and Acidic Fen
Salix sericea Marshall	Silky willow	Shrub, tree	×	
Toxicodendron vernix (L.) Kuntze	Poison sumac	Shrub, tree	×	
Vaccinium corymbosum L.	Highbush blueberry	Shrub		×
Vaccinium macrocarpon Aiton	Cranberry	Shrub		×
Vaccinium myrtilloides Michx.	Velvetleaf huckleberry	Shrub		×
Vaccinium oxycoccos L.	Small cranberry	Shrub		×
Viburnum lentago L.	Nannyberry	Shrub, tree	×	

Table ii. Non-woody plant species common to the North American Bog and Fen ecosystem. Key species were identified using USNVC floristic descriptions (USNVC, 2020), filtered by habitats occurring within the Midwest that collectively comprise the North American Bog and Fen ecosystem. Daggers (†) denote some species within the genus may be introduced to the region, though most are native. Taxonomic authority, common name, growth habit, and native status are determined according to the PLANTS Database (USDA, NRCS, 2025).

Species	Common name	Growth habit	North American Bog and Fen	Eastern North American Boreal-Subboreal Bog and Acidic Fen
Andropogon gerardii Vitman	Big bluestem	Graminoid	×	
Arnoglossum plantagineum Raf.	Groovestem Indian plantain	Forb/herb	×	
Calamagrostis canadensis (Michx.) P. Beauv.	Bluejoint	Graminoid	×	
Calamagrostis stricta (Timm) Koeler	Slimstem reedgrass	Graminoid	×	
Carex aquatilis Wahlenb.	Water sedge	Graminoid	×	
Carex chordorrhiza Ehrh. ex L. f.	Creeping sedge	Graminoid		×
Carex cryptolepis Mack.	Northeastern sedge	Graminoid	×	
Carex exilis Dewey	Coastal sedge	Graminoid		×
Carex haydenii Dewey	Hayden's sedge	Graminoid	×	×
Carex hystericina Muhl. ex Willd.	Bottlebrush sedge	Graminoid	×	
Carex lasiocarpa Ehrh.	Woollyfruit sedge	Graminoid	×	×
Carex leptalea Wahlenb.	Bristlystalked sedge	Graminoid	×	
Carex limosa L.	Mud sedge	Graminoid		×
Carex oligosperma Michx.	Fewseed sedge	Graminoid		×
Carex pauciflora Lightf.	Fewflower sedge	Graminoid		×
Carex pellita Muhl. ex Willd.	Woolly sedge	Graminoid	×	
Carex prairea Dewey ex Alph. Wood	Prairie sedge	Graminoid	×	
Carex sartwellii Dewey	Sartwell's sedge	Graminoid	×	
Carex sterilis Willd.	Dioecious sedge	Graminoid	×	
Carex stricta Lam.	Upright sedge	Graminoid	×	
Carex utriculate Boott	Northwest Territory sedge	Graminoid		×

Species	Common name	Growth habit	North American Bog and Fen	Eastern North American Boreal-Subboreal Bog and Acidic Fen
Cladium mariscoides (Muhl.) Torr.	Smooth sawgrass	Graminoid	×	
†*Eleocharis* spp. R. Br.	Spikerush	Graminoid	×	
Eriophorum angustifolium Honck.	Tall cottongrass	Graminoid	×	
Eriophorum vaginatum L.	Tussock cottongrass	Graminoid		×
Eriophorum virginicum L.	Tawny cottongrass	Graminoid		×
Eutrochium maculatum (L.) E.E. Lamont	Spotted joe pye weed	Forb/herb	×	
Filipendula rubra (Hill) B.L. Rob.	Queen of the prairie	Forb/herb	×	
Juncus canadensis J. Gay ex Laharpe	Canadian rush	Graminoid	×	
Liatris spicata (L.) Willd.	Dense blazing star	Forb/herb	×	
Lobelia kalmia L.	Ontario lobelia	Forb/herb	×	
Muhlenbergia glomerata (Willd.) Trin.	Spiked muhly	Graminoid	×	
Muhlenbergia richardsonis (Trin.) Rydb.	Mat muhly	Graminoid	×	
Oligoneuron ohioense (Frank ex Riddell) G.N. Jones	Ohio goldenrod	Forb/herb	×	
Parnassia glauca Raf.	Fen grass of Parnassus	Forb/herb	×	
Pleurozium schreberi (Brid.) Mitt.	Schreber's big red stem moss	Nonvascular		×
Rhynchospora alba (L.) Vahl	White beaksedge	Graminoid	×	×
Rhynchospora capillacea Torr.	Needle beaksedge	Graminoid	×	
Scheuchzeria palustris L.	Rannoch-rush	Forb/herb		×
Schoenoplectus pungens (Vahl) Palla	Common threesquare	Graminoid	×	
Silphium terebinthinaceum Jacq.	Prairie rosinweed	Forb/herb	×	
Spartina pectinata Bosc ex Link	Prairie cordgrass	Graminoid	×	
Sphagnum angustifolium (C.E.O. Jensen ex Russow) C.E.O. Jensen	Sphagnum	Nonvascular		×
Sphagnum capillifolium (Ehrh.) Hedw.	Sphagnum	Nonvascular		×
Sphagnum centrale C.E.O. Jensen	Sphagnum	Nonvascular		×

Species	Common name	Growth habit	North American Bog and Fen	Eastern North American Boreal-Subboreal Bog and Acidic Fen
Sphagnum fimbriatum Wilson	Sphagnum	Nonvascular		×
Sphagnum fuscum (Schimp.) Klinggr.	Sphagnum	Nonvascular		×
Sphagnum magellanicum Brid.	Magellan's sphagnum	Nonvascular		×
Sphagnum recurvum P. Beauv.	Recurved sphagnum	Nonvascular		×
Sphagnum rubellum Wilson	Sphagnum	Nonvascular		×
Sphagnum spp. L.	Sphagnum	Nonvascular		×
Trichophorum cespitosum (L.) Hartm.	Tufted bulrush	Graminoid		×
Triglochin maritima L.	Seaside arrowgrass	Graminoid	×	

Appendix 2

Climate projections are derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and include model outputs from 20 unique models.

CMIP5 Models:

- bcc-csm1-1
- bcc-csm1-1-m
- CNRM-CM5
- CSIRO-Mk3-6-0
- GFDL-ESM2M
- HadGEM2-CC365
- HadGEM2-ES365
- inmcm4
- IPSL-CM5A-LR
- PSL-CM5A-MR
- MIROC5
- MIROC-ESM
- MIROC-ESM-CHEM
- MRI-CGCM3
- NorESM1-M
- IPSL-CM5B-LR
- CanESM2
- CCSM4
- GFDL-ESM2G
- BNU-ESM

To capture variation across CMIP5 climate models, models with the lowest (minimum model) and highest (maximum model) projected values under the RCP8.5 scenario are presented in addition to the mean of all models. Table vi includes a list of all minimum and maximum models selected for each region and climate variable.

Table vi. Climate Projection Minimum and Maximum Models. For each region and climate variable, minimum and maximum models were determined by averaging the each climate variable projection for the RCP8.5 end of the century (2070–2099) scenario across each region.

Ecoregion	Climate Variable	Season	Minimum Model	Maximum Model
Great Lakes Plains	Warm Days	Annual	inmcm4	HadGEM2-CC365
Northern Hardwood Forest	Warm Days	Annual	inmcm4	HadGEM2-CC365
Great Lakes Plains	Precipitation	Annual	IPSL-CM5A-MR	CSIRO-Mk3-6-0
Northern Hardwood Forest	Precipitation	Annual	IPSL-CM5A-MR	GFDL-ESM2G
Midwest Region	Precipitation	Summer	HadGEM2-CC365	MRI-CGCM3
Northern Hardwood Forest	Mean Temperature	Annual	GFDL-ESM2M	MIROC-ESM-CHEM
Great Lakes Plains	Mean Temperature	Annual	MRI-CGCM3	HadGEM2-CC365
Midwest Region	Mean Temperature	Summer	inmcm4	HadGEM2-CC365
Northern Hardwood Forest	Vapor Pressure Deficit	Summer	GFDL-ESM2G	HadGEM2-CC365
Great Lakes Plains	Vapor Pressure Deficit	Summer	MRI-CGCM3	HadGEM2-CC365