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Michigan Forest Ecosystem Vulnerability Assessment and Synthesis:

A Report from the Northwoods Climate Change Response Framework Project

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ABSTRACT

The forests in northern Michigan will be affected directly and indirectly by changing climate during the 21st century. This assessment evaluates the vulnerability of forest ecosystems in the eastern Upper Peninsula and northern Lower Peninsula of Michigan under a range of future climates. We synthesized and summarized information on the contemporary landscape, provided information on past climate trends, and described a range of projected future climates. This information was used to parameterize and run multiple vegetation impact models, which provided a range of potential vegetative responses to climate. Finally, we brought these results before a multidisciplinary panel of scientists and land managers familiar with Michigan forests to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

The summary of the contemporary landscape identifies major forest trends and stressors currently threatening forests in the region. Observed trends in climate over the past century reveal that precipitation increased in the area, particularly in summer and fall, and that daily maximum temperatures increased, particularly in winter. Projected climate trends for the next 100 years using downscaled global climate model data indicate a potential increase in mean annual temperature of 2.2 to 8.1 °F for the assessment area. Projections for precipitation indicate an increase in winter and spring precipitation, and summer and fall precipitation projections vary by scenario. We identified potential impacts on forests by incorporating these climate projections into three forest impact models (Tree Atlas, LANDIS-II, and PnET-CN). Model projections suggest that northern boreal species such as black spruce and paper birch may fare worse under future conditions, but other species such as American elm and white oak may benefit from projected changes in climate. Published literature on climate impacts related to wildfire, invasive species, and diseases also contributed to the overall determination of climate change vulnerability. We assessed vulnerability for nine forest communities in the assessment area, which were a combination of U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis program forest types and Michigan Natural Features Inventory natural communities. The basic assessment was conducted through a formal elicitation process of 27 science and management experts from across the state, who considered vulnerability both in terms of potential impacts on a system and in terms of the system's adaptive capacity. Upland spruce-fir, jack pine, lowland conifers, and red pine-white pine forest communities were determined to be the most vulnerable. Barrens and lowland/riparian hardwood communities were perceived as less vulnerable to projected changes in climate. These projected changes in climate and the associated impacts and vulnerabilities will have important implications for economically valuable timber species, forest-dependent wildlife and plants, recreation, and long-range planning.

Cover Photo

Douglas Lake at the University of Michigan Biological Station. Photo by Stephen Handler, U.S. Forest Service.

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PREFACE

CONTEXT AND SCOPE

This assessment is a fundamental component of the Northwoods Climate Change Response Framework project. The Framework is a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. Three ecoregional Framework projects are underway, covering 135 million acres in the northeastern and midwestern United States: Northwoods, Central Appalachians, and Central Hardwoods. Each regional project interweaves four components: science and management partnerships, vulnerability assessments, adaptation resources, and demonstration projects.

We designed this assessment to be a synthesis of the best available scientific information. Its primary goal is to inform forest managers in northern Michigan, in addition to people who study, recreate, and live in these forests. As new scientific information arises, we will develop future versions to reflect that accumulated knowledge and understanding. Most importantly, this assessment does not make recommendations about how this information should be used.

The scope of the assessment is terrestrial forested ecosystems, with a particular focus on tree species. Climate change will also have impacts on aquatic systems, wildlife, and human systems, but addressing these issues in depth is beyond the scope of this assessment.

The large list of authors reflects the highly collaborative nature of this assessment. Stephen Handler served as the primary writer and editor of the assessment. Matthew Duveneck, Louis Iverson, Emily Peters, Robert Scheller, Kirk R. Wythers, and Peter Reich led the forest impact modeling and contributed writing and expertise to much of the assessment. All modeling teams coordinated their efforts impressively. Leslie Brandt, Patricia Butler, Maria Janowiak, Danielle Shannon, and Chris Swanston provided significant investment into the generation and coordination of content, data analysis and interpretation, and coordination among many other Climate Change Response Framework assessments. Amy Clark Eagle, Joshua Cohen, and Rich Corner provided substantial input throughout the document. Tim Baker, Sophan Chhin, Eric Clark, David Fehringer, Jon Fosgitt, James Gries, Christine Hall, Kimberly R. Hall, Robert Heyd, Christopher L. Hoving, Ines Ibáñez, Don Kuhr, Stephen Matthews, Jennifer Muladore, Knute Nadelhoffer, David Neumann, Matthew Peters, Anantha Prasad, Matt Sands, Randy Swaty, Leiloni Wonch, Jad Daley, Mae Davenport, Marla R. Emery, Gary Johnson, Lucinda Johnson, David Neitzel, Adena Rissman, Chadwick Rittenhouse, and Robert Ziel provided input to specific chapters.

In addition to the authors listed, many people made valuable contributions to the assessment. David Maercklein (Hiawatha National Forest) helped determine the overall structure and content of the assessment. Andrew Burton, Tara Bal, and Andrew Storer (Michigan Technological University) all provided summaries of ongoing research. Scott Robbins (Michigan Forest Products Council) provided data on certified forest land in Michigan.

We would especially like to thank Dan Kashian (Wayne State University), Jessica Miesel (Michigan State University), and Doug Pearsall (The Nature Conservancy), who provided formal technical reviews of the assessment. Their thorough reviews greatly improved the quality of this assessment.

CONTENTS

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EXECUTIVE SUMMARY

This assessment evaluates key vulnerabilities for forest ecosystems in northern Michigan across a range of future climate scenarios. This assessment was completed as part of the Northwoods Climate Change Response Framework project, a collaborative approach among researchers, managers, and landowners to incorporate climate change considerations into forest management.

The assessment summarizes current conditions and key stressors and identifies past and projected trends in climate. This information is then incorporated into model projections of future forest change. These projections, along with published research, local knowledge, and expertise, are used to identify the factors that contribute to the vulnerability of major forest systems within the assessment area during the next 100 years. A final chapter summarizes the implications of these impacts and vulnerabilities for forest management across the region.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

Summary

This chapter describes the major forest communities across Albert's Ecological Sections VII and VIII and summarizes current threats and management trends. This information lays the foundation for understanding how shifts in climate may contribute to changes in forests, and how climate may interact with other stressors on the landscape.

Main Points

- More than 70 percent of the forest land in Michigan occurs within the assessment area, most of which is owned by private landowners.
- Major stressors and threats to forests in the region include:
  - Fragmentation and land-use change
  - Fire regime shifts
  - Nonnative species invasion
  - Forest pests and disease
  - Overbrowsing by deer
- Management practices over the past century have tended to favor early successional stages of many forest types across the landscape and reduce species diversity and structural complexity.
- A major ecological transition zone for both terrestrial and aquatic systems occurs between the northern and southern halves of Michigan's Lower Peninsula.
- The forest products industry is a major contributor to the region's economy.

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

Summary

This chapter provides a brief background on climate change science, models that simulate future climate change, and models that project the effects of climate change on tree species and forest communities. This chapter also describes the climate data used in this assessment.

Main Points

- Temperatures have been increasing at a global scale and across the United States during the past century.
- Major contributors to warming are greenhouse gases from fossil fuel burning, agriculture, and changes in land use.

CHAPTER 3: OBSERVED CLIMATE CHANGE

Summary

This chapter summarizes our understanding of observed changes and climate trends in the assessment area and across the Midwest region, with a focus on the last century.

Large cedar in a lowland conifer forest. Photo by Bradford Slaughter, Michigan Natural Features Inventory, used with permission.

Main Points

- Mean, maximum, and minimum temperatures have been increasing across all seasons, with winter and spring temperatures showing the most rapid warming.
- The assessment area has received more precipitation, particularly in the summer and fall.
- More precipitation has been delivered in heavy events of 3 inches or greater.
- Annual snowfall has been increasing slightly across northern Michigan, and the number of large winter storms has increased.
- Climate change has also been indicated by trends in lake ice, growing season length, and wildlife range shifts.

CHAPTER 4: PROJECTED CHANGES IN CLIMATE, EXTREMES, AND PHYSICAL PROCESSES

Summary

This chapter examines how climate may change in the assessment area over the next century, according to a range of model projections. Published scientific literature provides the basis for describing possible trends in a range of climate-driven processes, such as extreme weather events and snowfall.

Main Points

- Temperature is projected to increase across all seasons during the next century, with dramatic warming projected in winter.
- Precipitation is projected to increase in winter and spring across a range of climate scenarios, but summer precipitation may decrease.
- Intense precipitation events may continue to become more frequent than in the past.
- Snowfall is projected to decline across the assessment area by the end of the 21st century, with more winter precipitation falling as rain.

- Soils are projected to be frozen for shorter periods during winter.

CHAPTER 5: FUTURE CLIMATE CHANGE IMPACTS ON FORESTS

Summary

This chapter summarizes the potential impacts of climate change on forests in northern Michigan, drawing on information from a coordinated series of model simulations and published research.

Main Points

- Boreal species such as quaking aspen, paper birch, tamarack, jack pine, and black spruce are projected to experience reduced suitable habitat and biomass across the assessment area.
- Species with ranges that extend to the south such as American basswood, black cherry, and white oak may experience increased suitable habitat and biomass across the assessment area.
- Many common species in northern Michigan may decline under the hotter, drier future climate scenario.
- Forest productivity will be influenced by a combination of factors such as carbon dioxide fertilization, water and nutrient availability, local disturbances, and species migration.
- Model projections do not account for many other factors that may be modified by a changing climate, including:
    - Drought stress
    - Changes in hydrology and flood regime
    - Wildfire frequency and severity
    - Altered nutrient cycling
    - Changes in invasive species, pests, and pathogens

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

Summary

This chapter focuses on the vulnerability of major forest systems in the assessment area to climate change, with an emphasis on shifts in dominant species, system drivers, and stressors. The adaptive capacity of forest systems was also examined as a key component of overall vulnerability. Synthesis statements are provided to capture general trends. Detailed vulnerability determinations are also provided for nine major forest systems (Table 1). We consider a system to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in acreage, health, or productivity.

Table 1.—Vulnerability determinations by forest system

Forest system	Vulnerability	Evidence	Agreement
Upland spruce-fir	High	Medium-High	Medium-High
Jack pine	High-Moderate	Medium	Medium-High
Red pine-white pine	High-Moderate	Limited-Medium	Medium
Lowland conifers	High-Moderate	Medium	Medium
Aspen-birch	Moderate	Medium	Medium
Northern hardwoods	Moderate	Medium	Medium
Lowland-riparian hardwoods	Moderate	Medium	Low-Medium
Oak associations	Low-Moderate	Medium	Medium
Barrens	Low-Moderate	Limited-Medium	Medium

Main Points

Potential Impacts on Drivers and Stressors

- **Temperatures will increase (robust evidence, high agreement).** All global climate models project that temperatures will increase with continued increases in atmospheric greenhouse gas concentrations.
- **Winter processes will change (robust evidence, high agreement).** All evidence agrees that temperatures will increase more in winter than in other seasons across the assessment area, leading to changes in snowfall, soil frost, and other winter processes.
- **Growing seasons will get longer (robust evidence, high agreement).** There is high agreement among information sources that projected temperature increases will lead to longer growing seasons in the assessment area.
- **The amount and timing of precipitation will change (medium evidence, high agreement).** All global climate models agree that there will be changes in precipitation patterns across the assessment area.
- **Intense precipitation events will continue to become more frequent (medium evidence, medium agreement).** There is some agreement that the number of heavy precipitation events will continue to increase in the assessment area. If they do increase, impacts from flooding and soil erosion may also become more damaging.
- **Droughts will increase in duration and area (limited evidence, low agreement).** A study using multiple climate models indicates that drought may increase in length and extent, and an episodic precipitation regime could mean longer dry periods between events.
- **Soil moisture patterns will change (medium evidence, high agreement), with drier soil conditions later in the growing season (medium evidence, medium agreement).** Studies show that climate change will affect soil moisture, but there is disagreement among climate and impact models on how soil moisture will change during the growing season.
- **Climate conditions will increase fire risks by the end of the century (medium evidence, medium agreement).** Some national and global studies suggest that wildfire risk will increase in the region, but few studies have specifically looked at wildfire potential in the assessment area.
- **Many invasive species, insect pests, and pathogens will increase or become more damaging (limited evidence, high agreement).** Evidence indicates that an increase in temperature and greater moisture stress may lead to increases in these threats, but research to date has examined few species.

Potential Impacts on Forests

- **Boreal species will face increasing stress from climate change (medium evidence, high agreement).** Impact models agree that boreal or northern species will experience reduced suitable habitat and biomass across the assessment area, and that they may be less able to take advantage of longer growing seasons and warmer temperatures than temperate forest communities.
- **Southern species will be favored by climate change (medium evidence, high agreement).** Impact models agree that suitable habitat and biomass will increase for many temperate species across the assessment area, and that longer growing seasons and warmer temperatures will lead to productivity increases for temperate forest types.
- **Forest communities will change across the landscape (limited evidence, high agreement).** Although few models have specifically examined how communities may change, model results from individual species and ecological principles suggest that recognized forest communities may change in composition as well as occupied range.

A MODIS satelite image of the Great Lakes on a cloudless summer day. Image by Jeff Schmaltz, NASA.

- **Forest productivity will increase across the assessment area (medium evidence, medium agreement).** Some model projections and other evidence support modest productivity increases for forests across the assessment area, although there is uncertainty about the effects of CO_2 fertilization. It is expected that productivity will be reduced in localized areas.

Adaptive Capacity Factors

- **Low-diversity systems are at greater risk (medium evidence, high agreement).** Studies have consistently shown that more-diverse systems are more resilient to disturbance, and low-diversity systems have fewer options to respond to change.
- **Species in fragmented landscapes will have less opportunity to migrate in response to climate change (limited evidence, high agreement).** The dispersal ability of individual species is reduced in fragmented landscapes, but the future degree of landscape fragmentation and the potential for human-assisted migration are two areas of uncertainty.
- **Systems that are limited to particular environments will have less opportunity to migrate in response to climate change (limited evidence, high agreement).** Despite a lack of published research demonstrating this concept in the assessment area, our current ecological understanding indicates that migration to new areas will be particularly difficult for species and systems with narrow habitat requirements.
- **Systems that are more tolerant of disturbance have less risk of declining on the landscape (medium evidence, high agreement).** Basic ecological theory and other evidence support the idea that systems adapted to more frequent disturbance will be at lower risk.

CHAPTER 7: MANAGEMENT IMPLICATIONS

Summary

This chapter summarizes the implications of potential climate change to forest management and planning in northern Michigan. This chapter does not make recommendations as to how management should be adjusted to cope with these impacts, because impacts and responses will vary across forest types, ownerships, management objectives, and site-specific conditions.

Main Points

- Plants, animals, and people that depend on forests may face additional challenges as the climate shifts.
- Greater financial investments may be required to manage forests and infrastructure and to prepare for severe weather events.
- Management activities such as wildfire suppression or recreation activities such as snowmobiling may need to be altered as temperatures and precipitation patterns change.
- Information on anticipated climate change impacts may allow the forest products industry, recreation, and other sectors to adapt and capitalize on potential new opportunities.

INTRODUCTION

CONTEXT

This assessment is part of a regional effort across the Northwoods region of Minnesota, Wisconsin, and Michigan called the Northwoods Climate Change Response Framework (Framework; www.forestadaptation.org). The Framework project was initiated in 2009 in northern Wisconsin with the overarching goal of helping managers incorporate climate change considerations into forest management. To meet the challenges brought about by climate change, a team of federal and state land management agencies, private forest owners, conservation organizations, and others have come together to accomplish three objectives:

1. Provide a forum for people working across the Northwoods to effectively and efficiently share experiences and lessons learned.
2. Develop new user-friendly information and tools to help land managers factor climate change considerations into decisionmaking.
3. Support efforts to implement actions for addressing climate change impacts in the Northwoods.

The Framework process is designed to work at multiple scales. The Northwoods Framework is coordinated across the region, but activities are generally conducted at the state level to allow for greater specificity. Therefore, this assessment will focus on the eastern Upper Peninsula and northern Lower Peninsula of Michigan and will serve as a companion for similar assessments completed in the rest of the Northwoods. Additionally, regional Framework projects are underway in the Central Hardwoods region (Missouri, Illinois, and Indiana) and the Central Appalachians region (Ohio, West Virginia, and Maryland).

The Northwoods Framework is an expansion of the original northern Wisconsin effort, and has been supported in large part by the U.S. Department of Agriculture (USDA), Forest Service. Across the Northwoods, the project is being guided by an array of partners with an interest in forest management, including:

- Northern Institute of Applied Climate Science
- U.S. Forest Service, Eastern Region
- U.S. Forest Service, Northern Research Station
- U.S. Forest Service, Northeastern Area (State & Private Forestry)
- Trust for Public Land
- The Nature Conservancy
- American Forest Foundation
- Great Lakes Forest Alliance
- Wisconsin Department of Natural Resources
- Minnesota Department of Natural Resources
- Michigan Department of Natural Resources

This assessment is designed to provide detailed information for forest ecosystems within the assessment area. Our primary focus is on major forest vegetation communities. Several independent efforts related to climate change, natural communities, and human well-being are also occurring in the state. This assessment should complement similar products created for Michigan and the region, and the Framework project will attempt to integrate corresponding information as well.

This assessment bears some similarity to other synthesis documents about climate change science, such as the National Climate Assessment (draft report at http://ncadac.globalchange.gov/) and the Intergovernmental Panel on Climate Change (IPCC) reports (e.g., IPCC 2007). Where appropriate, we refer to these larger-scale documents when discussing national and global changes. This assessment differs from these reports in many ways, however. This assessment was not commissioned by any federal government agency nor does it give advice or recommendations to any federal government agency. It also does not evaluate policy options or provide input into federal priorities. Instead, this report was developed by the authors to fulfill a joint need of understanding local impacts of climate change on forests and assessing which tree species and forest systems may be the most vulnerable in northern Michigan. Although it was written to be a resource for forest managers, it is first and foremost a scientific document that represents the views of the authors.

SCOPE AND GOALS

The primary goal of this assessment is to summarize potential changes to the forest ecosystems of northern Michigan under a range of future climate scenarios and determine the vulnerability of forest communities to these changes over the next 100 years. Included is a synthesis of information about the landscape as well as projections of climate and vegetation changes used to assess these vulnerabilities. Uncertainties and gaps in understanding are discussed throughout the document.

This assessment covers 16.6 million acres throughout Michigan's eastern Upper Peninsula and northern Lower Peninsula (Fig. 1). The assessment area boundaries are defined by Ecological Sections VII and VIII in Michigan (northern Lower Peninsula and eastern Upper Peninsula), as defined by Albert (1995). More generally, this area falls within Ecological Province 212 (Mixed Laurentian Forest) of the National Hierarchical Framework of Ecological Units (Bailey 1995, McNab et al. 2007), which is the overall focus of the Northwoods Framework. We used county-level information that most closely represented the assessment area when eco-regional data were not available, limiting our selections to the 40 counties that are most analogous to the area within Ecological Sections VII and VIII (Box 1). The western Upper Peninsula was not included in this assessment because that area is being described in combination with northern Wisconsin in a companion vulnerability assessment under the Northwoods Framework.

This assessment area covers 70.2 percent of the forested land within Michigan (U.S. Forest Service 2011). Within this landscape, major land ownerships include the Hiawatha National Forest (approx. 880,000 acres), Huron-Manistee National Forests (approx. 980,000 acres), and the Michigan Department of Natural Resources (approx. 3,260,000 acres in the assessment area) (U.S. Forest Service

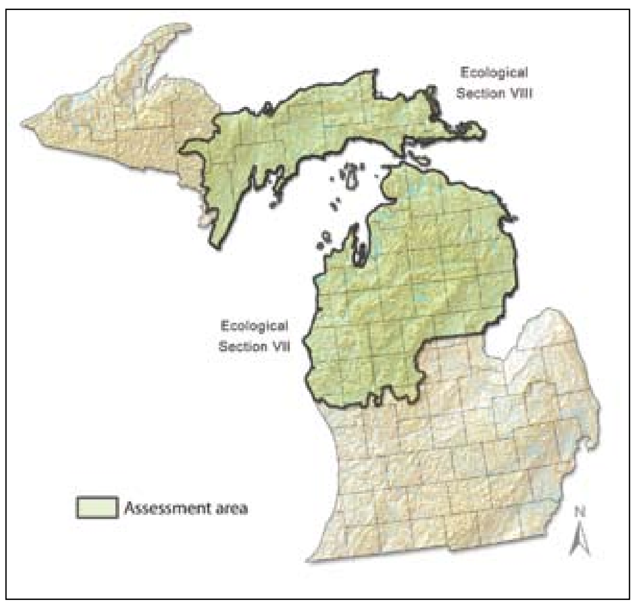


Figure 1.—Ecological Sections VII and VIII in Michigan (green shading), and the 40 counties that were used to approximate the assessment area when county-level data were required. Modified from Albert (1995).

Box 1: Counties Used to Represent the Assessment Area

Lower Peninsula: Ecological Section VII

Alcona	Manistee
Alpena	Mason
Antrim	Mecosta
Arenac	Missaukee
Benzie	Montcalm
Charlevoix	Montmorency
Cheboygan	Muskegon
Clare	Newaygo
Crawford	Oceana
Emmet	Ogemaw
Gladwin	Osceola
Grand Traverse	Oscoda
Iosco	Otsego
Isabella	Presque Isle
Kalkaska	Roscommon
Lake	Wexford
Leelanau	

Upper Peninsula: Ecological Section VIII

Alger	Mackinac
Chippewa	Menominee
Delta	Schoolcraft
Luce	

2011). Supplementary information specific to these landowners was used when available and relevant to the broader landscape. This assessment synthesizes information covering all of northeastern Michigan in recognition of the area's complex patterns of forest composition and land ownership.

ASSESSMENT CHAPTERS

This assessment contains the following chapters:

Chapter 1: The Contemporary Landscape describes existing conditions, providing background on the physical environment, ecological character, and broad socioeconomic dimensions of northern Michigan.

Chapter 2: Climate Change Science and Modeling contains background on climate change science, projection models, and impact models. It also describes the techniques used in developing climate projections to provide context for the model results presented in later chapters.

Chapter 3: Observed Climate Change provides information on the past and current climate of the assessment area in northern Michigan, summarized from The Nature Conservancy's interactive ClimateWizard database and published literature. This chapter also discusses relevant ecological indicators of observed climate change.

Chapter 4: Projected Changes in Climate, Extremes, and Physical Processes presents downscaled climate change projections for the assessment area, including future temperature and precipitation data. It also includes summaries of other climate-related trends that have been projected for northern Michigan and the Midwest region.

Chapter 5: Future Climate Change Impacts on Forests summarizes impact model results that were prepared for this assessment. Three modeling approaches were used to model climate change impacts on forests: a species distribution model (Climate Change Tree Atlas), a forest simulation model (LANDIS-II), and a biogeochemical model (PnET-CN). This chapter also includes a review of literature about other climate-related impacts on forests.

Chapter 6: Forest Ecosystem Vulnerabilities synthesizes the potential effects of climate change on the forested ecosystems of the assessment area and provides detailed vulnerability determinations for nine major forest communities.

Chapter 7: Management Implications draws connections from the forest vulnerability determinations to a wider network of related concerns shared by forest managers, including forest management, recreation, cultural resources, and forest-dependent wildlife.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

The contemporary landscape of Michigan results from a variety of interacting factors, including physical, ecological, and socioeconomic conditions. This chapter provides a brief introduction to northern Michigan in general and the forest ecosystems within the assessment area in particular. This context is critical for interpreting information presented in the remainder of this assessment. The references cited in each section will be helpful for readers looking for more in-depth information on a particular subject.

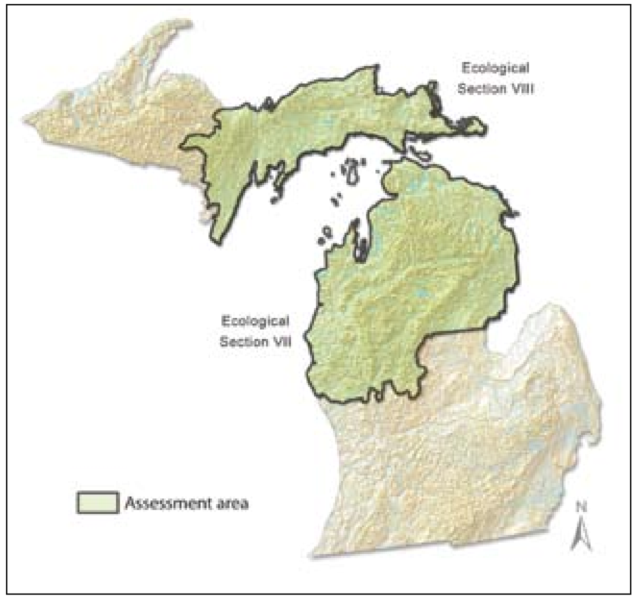


Figure 2.—Assessment area, defined by Ecological Sections VII and VIII in Michigan. Modified from Albert (1995).

LANDSCAPE SETTING

Physical Environment

This section draws information primarily from Albert's description of Regional Landscape Ecosystems in Michigan, Minnesota, and Wisconsin (Albert 1995) unless otherwise noted. Ecological Section VII (Northern Lacustrine-Influenced Lower Michigan, Michigan's northern Lower Peninsula) and Ecological Section VIII (Northern Lacustrine-Influenced Upper Michigan and Wisconsin, Michigan's eastern Upper Peninsula) define the boundary for this assessment (Fig. 2). Ecological sections have distinctive natural conditions based on differences in climate, geology, glacial landforms, and soils. The following descriptions summarize information for Ecological Sections VII and VIII.

Climate

Baseline climate data from 1971 through 2000 provide a general picture of contemporary climate averages for the assessment area (Table 2) (ClimateWizard 2012, Gibson et al. 2002). These averages are important to keep in mind when considering how the climate in the assessment area has changed and may continue to change. Observed climate trends for the 20th century are presented in Chapter 3, and projections of future climate trends are presented in Chapter 4.

The proximity of the Great Lakes is a fundamental factor that shapes the climate of the assessment area. Albert (1995) describes the profound lake influence as generally moderating temperatures compared to areas of similar latitude in the neighboring states of Minnesota and Wisconsin. Northern Michigan is generally cooler in the summer and warmer in the winter than would be expected at its latitude, although this trend depends on proximity to the surrounding Great Lakes. On average, the eastern Upper Peninsula is colder than the northern Lower Peninsula across all seasons, although the interior

Table 2.—Average climate information for the assessment area, 1971 through 2000 (ClimateWizard 2012)

Season	Average precipitation (inches)	Mean temperature (°F)	Mean maximum temperature (°F)	Mean minimum temperature (°F)
Annual	31.6	43.2	53.5	33.0
Winter (Dec. - Feb.)	5.5	20.5	28.9	12.1
Spring (Mar. - May)	7.2	41.0	52.2	29.8
Summer (June - Aug.)	9.7	64.9	76.8	52.9
Fall (Sept. - Nov.)	9.2	46.3	55.7	36.8

northern Lower Peninsula experiences shorter growing seasons and more continental winters than the rest of the state. Areas along the Great Lakes shorelines are generally warmer than interior areas. The growing season ranges from 70 days toward the interior of the Lower Peninsula to 160 days along the Lake Michigan coastline in the Upper Peninsula. Extreme minimum temperature ranges from -48.5 °F (-44.7 °C) toward the interior of the Lower Peninsula to -26 °F (-32.2 °C) along the Lake Huron coast (Albert 1995).

The assessment area also receives substantial lake-effect snow during the wintertime along the Great Lakes coastlines, which means that precipitation is generally more evenly distributed throughout the year when compared to neighboring states. Winter and spring each account for roughly 20 percent of annual precipitation, and summer and fall each contribute roughly 30 percent (ClimateWizard 2012). Average annual precipitation ranges from 28 to 34 inches throughout the assessment area, with a gradient of wetter to drier from the southwest to the northeast across the Lower Peninsula (Albert 1995, ClimateWizard 2012). Snowfall averages between 40 inches per year along the eastern edge of the Lower Peninsula and 140 inches per year along the Upper Peninsula's Lake Superior coastline (Albert 1995).

Geology and Landform

In Ecological Section VII, bedrock geology of the assessment area includes limestone, shale, dolomite, sandstone, and gypsum, along with occasional coal deposits. Ecological Section VIII is underlain with sandstone along the Lake Superior coast and sandstone and dolomite inland. Bedrock is exposed as lakeshore cliffs, bedrock lakeshores, and cobble shores along the shores of the Great Lakes. Inland bedrock systems within the assessment area include alvar and bedrock glades. County-level geological summaries are available for detailed information across the state (Apple and Reeves 2007). A map of bedrock geology for Michigan is available through the Michigan Department of Environmental Quality (Michigan Department of Environmental Quality 2013).

Glacial activity has shaped the soils and terrain of northern Michigan. The last glacier receded approximately 13,000 years ago from the Lower Peninsula, and 10,000 years ago from the Upper Peninsula (Millar 1940). Glaciers were active for thousands of years during the most recent Ice Age, so the terrain of Michigan reflects a complicated pattern of glacial advance and retreat. Till plains, moraines, and outwash plains occur throughout the assessment area, and glacial lake plains exist along the Great Lakes shorelines (Jerome 2006).

Hydrology

Michigan is bounded by four Great Lakes, with more than 11,000 inland lakes and 36,000 miles of rivers and streams. Its proximity to Lake Superior, Lake Michigan, and Lake Huron shapes the climate regimes and seasonal weather patterns within the assessment area, as mentioned above. The National Land Cover Database (NLCD) categorizes more than 26 percent of the assessment area as wetland and almost 4 percent as open water (U.S. Geological Survey 2011a).

Chase and others (1991) summarize the hydrologic regime across the entire state. Precipitation averages 1.5 to 2.0 inches per month from December to March and 3.0 to 4.0 inches per month from May to September. Data from 1971 through 2000 for the assessment area confirm this pattern (Table 2) (ClimateWizard 2012). Historically, surface water supplies have been continually replenished throughout the year. Humidity is generally moderate, so evaporation is slow. Severe droughts have been infrequent, as have severe floods. Floods usually occur in late winter or early spring with warming temperatures and rainfall on frozen or saturated ground.

Within the assessment area, the largest watersheds are the Escanaba, Manistique, Tahquamenon, Cheboygan, Au Sable, Thunder Bay, Manistee, Muskegon, and Tittabawasee Rivers (Clark 1999). According to U.S. Geological Survey streamflow stations on major rivers in the assessment area, peak surface flow typically arrives in a major pulse during April and May, with flows substantially reduced from June through August (U.S. Geological Survey 2011b). August typically has the lowest streamflow during the growing season.

Rivers and streams in Michigan have been categorized based on catchment area, July mean water temperature, and diagnostic fish species (Zorn et al. 2008). Nearly all of the streams and rivers in the assessment area are cold, cold transitional, or warm transitional, which means they have an average July water temperature less than 70 °F (21.0 °C) (Fig. 3). At the southern boundary of the assessment there is a relatively abrupt change to warm streams and rivers.

Soils

The combination of underlying bedrock and glacial activity has resulted in clearly different soils between the Upper and Lower Peninsulas. In the northern Lower Peninsula, soils are generally deep and sandy, with sandy end moraines, sandy glacial lake plains, and sandy ground moraines. Soils in this section are mostly well drained, except along streams and rivers. Glacial drift can be 1,000 feet thick, with large hills and rolling topography (Albert 1995, Apple and Reeves 2007). In this half of the assessment area, bedrock is exposed only along the shorelines or in close proximity to the shore.

In the eastern Upper Peninsula, soils are sands or clays within the lake plains and are generally wetter, and bedrock is closer to the surface. Lake-bottom sand or clay deposits occur in combination with organic soils in the eastern half of the Upper Peninsula (Albert 1995, Apple and Reeves 2007). Along the lake plains, forested dune fields are commonly interspersed with bogs and wetlands (Arbogast et al. 2002).

Fine-scale information on soil types is available in Albert's descriptions of Regional Landscape Ecosystems (Albert 1995), and the USDA Natural Resources Conservation Service Web Soil Survey portal (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm).

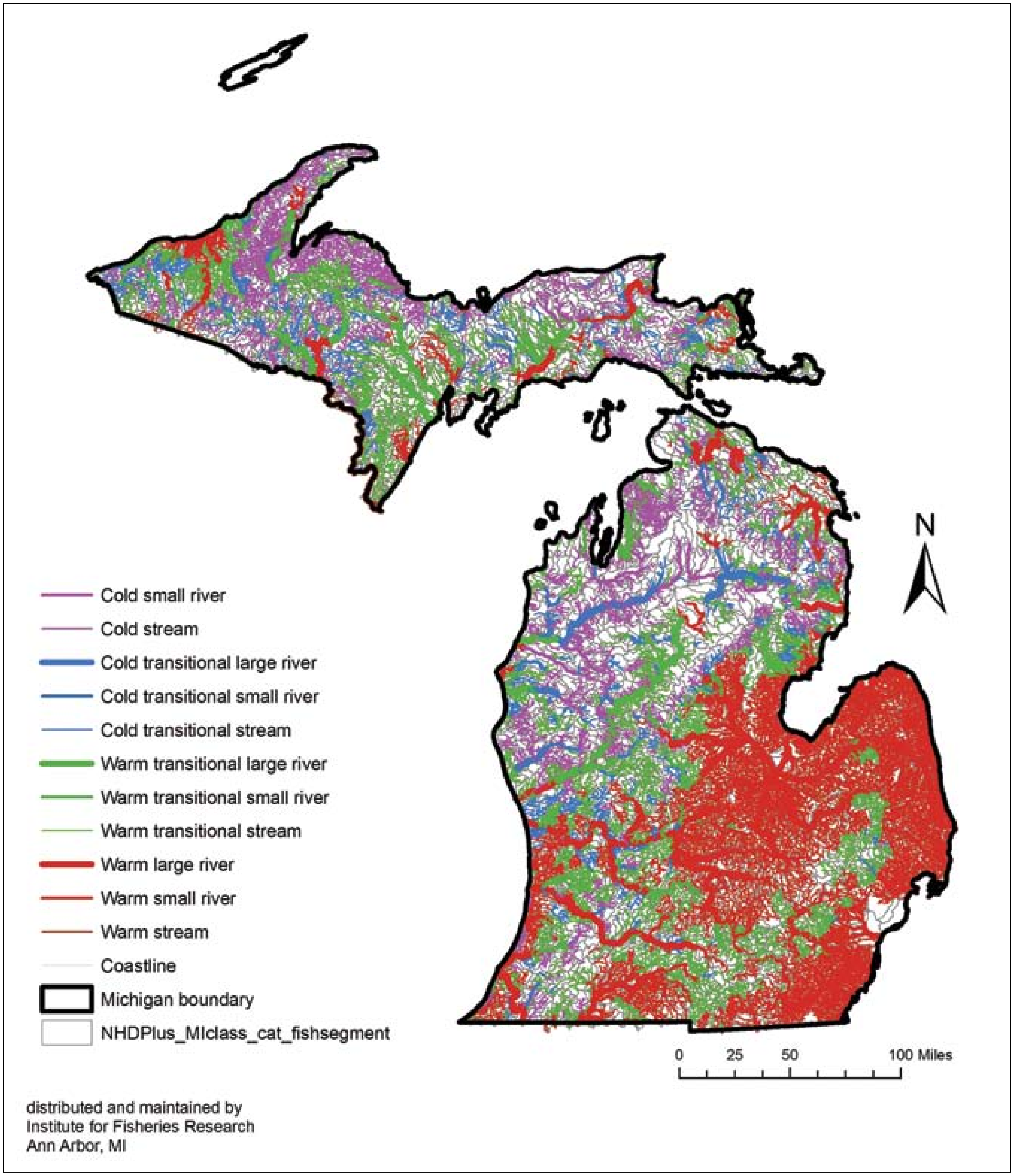


Figure 3.—River classification map based on catchment area, July mean water temperature, and diagnostic fish species. Cold = July mean water temperature is less than 63.5 °F (17.5 °C), Cold-transitional = July mean water temperature is between 63.5 °F (17.5 °C) and 67 °F (19.5 °C), Warm-transitional = July mean water temperature is between 67 °F (19.5 °C) and 70 °F (21.0 °C), Warm = July mean water temperature is greater than 70 °F (21.0 °C). Stream = Segment catchment area is less than 80 square miles, Small river = Segment catchment area is between 80 and 300 square miles, Large river = Segment catchment area is greater than 300 square miles. Figure from Zorn et al. (2008) and used with the permission of the authors.

Land Cover

This assessment covers 16.6 million acres throughout the eastern Upper Peninsula and northern Lower Peninsula of Michigan (Fig. 2). According to the NLCD, wetlands account for 26.3 percent of the overall land cover in the assessment area (Table 3) (U.S. Geological Survey 2011a). Much of the terrain in the assessment area is occupied by peatlands and lowland forests, which are categorized as wetland in the NLCD. According to data from the U.S. Forest Service Forest Inventory and Analysis (FIA) program, forest land covers 70.3 percent of the assessment area (11.6 million acres) (U.S. Forest Service 2011). The FIA estimate of forest land is higher than that of the NLCD because FIA captures many of the forested wetland and planted forest stands that the NLCD may have classified as "wetland" or "planted."

Figure 4 presents a map of land cover for Michigan, based on a classification system different from the NLCD (Fry et al. 2011). This map shows the clear gradation from forest to nonforest cover that occurs along the southern boundary of the assessment area.

The original land cover in Michigan has been estimated from General Land Office surveys that occurred from 1815 to 1860 and from notes of early European settlers (Comer et al. 1995). Estimates are that approximately 95 percent of Michigan's vegetation was forest (Dickmann and Leefers 2003, Sparhawk and Brush 1929). Bailey (1995) defines the Laurentian Mixed Forest Province (Province 212) as a transitional zone between boreal zones to the north and broadleaf deciduous zones to the south. Albert (1995) offers a more complete summary of presettlement vegetation throughout the assessment area. Tables 20 through 22 in Appendix 1 list common and scientific names of plant, fauna, and other species mentioned in this assessment. Northern hardwoods were common on finer-textured soils common to moraines and drumlin fields. Forests of white pine and red pine were located on sandier soils in narrow outwash channels and on moraines at the edges of outwash plains, where fires were relatively common but less frequent or severe than on outwash plains. Jack pine and northern pin oak dominated sandier soils on flat, droughty outwash plains, particularly in the northern Lower Peninsula. Northern grasslands were also present in areas associated with jack pine barrens. In southern portions of the northern Lower Peninsula, forests transitioned to oak-pine barrens and dry sand prairie in outwash areas. Conifer and hardwood-conifer swamps covered large portions of glacial lake plains, but also occurred along drainages throughout the section. Peatlands also existed in sandy lake plains. On clay lake plains, forests were a diverse mix of conifer and hardwood species, including white spruce, balsam fir, white pine, eastern hemlock, quaking aspen, balsam poplar, and red maple.

Table 3.—Land cover classifications within the assessment area (U.S. Geological Survey 2011a)

Land cover class	Cover (%)
Forest	44.3
Wetlands	26.3
Planted/cultivated	10.3
Herbaceous	6.8
Developed	6.0
Water	3.6
Shrubland	2.1
Barren	0.5

Current estimates are that 53 percent of Michigan is forested (Price 2010). Data from FIA inventories indicate that following a decline in forest cover from 1955 to 1980, forest cover has been slowly increasing within the assessment area (Pugh et al. 2012). The trend has continued to the most recent FIA inventories. Forest land in the eastern Upper Peninsula increased 2.2 percent from 2004 to 2009, while the percentage of forest land in the northern Lower Peninsula remained nearly constant (Pugh et al. 2012). Alger County has the largest percentage of forest area at 88 percent, and Isabella County has only 6 percent forest land (Headwaters Economics 2011). Counties with smaller percentages of forest land are located in the agricultural areas along the southern edge and the northwestern quarter of the Lower Peninsula.

Although forest land is the primary land cover type in the assessment area, much of this forest land exists as fragmented edges or patches (Pugh et al. 2009) (Fig. 5). Very little interior forest (minimum 5.6 acres or at least 200 feet from a forest edge) remains in the northern Lower Peninsula,

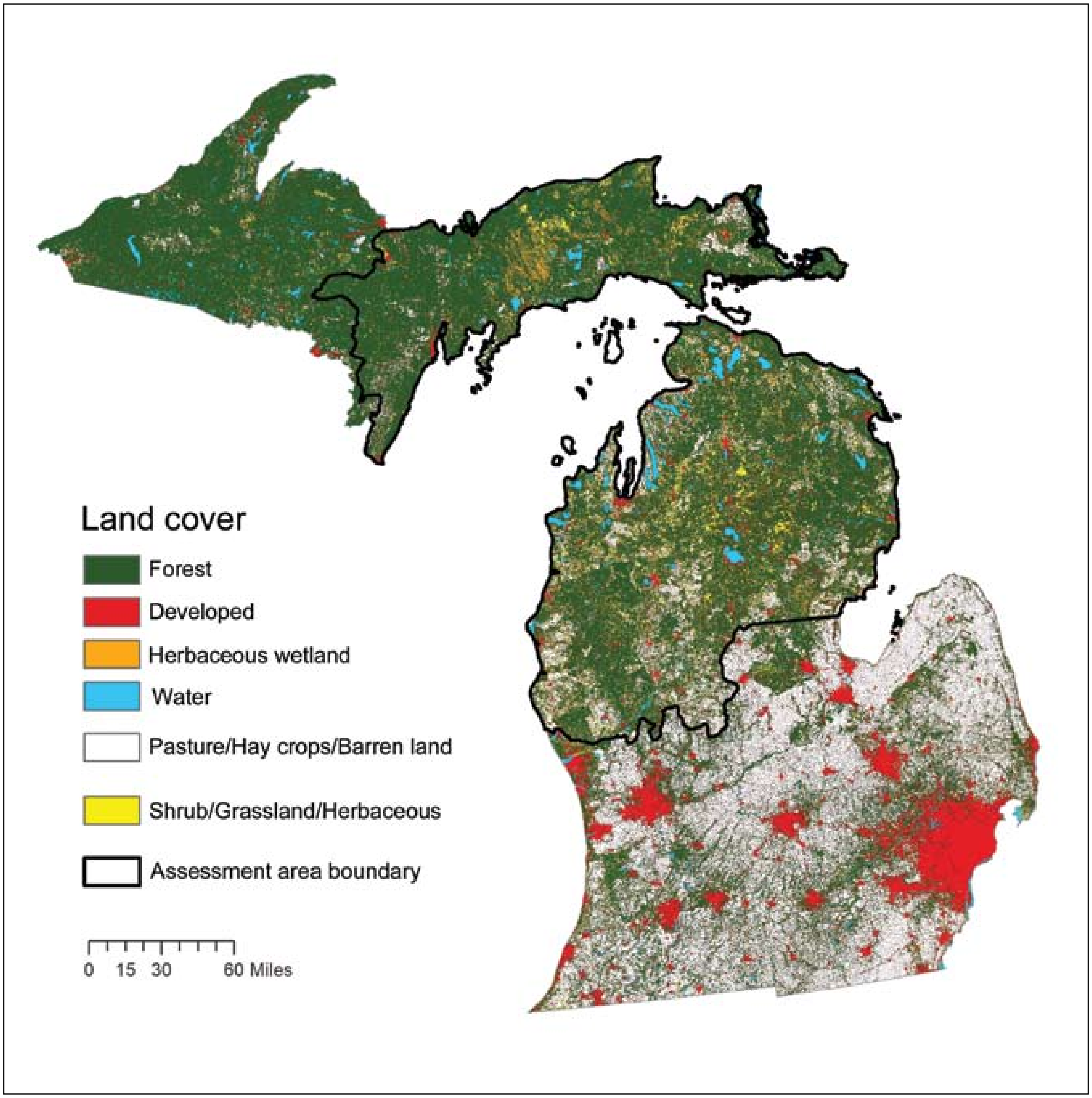


Figure 4.—Land cover in Michigan based on the U.S. Geological Survey National Land Cover Database (2006).

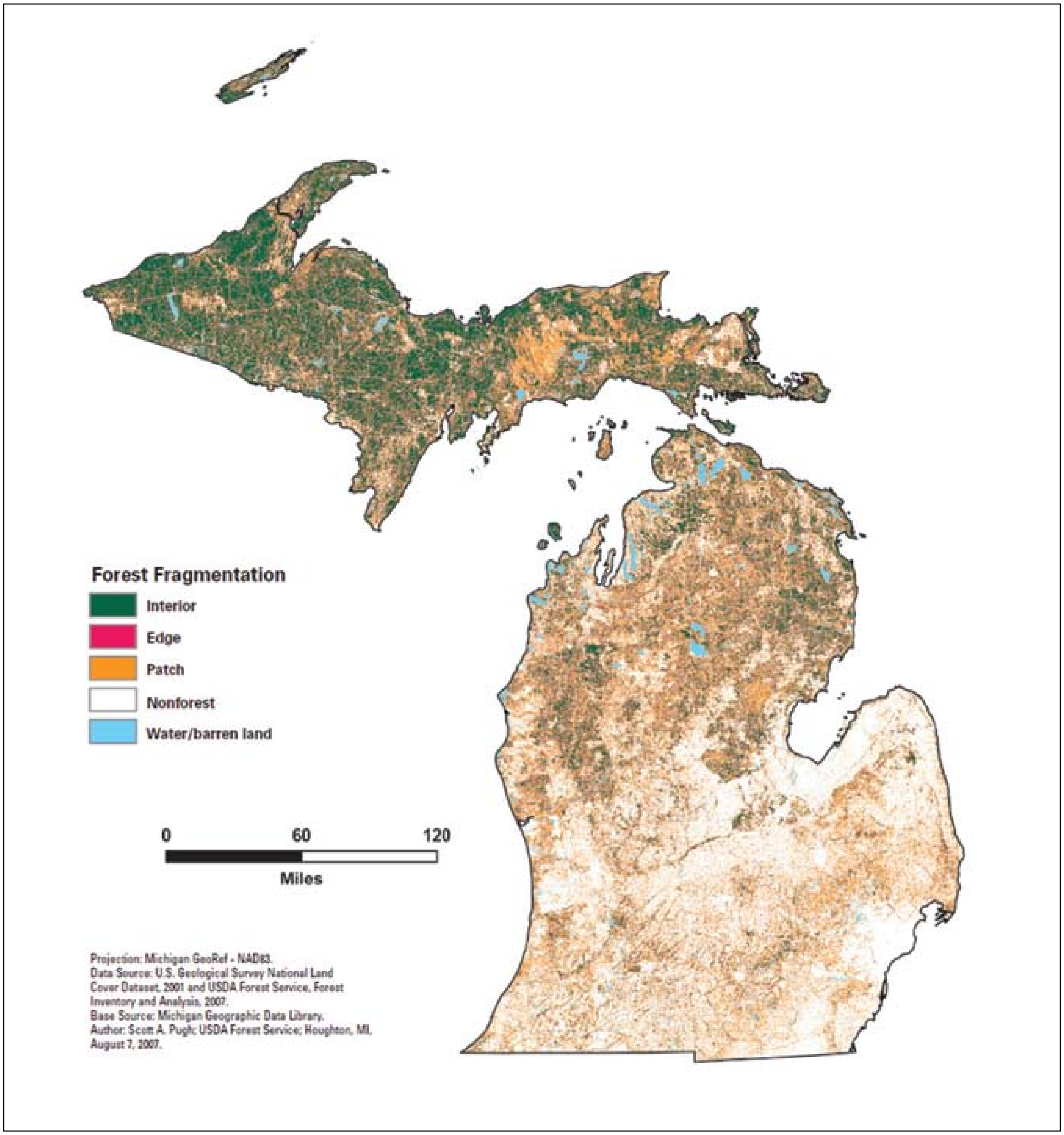


Figure 5.—Forest fragmentation in Michigan, from Pugh et al. (2009). In that assessment 30-meter (98-foot) pixels were classified as "interior forest" if they had a continuous forest canopy and were part of a minimum of 5.6 acres or at least 200 feet from the nearest forest edge.

and the remaining interior forest in the eastern Upper Peninsula is mostly within the Hiawatha National Forest and state forest boundaries. This fragmentation is due to a variety of factors, including agriculture, urban development, and forest management practices.

Forest Communities

For the purposes of this assessment, we rely on a combination of data sources to categorize forest communities in northern Michigan. The resulting forest systems are a combination of FIA forest-type groups and natural communities described by the Michigan Natural Features Inventory (MNFI; Table 4). For complete descriptions of the MNFI natural communities, including associated landforms, soil types, disturbance regimes, and common species, see *Natural Communities of Michigan: Classification and Description* (Kost et al. 2007) and related natural community abstracts. Box 2 provides more information on FIA forest-type groups and MNFI natural communities.

Other forested natural communities present in northern Michigan but not considered explicitly in this assessment include muskeg communities and wooded dune and swale complexes. These communities and others are described in detail in *Natural Communities of Michigan: Classification and Description* (Kost et al. 2007) and the associated MNFI community abstracts.

White pine and red pine forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Table 4.—Forest systems considered in this assessment, with a summary of major drivers and species for each system (Cohen 2000a, 2000b, 2001, 2002a, 2002b, 2006, 2007; Comer 1996; Courteau et al. 2006; Kost 2002; Kost et al. 2007; Slaughter et al. 2007; Tepley et al. 2004; Weber et al. 2006, 2007)

Forest system	Major drivers	Characteristic species*	Related natural communities or associations
Upland spruce-fir	thin nutrient-poor soils or glacial lake plains, high snowfall areas with short growing seasons, moderated climate in lake-effect areas, catastrophic disturbances from fire, wind, and pests	balsam fir, white spruce, eastern white pine, red maple, northern white-cedar, paper birch, quaking aspen, eastern hemlock	Boreal forest
Jack pine (including pine-oak)	coarse-textured soils, upland areas, drought-tolerant, fire-return intervals 50 to 250 years, requires scarification or fire for regeneration, favored by cold temperatures	jack pine, red pine, eastern white pine, red maple, northern red oak, northern pin oak, black oak	Dry northern forest
Red pine-white pine	sandy to dry-mesic soils, limited by high summer temperatures, dependent on disturbance for regeneration, red pine regeneration primarily through planting, favored by drought, fire-return intervals 50 to 250 years	red pine, eastern white pine, jack pine, red maple, black cherry, bigtooth aspen, black oak, eastern hemlock, northern red oak	Dry northern forest Dry-mesic northern forest
Lowland conifers	peat or mineral soils, low landscape positions, saturated throughout growing season, groundwater seepage, windthrow events, stand-replacing fire on long cycles, limited by drought	northern white-cedar, black spruce, tamarack, balsam fir, paper birch, quaking aspen, eastern hemlock, white spruce	Poor conifer swamp Rich conifer swamp Hardwood-conifer swamp
Aspen-birch	gradient of soil types and landforms, frequent disturbance or management, limited by warm temperatures and moisture stress	quaking aspen, bigtooth aspen, red maple, northern white-cedar, paper birch, balsam fir, balsam poplar	Aspen association
Northern hardwoods	mesic soils or deep impermeable layers, consistent moisture and nutrients, gap-phase disturbances with stand-replacing events every 400 to 2,000 years	sugar maple, red maple, American beech, American basswood, eastern hemlock, northern red oak, white ash, black cherry, northern white-cedar, yellow birch, balsam fir, eastern white pine, white spruce	Mesic northern forest
Lowland-riparian hardwoods	alluvial soils or impermeable clay lenses, nutrient-rich soils, seasonally or annually inundated or saturated, connectivity to river or water table, tip-up mounds and periodic dry conditions important for regeneration	red maple, northern white-cedar, silver maple, black ash, green ash, quaking aspen, balsam fir, paper birch, eastern hemlock, yellow birch, American elm, balsam poplar, American basswood, sycamore, swamp white oak, hackberry, black willow, white ash, eastern cottonwood	Hardwood-conifer swamp Floodplain forest Northern hardwood swamp
Oak associations	sandy to dry-mesic soils, limited by cold temperatures, dependent on disturbance for regeneration, drought-tolerant, fire-return intervals 50 to 250 years or longer	northern red oak, white oak, black oak, northern pin oak, eastern white pine, red pine, quaking aspen	Oak association
Barrens	coarse-textured soils, excessively drained and drought-prone, fire-return intervals 1 to 50 years, canopy cover only 5 to 25 percent, subject to cold temperatures and frost pockets	jack pine, black oak, northern pin oak, white oak, red pine, eastern white pine	Oak-pine barrens Oak barrens Pine barrens

*The list of characteristic species is not exhaustive, and composition may differ substantially from site to site across the assessment area. Scientific names are in Appendix 1.

Box 2: Forest Types and Natural Communities

In this assessment, we use two different sources of data for classifying forest systems: FIA forest-type groups and MNFI natural communities. These classification systems are used for different reasons and convey different types of information. Although there are some general relationships between the two systems, they are organized differently enough that one cannot be substituted for the other. Both types of information are relevant to this assessment, so we use both classification systems.

FIA classifications describe existing vegetation, and only for vegetated areas dominated by trees (i.e., forests). Forest-type groups are defined as a combination of forest types that share closely associated species or site requirements (e.g., maple/beech/birch). Forest types are a classification of forest land based upon and named for the dominant tree species (e.g., aspen). There are several advantages to the FIA classification system. The FIA system measures tree species composition on a set of systematic plots across the country and uses that information to provide area estimates for each forest type, making it a good way of estimating what is currently on the landscape and the relative abundance of different forest types. It does not, however, make any inferences about what vegetation was historically on the landscape and does not distinguish between naturally occurring and human-influenced conditions. Something that is classified as "forest land" by FIA may have been historically a prairie, glade, woodland, or savanna. Likewise, areas dominated by tree species that are not native to the area would still be assigned to a forest type and forest-type group based on dominant species. Forest-type groups have been mapped for Michigan (Fig. 6) (Pugh et al. 2009, 2012).

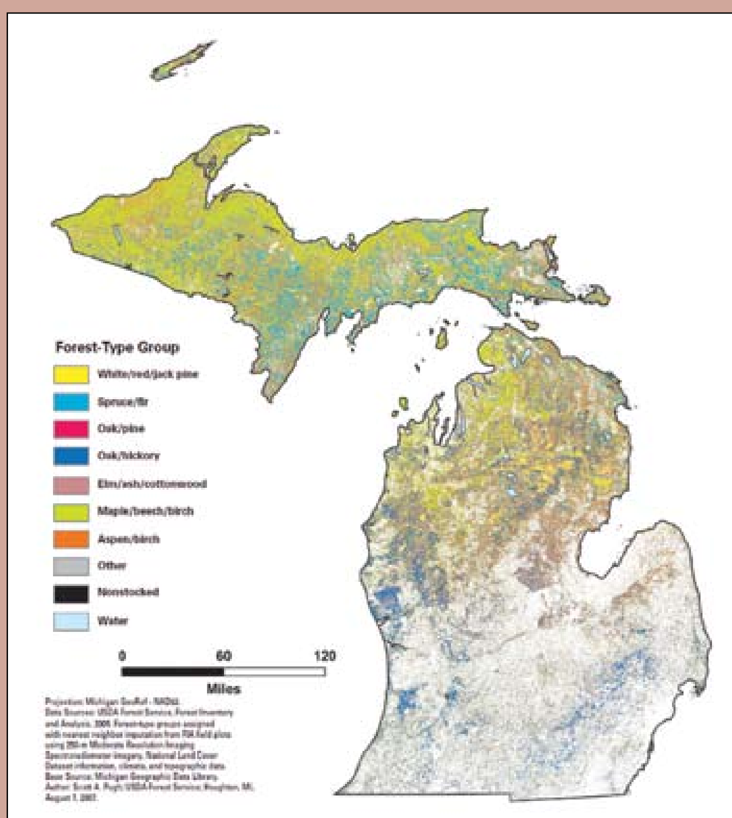


Figure 6.—Distribution of FIA forest-type groups in Michigan as of 2005, from Pugh et al. (2009).

Box 2: Forest Types and Natural Communities (continued)

By contrast, natural communities are defined as an assemblage of interacting plants, animals, and other organisms that repeatedly occurs across the landscape under similar environmental conditions (Kost et al. 2007). The Michigan Natural Features Inventory has prepared a classification of natural communities in Michigan, mapped representative occurrences of these communities across the state, and created distribution maps of the natural communities across the state by using the ecoregional framework of ecological subsections and sub-subsections (Albert et al. 2008, Kost et al. 2007). It recognizes 77 natural communities, many of which occur within the assessment area. See Figure 7 for an example of the natural community distribution maps (Albert et al. 2008). The advantage to the natural community system is that it is based on ecological relationships between native organisms and their physical environment. Natural communities describe existing vegetation in remaining natural forest areas, so they present a picture of vegetation that may have been present if the landscape had been left unaltered by human intervention. The disadvantage to using natural community classifications is that they have not yet been quantified spatially across the state.

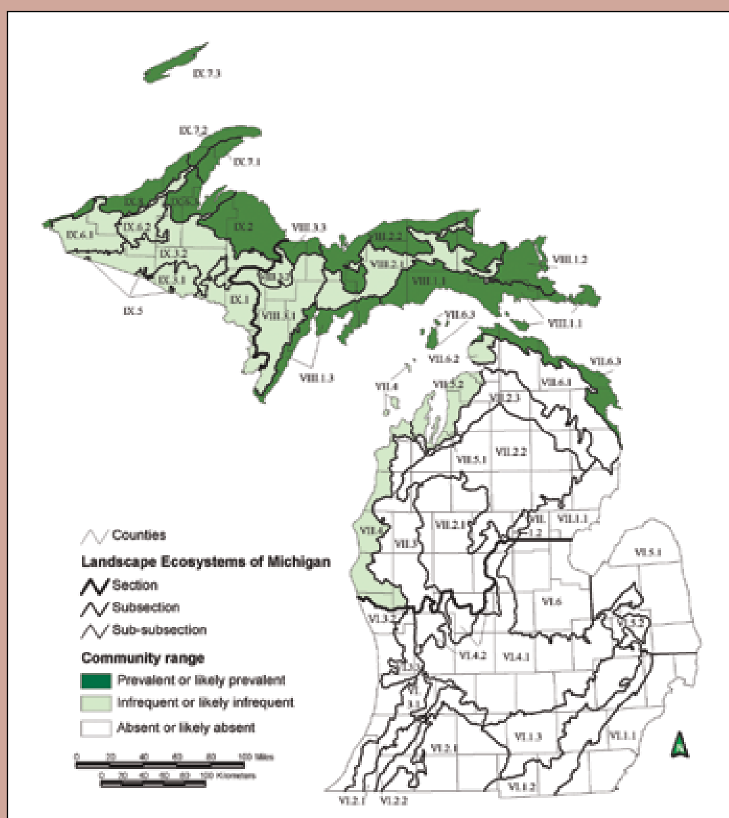


Figure 7.—Distribution of the boreal forest natural community, from Albert et al. (2008). This is an example of a series of similar distribution maps for other natural communities described by the Michigan Natural Features Inventory.

Forest Composition and Abundance

FIA Forest-type Groups

FIA inventory data are useful to organize forest land into broad forest-type groups to facilitate comparison among similar species (Table 5) (U.S. Forest Service 2011). The FIA forest-type groups do not perfectly align with the forest systems described above, but FIA data are useful for describing forest abundance, growth, and other metrics. There are more than 11.6 million acres of forest land in the assessment area, which includes a variety of forest types (U.S. Forest Service 2011).

Within the assessment area maple/beech/birch is the most common forest-type group, followed by aspen/birch, spruce/fir, white pine/red pine/jack pine, and oak/hickory. Compared to the state as a whole, the assessment area contains similar proportions of these forest-type groups. The percentage cover of each forest-type group differs by less than 5 percent between the assessment area and the entire state. Aspen/birch, spruce/fir, and white/red/jack pine are slightly more common in the assessment area than across the state, and elm/ash/cottonwood, maple/beech/birch, and oak/hickory are slightly less common in the assessment area. Forest-type group distribution differs by region, however. More than half (51 percent) of all the aspen in the state occurs in the northern Lower Peninsula, along with most of the state's pine- and oak-dominated forests (Pugh et al. 2012). More than half of all the northern white-cedar in the state can be found in the eastern Upper Peninsula (Pugh et al. 2012).

Table 5.—Acres occupied and cover percentages of FIA forest-type groups on forest land within the assessment area and for the entire state (U.S. Forest Service 2011)

	Assessment area		Michigan (statewide)	
Forest-type group	Acres	Cover (%)	Acres	Cover (%)
Aspen/birch	2,203,228	18.9	3,210,171	16.2
Douglas-fir	2,378	<0.0	2,378	<0.0
Elm/ash/cottonwood	866,201	7.4	2,055,440	10.4
Exotic hardwoods	—	—	11,860	0.1
Exotic softwoods	105,295	0.9	172,952	0.9
Fir-spruce/mountain hemlock	9,048	0.1	13,652	0.1
Maple/beech/birch	2,934,672	25.2	5,838,968	29.5
Oak/gum/cypress	—	—	12,133	0.1
Oak/hickory	1,515,636	13.0	3,275,139	16.5
Oak/pine	465,311	4.0	589,520	3.0
Other eastern softwoods	—	—	3,888	<0.0
Other hardwoods	73,851	0.6	125,618	0.6
Spruce/fir	1,816,651	15.6	2,530,814	12.8
White/red/jack pine	1,653,396	14.2	1,980,580	10.0
Total	11,645,667		19,823,113	

Box 3: Forest Carbon

Forest ecosystems around the world play a valuable role as carbon (C) sinks. Terrestrial C within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represents an enormous store of C (Birdsey et al. 2006). Terrestrial C stocks in the region have generally been increasing for the past few decades, and there is increased attention on the potential to manage forests to maximize and maintain this C store (Malmsheimer et al. 2011, Price 2010). Carbon sequestration and storage in forest ecosystems depends on the health and function of those ecosystems in addition to human management, episodic disturbances, and forest stressors.

Forest land within the assessment area is estimated to hold nearly 1.1 billion metric tons C, or roughly 95 metric tons per acre (U.S. Forest Service 2011). There is only a little difference in the amount of C stored per acre across the major forest ownership categories. National Park Service lands generally hold more C than the average (105.8 metric tons per acre), and private lands, national forests, and state forests are roughly equal to the average. County and municipal lands tend to hold less C than the average for the assessment area (89.8 metric tons per acre). The pattern of C allocation in forest ecosystems is relatively consistent across ownerships. Soil organic C is by far the largest C pool, followed by aboveground live biomass, litter, live belowground biomass, and deadwood pools.

Among different forest-type groups, however, the amount of C stored per acre differs widely (Fig. 8). Of all the forest-type groups, spruce/fir holds the most C per acre, mainly in the soil organic C pool. Maple/beech/birch forests tend to store the most aboveground C compared to other forest-type groups. Climate is one of the factors that dictate the size of these per-acre C pools. Spruce/fir forests tend to grow in colder areas on poorer soils, where decomposition is slow and tree growth is slow, so most C is stored in the soil. Maple/beech/birch forests tend to grow in warmer areas on more productive soils, so decomposition rates are faster and more C is stored in living biomass.

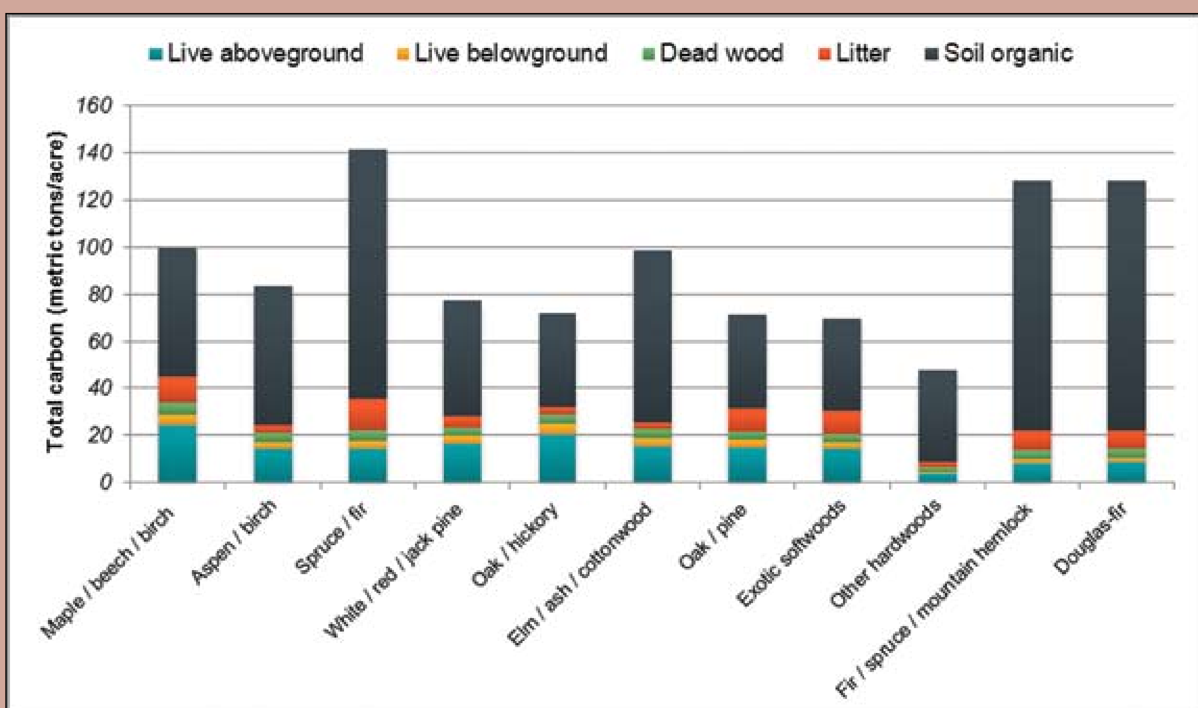


Figure 8.—Average carbon density (amount of carbon stored per acre) of major forest-type groups within the assessment area (U.S. Forest Service 2011).

Drivers of Change in Forests

Past Forest Ecosystem Change

The status of Michigan's forests reflects a dynamic past. Pollen records indicate that as the last glacial ice sheets receded between 10,000 and 12,000 years ago, species like spruce and tamarack were relatively quick to colonize the expanding northward habitat in the Great Lakes region (Davis and Shaw 2001, Dickmann and Leefers 2003, Stearns 1997). Pollen records also reveal that balsam fir, jack pine, and red pine were present in northern Lower Michigan shortly thereafter, followed by white pine around 9,000-10,000 years ago. Oak species also expanded their ranges northward, albeit at a slower pace, reaching the northern Lower Peninsula roughly 9,000 years before the present. Maples appear to be more recent migrants into northern Michigan, arriving around 6,000 years ago, followed by hemlock (Davis 1983, Stearns 1997).

Pollen records that reveal the range expansions of these species also indicate that species moved independently of one another, and that species that coexist today did not necessarily coexist in the past or respond similarly to past climate changes (Davis 1983). Refuge location, seed size, germination requirements, competitive ability, and dispersal vectors were all important factors determining how species responded to this period of dramatic climatic change. Following the initial colonization of the Great Lakes area after glacial retreat, periodic fluctuations in climate resulted in advance and retreat of the prairie-forest border, with grassland and savanna entering Michigan on occasion (Dickmann and Leefers 2003).

Small mining sites and settlements from the Woodland era (3,000 to 300 years before the present day) have been uncovered throughout Michigan, although extensive settlement was limited in the northern forests (Sparhawk and Brush 1929, Stearns 1997). In the eastern Upper Peninsula, settlements were typically restricted to flat areas next to Great Lakes shorelines (Silbernagel et al. 1997). In savannas and pine forests, Native Americans intentionally set fires to aid in hunting and to make travel easier (Stearns 1997). Other impacts were minimal, including small agricultural conversions and wood harvesting. Similarly, early French and British settlement in the region appears to have had little impact on forests until the early 1800s. Indirect impacts to forests, particularly forested wetlands, likely occurred due to hunting and trapping of keystone species such as beaver.

Abandoned field below mixed white pine and hardwood stand in the northern Lower Peninsula. Photo by Matthew Duveneck, Portland State University, used with permission.

The Government Land Survey began in Michigan in 1815 and initiated an era of intense logging of Michigan forests. White pine logging operations expanded along river corridors until peaking around the turn of the 20th century (Stearns 1997). The expansion of railroad lines soon facilitated logging in upland areas farther from waterways. As white pine declined, logging shifted to other species such as hemlock and hardwoods. By 1910, virtually all of the merchantable timber in the state had been harvested. The effects of this logging boom are well documented, including widespread catastrophic wildfires, eroded and dammed streams and waterways, and cascading impacts on vegetation and wildlife communities (Dickmann and Leefers 2003, Frelich and Reich 1996, Sparhawk and Brush 1929, Stearns 1997). Contemporary observers estimated that 92 percent of original forests had been harvested or destroyed by wildfires, and that 25 percent of the original standing timber was wasted in the lumbering operation or destroyed by subsequent fires (Pugh et al. 2009, Sparhawk and Brush 1929). The ecological effect of the era was that the region was converted from a complex mosaic of forest types and successional stages to primarily early successional forests.

After the wave of logging and wildfire, the first State-owned forests were established in 1903, and the Huron National Forest was established in 1904 (Stearns 1997). The Hiawatha and Manistee National Forests were created in 1931. The Great Depression era brought about increased attempts at reforestation and fire suppression. The end of World War II generally coincided with the rise of the paper and pulp industry and the beginning of the industrial forestry era in Michigan. Forests in Michigan have generally been recovering and maturing during the past 80 years (Pugh et al. 2009). Early successional species such as aspen and paper birch became much more prevalent after this period of intense landscape disturbance, but these forest types have reached their maximum acreage and are now declining (Pugh et al. 2012). Wildfire suppression over the past century has hastened the conversion of early successional forest types to more mesic forest types.

Natural Disturbance Regimes

Natural disturbance has historically been a regular component of forest ecosystems in Michigan. Disturbances like fire, windthrow, ice damage, and insect defoliation can be highly variable across a large landscape, influenced by climate, soils, landform, and vegetation. Forest systems have distinct disturbance regimes, characterized in part by the soils, landforms, and vegetation. *Natural Communities of Michigan: Classification and Description* contains detailed descriptions of disturbance regimes for each forested natural community in Michigan (Kost et al. 2007), and Table 4 summarizes many of the major natural disturbances characteristic of the forest systems in this assessment.

Pests and Diseases

Native pests are often recurring and cyclic, and introduced pests and diseases pose unknown threats to Michigan's forests. There are indications that a few of the most threatening pests and diseases such as the emerald ash borer (EAB) are having accelerating impacts. In just 5 years between the most recent FIA assessments in Michigan (2004 to 2009), the ash mortality rate increased substantially as EAB expanded its range in the state (fourfold increase for white ash, sevenfold increase for green ash) (Pugh et al. 2012). During this same period, American beech had a fivefold increase in mortality, which can be mostly attributed to beech bark disease (Pugh et al. 2012). Nonnative species are one of the primary concerns for private landowners in Michigan today (Pugh et al. 2009). Major insect pests are summarized for the forest systems in the assessment area in Table 6.

Table 6.—Major current stressors and impacts for forest systems in northern Michigan

Forest system	References
Upland spruce-fir	
Insect pests such as spruce budworm and balsam fir bark beetle cause reduced growth or mortality of target species.	(Cohen 2007; Michigan Department of Natural Resources 2011; Pugh et al. 2009. 2012)
Excessive drought causes reduced growth or mortality.	(Cornett et al. 2000, Hanson and Weltzin 2000)
Deer and moose herbivory results in reduced growth and mortality of seedling and saplings of target browse species, particularly for northern white-cedar.	(Cohen 2007, Côté et al. 2004, Waller and Alverson 1997, White 2012)
Invasive plants such as glossy buckthorn and Japanese barberry reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Cohen 2007)
Jack pine (including pine-oak)	
Suppression of natural fire regimes has reduced structural and species diversity, allowed hardwood encroachment on many sites, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004, Cohen 2002b, Nowacki and Abrams 2008)
Insect pests such as jack pine budworm, white pine tip weevil, and bark beetles cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Diseases such as *Armillaria* and scleroderis lead to damage and mortality.	(Burns and Honkala 1990)
Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Cohen 2002b, Nowacki and Abrams 2008)
Red pine-white pine	
Suppression of natural fire regimes has reduced structural and species diversity, allowed mesophytic encroachment on many sites, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004; Cohen 2002a, 2002b; Nowacki and Abrams 2008)
Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Cohen 2002a, 2002b; Nowacki and Abrams 2008)
Insect pests such as jack pine budworm, white pine tip weevil, and redheaded pine sawfly cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Munck et al. 2009; Pugh et al. 2009, 2012; Stanosz et al. 2001)
Diseases such as white pine blister rust, shoot blights (*Diplodia*, sirrococcus, and sphaeropsis), and *Armillaria* lead to damage and mortality.	(Burns and Honkala 1990)
Deer herbivory results in reduced growth and mortality of seedling and saplings of target browse species.	(Cohen 2002a, Côté et al. 2004, Waller and Alverson 1997, White 2012)

(Table 6 continued on next page)

Table 6 (continued)

Forest system	References
Lowland conifers	
Raised water tables can result in tree mortality, and lowered water tables can lead to improved tree growth but also susceptibility to drought.	(Cohen 2006, Kost 2002, Swanson and Grigal 1991)
Road or ditch building leads to altered drainage patterns.	(Cohen 2006, Kost 2002, Swanson and Grigal 1991)
Insect pests such as tamarack sawfly, larch case bearer, eastern larch beetle, and spruce budworm cause reduced growth or mortality of target species.	(Cohen 2006; Kost 2002; Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Diseases such as dwarf mistletoe lead to damage and mortality.	(Baker et al. 2012)
Invasive plants such as mutiflora rose and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Pugh et al. 2009, 2012)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species, particularly northern white-cedar.	(Cornett et al. 2000, Côté et al. 2004, Waller and Alverson 1997, White 2012)
Management practices may remove coarse woody debris or reduce species diversity.	(Cohen 2006, Kost 2002)
Excessive drought causes reduced growth or mortality.	(Cornett et al. 2000, Hanson and Weltzin 2000, Kost 2002, Swanson and Grigal 1991)
Aspen-birch	
Suppression of natural fire regimes has allowed succession to other forest types, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004, Nowacki and Abrams 2008)
Insect pests such as forest tent caterpillar, birch leaf miner, bronze birch borer, and gypsy moth cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Excessive drought causes reduced growth or mortality.	(Auclair et al. 2010, Cornett et al. 2000, Hanson and Weltzin 2000, Worrall et al. 2013)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000, Côté et al. 2004, Waller and Alverson 1997, Weber et al. 2006, White 2012)
Diseases such as hypoxylon canker lead to damage and mortality.	(Burns and Honkala 1990, Weber et al. 2006)
Northern hardwoods	
Exotic earthworms reduce forest litter, alter nutrient and water cycling, alter soil conditions, facilitate exotic plant species, decrease regeneration suitability for many forest species, and increase drought susceptibility for sugar maple.	(Frelich et al. 2006, Hale et al. 2005)
Invasive plants such as garlic mustard and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Powers and Nagel 2009; Pugh et al. 2009, 2012)
Insect pests such as emerald ash borer, forest tent caterpillar, and white pine tip weevil cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Diseases such as beech bark disease, white pine blister rust, and *Armillaria* lead to damage and mortality.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Soil frost and freeze-thaw cycles damage roots and new growth, and may cause crown dieback or widespread decline of maple and birch species.	(Auclair et al. 2010, Bourque et al. 2005, Tierney et al. 2001)
Excessive drought causes reduced growth or mortality.	(Auclair et al. 2010, Hanson and Weltzin 2000)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000, Côté et al. 2004, Powers and Nagel 2009, Waller and Alverson 1997, White 2012)
Management practices may remove coarse woody debris or reduce species diversity.	(Cohen 2000a, Powers and Nagel 2009)

(Table 6 continued on next page)

Table 6 (continued)

Forest system	References
Lowland-riparian hardwoods	
Altered hydrologic regimes lead to excessive waterlogging or excessive drought and result in reduced growth, lack of suitable conditions for regeneration, and susceptibility to dieback and decline.	(Opperman et al. 2010, Romano 2010, Slaughter et al. 2007, Tepley et al. 2004, Weber et al. 2007)
Ash decline causes reduced growth, crown dieback, or mortality of ash species.	(Benedict and Frelich 2008, Palik et al. 2011, Tepley et al. 2004, Weber et al. 2007)
Invasive plants such as reed canarygrass, Japanese barberry, multiflora rose, and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Pugh et al. 2009, 2012; Tepley et al. 2004; Weber et al. 2007)
Insect pests such as emerald ash borer and gypsy moth cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012; Slaughter et al. 2007; Tepley et al. 2004; Weber et al. 2007)
Diseases such as Dutch elm disease lead to damage and mortality disease.	(Pugh et al. 2009, 2012)
Excessive drought causes reduced growth or mortality.	(Hanson and Weltzin 2000, Slaughter et al. 2007)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Côté et al. 2004, Slaughter et al. 2007, Waller and Alverson 1997, White 2012)
Oak associations	
Suppression of natural fire regimes has reduced structural and species diversity, allowed hardwood encroachment on many sites, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004, Courteau et al. 2006, Nowacki and Abrams 2008)
Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Courteau et al. 2006, Nowacki and Abrams 2008)
Oak wilt and oak decline cause reduced growth, crown dieback, or mortality of oak species.	(Courteau et al. 2006; Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Deer and rabbit herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Côté et al. 2004, Courteau et al. 2006, Waller and Alverson 1997, White 2012)
Invasive plants such as garlic mustard and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Pugh et al. 2009, 2012)
Excessive drought causes reduced growth or mortality.	(Hanson and Weltzin 2000)
Soil frost damages roots and new growth, and may cause crown dieback or widespread decline of oak species.	(Burns and Honkala 1990)
Barrens	
Suppression of natural fire regimes has reduced structural and species diversity, allowed hardwood encroachment on many sites, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004; Cohen 2000b, 2001; Comer 1996; Nowacki and Abrams 2008)
Insect pests such as jack pine budworm cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Oak wilt and oak decline cause reduced growth, crown dieback, or mortality of oak species.	(Courteau et al. 2006; Michigan Department of Natural Resources 2011; Pugh et al. 2009, 2012)
Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Cohen 2000b, 2001; Comber 1996; Nowacki and Abrams 2008)
Invasive plants such as spotted knapweed, leafy spurge, and autumn olive reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Cohen 2000b, 2001; Comer 1996; Pugh et al. 2009, 2012)

Nonnative Plant Species

Nonnative plant species are a risk to forests when they become invasive. These species affect forest communities through direct competition for resources and alteration of fire, hydrology, or soil. In Michigan, most nonnative plant species are understory species. Nonnatives are usually more pronounced in fragmented settings (Pugh et al. 2009). As mentioned above, forests in the northern Lower Peninsula are much more fragmented than forests in the eastern Upper Peninsula. Figure 9 displays information on the relative proportion and cover of nonnative species in forest plots across the region. Plots in the northern Lower Peninsula generally had higher nonnative species occurrence and extent than plots in the eastern Upper Peninsula. Key invasive species are presented in Table 6.

Current Stressors

Each of the forest systems addressed in this assessment faces a particular suite of threats and stressors (Table 6). We define stressors as agents

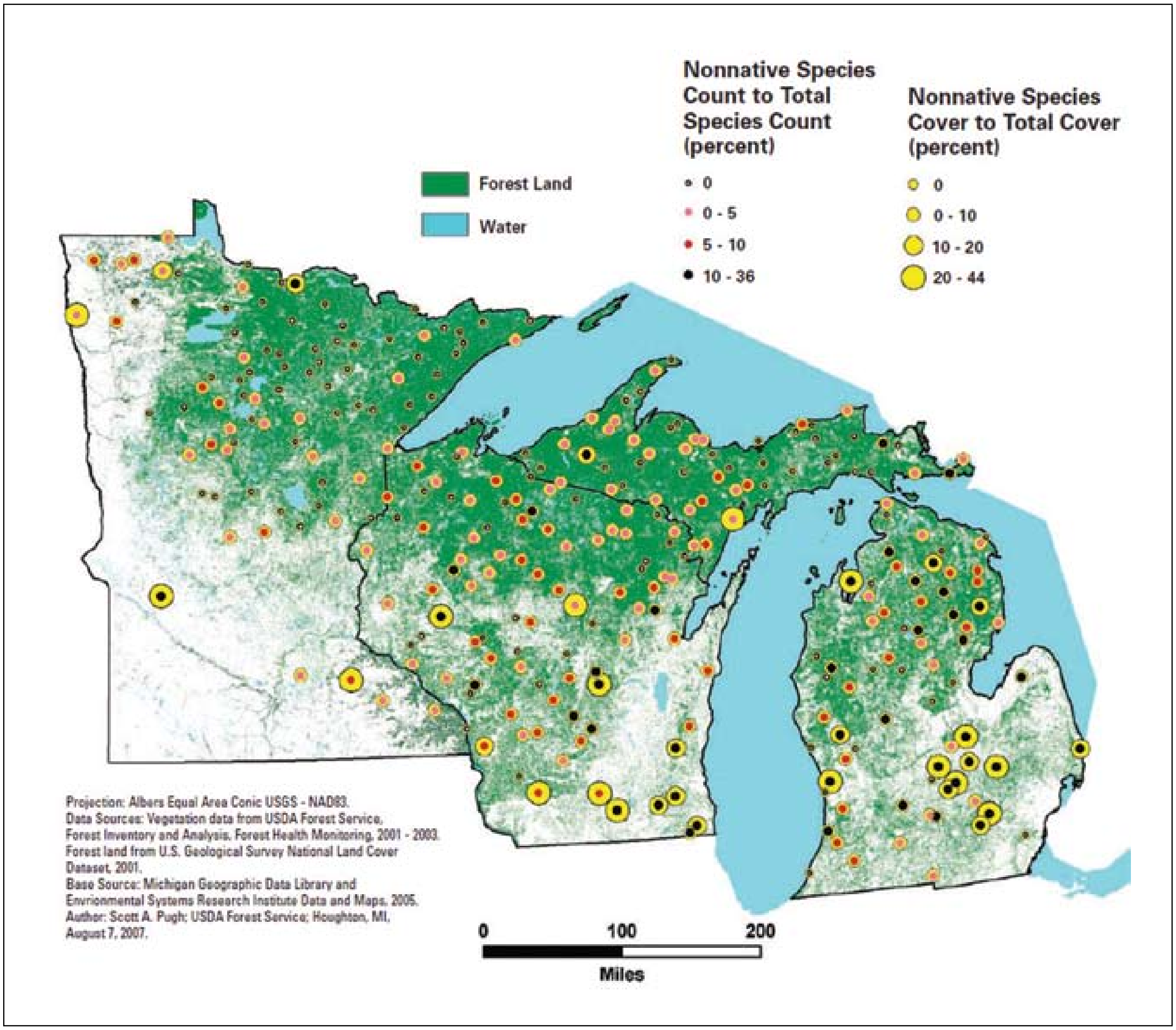


Figure 9.—Frequency and cover of nonnative species, as a percentage of all species sampled in standard FIA plots and Vegetation Diversity and Structure Indicator plots from 2001 through 2003, from Pugh et al. (2009).

that tend to disrupt the natural functioning of forest ecosystems or impair their health and productivity. This information is collected from published literature as well as from local forest managers. The impacts of particular threats and stressors are very dependent on local conditions and are not consistent across an area as large and diverse as the assessment area.

These particular threats should be considered in addition to landscape-level threats such as forest fragmentation, the legacy of past management practices, and altered disturbance regimes. It is often difficult to examine the effects of just one of these landscape-level threats in isolation, because they all have interacted across the assessment area during the past century. Fragmentation caused by agricultural and urban development, forest management, and other factors has tended to reduce the ratio of interior to edge conditions in forests (Pugh et al. 2012, Radeloff et al. 2005). The legacy of forest management and land use in northern Michigan has been well documented; general outcomes are a transition to more early successional forests with reduced structural, spatial, and species diversity (Dickmann and Leefers 2003, Sparhawk and Brush 1929). The disruption of natural disturbance regimes has included fire suppression in upland systems as well as hydrologic disruption in riparian and lowland forests. Natural regeneration and succession of forests are strongly tied to disturbance regimes, so in many cases alteration of disturbance regimes has resulted in less regeneration of disturbance-adapted species and reduced landscape diversity (Kost et al. 2007, Nowacki and Abrams 2008, Romano 2010).

Conservation Status

The Michigan Natural Features Inventory has assigned conservation ranks to the natural communities that occur within the state, and NatureServe has assigned global conservation ranks to natural communities (Table 7). These rankings are designed to categorize the risk of elimination of the community from Michigan and around the world (Kost et al. 2007, NatureServe 2013). The rankings range from “critically imperiled” to “secure, common, and widespread.” These rankings consider inherent geographic ranges, the amount of potential range currently occupied, long-term trends, and other factors.

Forest-dependent Wildlife and Plants

Forests are important for many wildlife and understory plant species in Michigan. The Michigan State Wildlife Action Plan identifies wildlife species, and their habitats, that are in greatest conservation need (Eagle et al. 2005). The Forest Plans of the Hiawatha and Huron-Manistee National Forests include several forest-dependent wildlife species with particular management emphasis. Examples of these species are displayed in Table 8. Additionally, *Michigan’s Special Animals* and *Michigan’s Special Plants* include information on Michigan’s 665 endangered, threatened, and special concern species (MNFI 2013a, 2013b). Many of these species occur in the assessment area, including 189 species in the eastern Upper Peninsula and 233 species in the northern Lower Peninsula.

SOCIOECONOMIC CONDITIONS

Forest Ownership Trends

Most forest land in the assessment area is privately owned, which matches the statewide pattern (Table 9, Fig. 10). The State of Michigan is the next largest landowner in the assessment area, with 28 percent. More than 75 percent of all Michigan’s State-owned forest land occurs within the assessment area.

The breakdown of forest-type groups within these different ownerships is not uniform. Proportionally, private lands contain almost twice as much maple/beech/birch and elm/ash/cottonwood forests as state or national forests. By contrast, national forests contain proportionally more white pine/red pine/jack pine forests than the other ownerships. The breakdown of aspen/birch, spruce/fir, and remaining FIA forest-type groups is more even among the major ownership categories.

Table 7.—Forest systems considered in this assessment, related natural communities, and state and global conservation status ranks (modified from Kost et al. 2007)

Forest system	Related natural communities	Conservation status*
Upland spruce-fir	Boreal forest	State: vulnerable Global: unrankable
Jack pine (including pine-oak)	Dry northern forest	State: vulnerable Global: vulnerable
Red pine-white pine	Dry northern forest	State: vulnerable Global: vulnerable
	Dry-mesic northern forest	State: vulnerable Global: apparently secure
Lowland conifers	Poor conifer swamp	State: apparently secure Global: apparently secure
	Rich conifer swamp	State: vulnerable Global: apparently secure
	Hardwood-conifer swamp	State: vulnerable Global: apparently secure
Aspen-birch	Aspen association	NA
Northern hardwoods	Mesic northern forest	State: vulnerable Global: apparently secure
Lowland-riparian hardwoods	Hardwood-conifer swamp	State: vulnerable Global: apparently secure
	Floodplain forest	State: vulnerable Global: vulnerable
	Northern hardwood swamp	State: vulnerable Global: apparently secure
Oak associations	Oak association	NA
Barrens	Oak-pine barrens	State: imperiled Global: vulnerable
	Oak barrens	State: critically imperiled Global: imperiled
	Pine barrens	State: imperiled Global: vulnerable

* Critically imperiled: at very high risk of extinction due to extreme rarity, very steep declines, or other factors. Vulnerable: at moderate risk of extinction due to a restricted range, relatively few occurrences, recent and widespread declines, or other factors. Apparently secure: uncommon but not rare; some cause for long-term concern due to declines or other factors. Unrankable: currently unrankable due to lack of information or substantially conflicting information about status or trends. NA: not considered in Kost et al. (2007).

Table 8.—Some forest-dependent wildlife species and associated habitats identified in Michigan's State Wildlife Action Plan (Eagle et al. 2005) or the Forest Plans of the Hiawatha and Huron-Manistee National Forests (Hiawatha National Forest [HNF] 2006, Huron-Manistee National Forest [HMNF] 2006)

Species*	DNR	HNF	HMNF	Associated habitats and important features
American marten	X	X	X	lowland conifer, mesic conifer, dry conifer, forest opening, bog, snag/tree cavity, down woody debris
American woodcock	X			idle/old field, pasture, row crop, lowland shrub, upland shrub, lowland hardwood, mesic hardwood, dry hardwood, lowland conifer, forest opening, river/stream/riparian floodplain corridor, forest edges, late successional forest, down woody debris
Black-backed woodpecker	X	X		mature conifer forests
Canada lynx	X	X		heavy snowfall areas, lowland shrub, upland shrub, lowland conifer, mesic conifer, dry conifer, bog, swamp, large contiguous natural landscape, down woody debris
Eastern massasauga	X		X	aquatic and terrestrial habitats, northern Lower Peninsula
Golden-winged warbler	X			idle/old field, lowland shrub, upland shrub, lowland hardwood, mesic hardwood, forest opening, bog, swamp, forest edges
Indiana bat	X		X	large tree cavities, oak/hickory forests, elm, ash, and cottonwood species, forest opening
Karner blue butterfly	X		X	savanna, lupine understory
Kirtland's warbler	X	X	X	savanna, upland shrub, young jack pine, forest opening, large contiguous natural landscape
Moose	X			lowland shrub, lowland hardwood, lowland conifer, forest opening, inland emergent wetland, inland lake, river/stream/riparian floodplain corridor, large contiguous natural landscape
Northern goshawk	X	X	X	savanna, lowland hardwood, mesic hardwood, dry hardwood, lowland conifer, mesic conifer, dry conifer, forest opening, suburban/small town, large contiguous natural landscape, late successional forest
Red-headed woodpecker	X			prairie, idle/old field, row crop, savanna, lowland hardwood, mesic hardwood, dry hardwood, dry conifer, forest opening, swamp, river/stream/riparian/floodplain corridor, edge, snag/cavity, late successional forest, down woody debris
Red-shouldered hawk	X	X	X	lowland shrub, lowland hardwood, mesic hardwood, dry hardwood, lowland conifer, mesic conifer, dry conifer, forest opening, inland emergent wetland, submergent wetland, ephemeral wetland, swamp, river/stream/riparian/floodplain corridor, coastal emergent wetland, edge, snag/cavity, large contiguous natural landscape, late successional forest

*Scientific names are in Table 21 in Appendix 1.

Table 8 (continued)

Species*	DNR	HNF	HMNF	Associated habitats and important features
Ruffed grouse	X		X	young and mature aspen
Sharp-tailed grouse	X	X		prairie, idle field, pasture, savanna, lowland shrub, upland shrub, dry conifer, forest opening, bog, inland emergent wetland, fen, ephemeral wetland, river/stream/riparian floodplain corridor, snag/cavity
Snowshoe hare	X			lowland shrub, lowland hardwood, mesic hardwood, dry hardwood, lowland conifer, mesic conifer, dry conifer, bog, swamp, forest edges, dense understory, down woody debris
Spruce grouse	X			conifer forests in northern Lower Peninsula and eastern Upper Peninsula, low berries (especially blueberry), early successional spruce-jack pine forest

*Scientific names are in Table 21 in Appendix 1.

An eastern massasauga, Michigan's only poisonous snake. Photo by U.S. Forest Service, Huron-Manistee National Forest.

Table 9.—Forest land acreage for major ownership classifications within the assessment area and for the entire state, according to FIA data (U.S. Forest Service 2011)

	Assessment area		Michigan (statewide)	
Ownership	Acres[a]	Cover (%)	Acres[a]	Cover (%)
Private	6,391,864	54.9	12,406,958	62.0
State	3,258,428	28.0	4,199,896	21.0
National forest	1,743,590	15.0	2,688,094	13.4
Other federal[b]	162,309	1.4	320,325	1.6
County and municipal	89,475	0.8	388,197	1.9
Total forest land area (acres)	11,645,666		20,003,470	

[a] Nonstocked lands are not included in the numbers presented in this table.
[b] Includes National Park Service, Fish and Wildlife Service, Department of Defense, Bureau of Land Management, and other federal agencies.

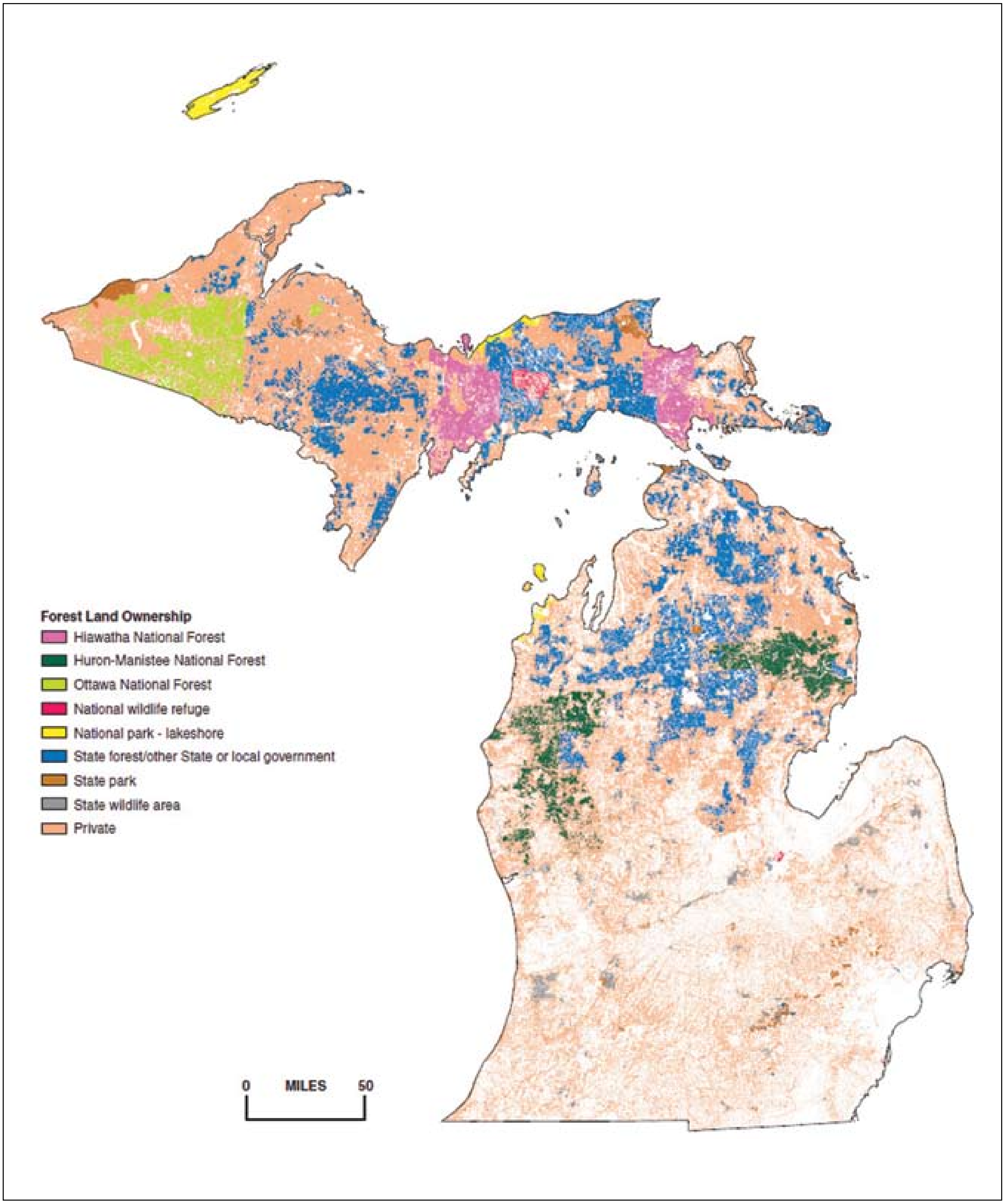


Figure 10.—Land ownership across Michigan in 2009, from Pugh et al. (2012).

General Trends in Land Use

In Michigan, two major factors have contributed to forest fragmentation in recent years: large-scale divestiture of forest industry land and parcelization of nonindustrial private forests (Froese et al. 2007, Price 2010). Parcelization is the division of larger landholdings into smaller units. In the Upper Peninsula, more than 1 million acres of forest land transferred from traditional industrial ownership to large-scale forest investment companies in 2005 and 2006 (Froese et al. 2007). These ownership changes may make certain forest land, such as lakeshore property, more subject to parcelization and development. Although parcelization may not immediately result in direct impacts, this pattern often has consequences for forests as well as for the forest industry (Gobster and Rickenbach 2004, Haines et al. 2011). Long-term studies in northern Wisconsin have shown that parcelization is often a precursor to fragmentation and land-use change in forests (Haines et al. 2011).

Within the assessment area, 35.6 percent of all private land is developed as residential land (Headwaters Economics 2011). Residential development within the assessment area proceeded faster than the U.S. average between 1980 and 2000, with the large majority of this change as exurban development (lot size between 1.7 and 40.0 acres). For the counties included in this assessment, residential acreage increased overall by 46.2 percent. Six counties, all in the northern Lower Peninsula, had more than 100-percent increases in residential acreage. Benzie County had the greatest increase, at 165 percent. The smallest increases occurred in counties with sizeable federal land holdings (Alger, Delta, Luce, Chippewa, Schoolcraft, and Iosco Counties) (Headwaters Economics 2011).

Land-use change is projected to proceed according to the same pattern in northern Michigan through the year 2020, with conversion of rural land to exurban and urban development (Theobald 2005). Land development will be constrained in the eastern Upper Peninsula due to the high proportion of federal, state, and county-owned land, but much faster development is projected to occur near existing municipalities within the northern Lower Peninsula.

Human Population Patterns

The 2010 population for counties included in this assessment was roughly 1.2 million people, compared to the total state population of 9.8 million people. Counties in northern lower Michigan have generally had small but growing populations since the 1960s, whereas counties in the eastern half of the Upper Peninsula have maintained steady or slightly declining populations during the past 50 years (Headwaters Economics 2011). The overall population growth for the assessment area from 1990 to 2008 was 13.8 percent, compared to the overall U.S. growth of 21.9 percent (Headwaters Economics 2011). In the eastern Upper Peninsula, all of the counties lost between 1 and 9,999 residents between the 2000 and 2010 Census. In the northern Lower Peninsula, the trend is divided between northeastern counties, nearly all of which experienced slight population declines, and northwestern counties, which nearly all experienced slight population increases (Mackun et al. 2011). All of these absolute changes are between 0 and 10 percent of the overall population for the counties in the assessment area. The population density for the assessment area remains between 1 and 49 people per square mile, with the exception of a few counties along the southern edge of the assessment area and four counties neighboring Traverse City, which have higher densities (Mackun et al. 2011).

A socioeconomic study of Michigan's national forests offers a view of the proximity of human populations to the forested areas of the state.[1] In the year 2000, the Hiawatha National Forest had roughly 400,000 U.S. residents living within 60 miles of the Forest boundary, and the Huron-Manistee National Forest had more than 2.4 million people within 60 miles. Therefore, even though the assessment area hosts only a small human population, demand is high for access and resources, especially toward the southern edge of the assessment area.

Economic Sectors

Overall

Compared with Michigan as a whole, the economy of the assessment area is slightly depressed. As of 2000, median household incomes in the assessment area were 18 to 24 percent below the statewide median (see footnote 1). The proportion of households receiving Social Security or retirement income was higher than the state average. From 1970 to 2009, personal income for counties within the assessment area grew 130 percent, compared to the U.S. average of 164 percent (Headwaters Economics 2011). As of 2010, unemployment in the assessment area was 13 percent, compared to the U.S. average of 10 percent (Headwaters Economics 2011). Per capita income in the assessment area was less than 75 percent of the U.S. average (Headwaters Economics 2011).

Agriculture

Michigan is a major agricultural state, ranking 15th overall in the United States for total market value of agricultural products (Michigan Department of Agriculture 2009). Counties in southern Michigan are engaged in commercial agriculture more than the counties within the assessment area. The Michigan Department of Agriculture and Rural Development Food and Agricultural Systems Profiles includes information by districts within the state and by individual counties (Michigan Department of Agriculture 2009). Within the northern Lower Peninsula, major products are potatoes, maple syrup, sugar beets, cattle, beans, tart cherries, sweet cherries, Christmas trees, grapes, asparagus, apples, and oats. Agricultural land accounts for 10 to 40 percent of the land area in the agricultural districts in the northern Lower Peninsula. The entire Upper Peninsula is a single agricultural district, which ranks last in the state in agricultural revenues, and only 4.9 percent of this area is in agricultural production. The western portion of the northern Lower Peninsula along the shore of Lake Michigan is a popular location for fruit orchards, which are particularly concentrated around Grand Traverse Bay.

Farm employment accounts for 3.1 percent of total jobs for counties within the assessment area, with the highest percentages occurring in Osceola and Missaukee Counties (both at 11.1 percent) (Headwaters Economics 2011). In 2009, employment in this sector amounted to 17,554 jobs. Within the assessment area, agriculture is slightly less profitable compared to the United States as a whole (Headwaters Economics 2011).

Forest Industry

The forest products industry is also a regionally important source of income and employment in Michigan. The wood products and paper industries in Michigan account for almost $8 billion in economic output (Price 2010, Pugh et al. 2012). In Alger and Luce Counties the forest products industry contributed about 50 percent of the total economic output (Leefers 2007). In Delta, Menominee, and Schoolcraft Counties, this sector represented about 30 percent of total economic output.

[1] Leefers, L.; Potter-Witter, K.; McDonough, M. 2003. Social and economic assessment for the Michigan national forests. Report submitted to Hiawatha, Huron-Manistee, and Ottawa National Forests on July 25, 2003. On file with L. Leefers, Michigan State University, East Lansing, MI.

Within the assessment area, the forest products sector generated 2.2 percent of total jobs in 2009 (6,678 jobs) (Headwaters Economics 2011). For seven counties, employment in this sector accounts for greater than 10 percent of total employment, with the greatest percentage in Alger County (30.7 percent). From 1998 to 2009, employment related to the forest products industry declined by 33.5 percent for counties within the assessment area. According to the *Michigan's Forests 2009* assessment from FIA, there were 201 active wood-using mills in Michigan as of 2008, which is about 50 percent of the number of mills that were operating in the state in 1990 (Pugh et al. 2012). Most of the reduction came from smaller sawmills processing less than 5 million board feet per year.

Travel and Tourism

Travel, tourism, and outdoor recreation are major activities in northern Michigan, contributing greatly to the economy and local character of the area. The assessment area includes two national forests, two national lakeshores, many state parks and recreation areas, and several popular tourist destinations like Mackinac Island and Grand Traverse Bay. Michigan has more than 900 public and private campgrounds, most of which are in forested areas (Dickmann and Leefers 2003). More than 935,000 people hunt in Michigan each year, the most of any state in the country (Dickmann and Leefers 2003). Hunting is just one form of outdoor recreation, but it reflects the high levels of outdoor recreation in the state.

In 2009, Mackinac County had the highest share of employment in sectors related to travel and tourism, with 37.2 percent of the jobs in the county occurring within this sector. Seven of the 40 counties in this assessment area had more than 25 percent of total employment in this sector. The average for the entire assessment area was 18.6 percent, which is higher than the U.S. average. Within the assessment area, travel and tourism accounted for 57,354 jobs, which was a 6.2-percent decline from 1998 (Headwaters Economics 2011).

Oil and Gas Production

Fossil fuel extraction is also an important economic activity within northern Michigan, and the state ranks high nationally in natural gas extraction. Michigan has more than 13,000 oil wells and more than 12,000 gas wells, most of which are located in the northern Lower Peninsula (Michigan Department of Environmental Quality 2013). The majority of these wells have been developed in large clusters since 1970, with high densities occurring in Manistee, Grand Traverse, Kalkaska, Antrim, Otsego, Montmorency, and Alpena Counties (Michigan Department of Environmental Quality 2013). No active wells exist in the Upper Peninsula.

Oil and gas extraction accounts for less than 1 percent of the total employment in all the counties within this assessment area, with the exceptions of Crawford (2.1 percent), Grand Traverse (1.2 percent), Isabella (1.7 percent), Mason (1.8 percent), Montmorency (1.0 percent), Osceola (3.0 percent), Otsego (3.1 percent), and Roscommon (1.1 percent). Kalkaska County is an outlier in the region, with 17.7 percent of employment associated with oil and gas exploration. From 1998 to 2009, employment in this sector held virtually constant throughout the assessment area.

Forest Harvest and Products

As mentioned above, the forestry sector is a major economic contributor in Michigan and within the assessment area in particular. In the northern Lower Peninsula, 121 million cubic feet of roundwood were harvested in 2008, and the eastern Upper Peninsula generated about 67 million cubic feet (Pugh et al. 2012). More than half the total harvested roundwood was used as pulpwood and around 30 percent was used as saw logs, with the remainder being diverted to a variety of uses. Pulpwood production peaked in 1994 and has been gradually declining during recent years.

Annual net growth of growing stock differs by area within Michigan. The eastern Upper Peninsula has a significantly lower growth rate (2.5 percent) than the northern Lower Peninsula (4.0 percent) (Pugh et al. 2009). The growth-to-removals ratio of live trees on forest land provides a simple metric for determining whether the withdrawals of harvesting are outpacing the gains of growth. This ratio takes into account gross growth, mortality, and removals. Across all ownership classes in the assessment area, the growth-to-removals ratio was 2.2 for the most recent FIA inventory period, meaning that growth generally was twice the volume of harvest removals in the assessment area (U.S. Forest Service 2011). The ratio was highest for national forests (5.6), and lowest for state lands (1.8), indicating higher levels of harvest or mortality, or both, on state lands.

The FIA removals data also show the proportion of species harvested in the assessment area (Table 10) (U.S. Forest Service 2011). Among the major forest-type groups, white/red/jack pine had the highest growth-to-removals ratio (4.4), and aspen/birch, elm/ash/cottonwood, oak/pine, and spruce/fir were all above the ratio for the assessment area as a whole. Maple/beech/birch had the lowest growth-to-removals ratio (1.3), probably because this forest-type group accounted for more than 40 percent of the harvest removals by volume for the entire assessment area. Aspen/birch was the second-most harvested forest-type group, with almost 19 percent of the total harvest removals.

Forest Certification

Forest certification programs allow a public or private landowner to voluntarily submit to third party audits that ensure environmental, social, and economic best practices on enrolled lands. In exchange, certification programs recognize these landowners with a seal of approval. There is not a consistent set of management practices that are followed on all of these ownerships. The extent of forest certification does provide an indication of the amount of forest land that is being managed with formal management plans according to general principles of sustainability, with regular audits.

More than 6 million acres of Michigan's forest land is certified according to one or more certification standards, or almost a third of all forest land in the state (Table 11). As of 2011, Michigan ranked 4th among all states for most forest land certified under the Forest Stewardship Council (FSC) system (Pingrey 2011).

Table 10.—Annual net growth and removals and the ratio of growth to removals for major forest-type groups in the assessment area, organized according to net annual growth (U.S. Forest Service 2011)

Forest-type group	Net growth (cubic feet per year)	Removals (cubic feet per year)	Growth:Removals
Maple/beech/birch	103,000,708	76,307,693	1.3
Aspen/birch	83,503,219	34,109,196	2.4
White/red/jack pine	79,700,938	18,171,055	4.4
Oak/hickory	54,563,028	28,138,632	1.9
Spruce/fir	38,974,616	10,652,799	3.7
Elm/ash/cottonwood	20,866,885	5,977,897	3.5
Oak/pine	15,502,014	5,727,044	2.7
Exotic softwoods	4,805,622	708,079	6.8
Total	402,005,489	180,156,771	2.2

Table 11.—Acres of certified forest land in Michigan under four common certification standards as of December 2011

Landowner	Certification standard[a]					Total
	FSC only	Dual FSC/SFI	SFI only	Tree Farm - PEFC	ATFS Group	
Michigan state forests		4,200,000				
Plum Creek			588,000			
GMO/AFM			440,045			
The Forest Land Group	350,000					
Molpus			96,764			
JM Longyear	72,660					
Keweenaw	161,263					
Traditional (non-MFL group) tree farms				93,153[b]		
Group tree farms					142,214	
The Nature Conservancy	24,000					
Total by standard	607,923	4,200,000	1,124,809	93,153	142,214	6,168,099

[a] FSC: Forest Stewardship Council; SFI: Sustainable Forestry Initiative; PEFC: Programme for the Endorsement of Forest Certification schemes; ATFS Group: American Tree Farm System Group Certification; GMO/AFM: GMO Threshold Timber Corporation forest land enrolled in American Forest Management's certification program; MFL: Managed Forest Law (Scott Robbins, Michigan Forest Products Council, pers. commun.; Christine Hall, The Nature Conservancy, pers. commun., Aug. 8, 2013).
[b] This figure accounts only for tree farms that have been certified within the past 5 years, in order to remain conservative. The actual figure is possibly much higher, on the order of 695,000 acres (S. Robbins, pers. commun., December 6, 2011).

SUMMARY

Forests are a defining feature across Michigan, and particularly within the assessment area. The forest ecosystems in the assessment area are dynamic, and they have been shaped by a multitude of factors, including climate, geology, glaciation, land conversion and development, and human management. In addition to being the dominant land cover, forests are important for wildlife habitat, C storage, economic and cultural resources, and other values. The context presented in this chapter will be helpful for interpreting information contained in the chapters that follow. It may be particularly important to refer back to this information when considering information on climate change impacts (Chapter 5), forest ecosystem vulnerability (Chapter 6), and connections with other aspects of forest management and planning (Chapter 7).

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

This chapter provides a brief background on climate change science, climate simulation models, and models that project the impacts of changes in climate on species and ecosystems. Throughout the chapter, boxes indicate resources for more information on each topic. The resources listed are up-to-date, nontechnical reports based on the best available science. A more detailed scientific review of climate change science, trends, and modeling can be found in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007) and the whitepaper contributions to the Midwest Chapter of the 2013 National Climate Assessment (Andresen et al. 2012, Winkler et al. 2012).

CLIMATE CHANGE

Climate is not the same thing as weather. Climate is defined as the average, long-term meteorological conditions and patterns for a given area. Weather, in contrast, is the set of the meteorological conditions for a given point in time in one particular place. The IPCC (2007) defines climate change as "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer." A key finding of the IPCC in its Fourth Assessment Report (2007) was that "warming of the climate system is unequivocal." This was the first Assessment Report in which the IPCC considered the evidence strong enough to make such a statement. In addition to evidence of increased global surface, air, and ocean temperatures, this conclusion was based on thousands of long-term (more than 20 years) data series from all continents and most oceans. These data showed significant changes in snow, ice, and frozen ground; hydrology; coastal processes; and terrestrial, marine, and biological systems. The IPCC's Fifth Assessment Report is underway, and scheduled to be released in 2014. The United States Global Research Program has released a series of reports detailing the past and projected changes in climate at a national level, with a comprehensive report (National Climate Assessment, NCA) scheduled to be released in 2014 (see Box 4 for more information).

The Warming Trend

The Earth is warming, and the rate of warming is increasing. Measurements from weather stations across the globe indicate that the global mean temperature has risen by 1.4 °F (0.8 °C) over the past 50 years, nearly twice the rate of the last 100 years (Fig. 11) (IPCC 2007). The first 12 years of the 21st century rank among the warmest 14 years in the 133-year period of record of global temperature (National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center 2012a). Temperatures in the United States have risen by 2.0 °F (1.1 °C) in the last 50 years (Karl et al. 2009). The year 2012 ranked as the warmest year on record in the United States, 1.0 °F (0.6 °C) warmer than the previous record year of 1998 and 3.3 °F (1.9 °C) above the 20th-century average (NOAA National Climatic Data Center 2012b).

Average temperature increases are simplifications of a more complex pattern of regional and seasonal climate changes. For example, the frequency of cold

Box 4: Global, National, and Regional Assessments

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. The most recent report is available for download at the Web address below.

Climate Change 2007: Synthesis Report

www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP; globalchange.gov) is a federal program that coordinates and integrates global change research across 13 government agencies to ensure that it most effectively and efficiently serves the nation and the world. Mandated by Congress in the Global Change Research Act of 1990, the USGCRP has since made the world's largest scientific investment in the areas of climate science and global change research. It has released several national synthesis reports on climate change in the United States, which are available for download below.

Global Change Impacts on the United States

www.globalchange.gov/what-we-do/assessment/nca-overview.html

Synthesis and Assessment Products

library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products

National Climate Assessment

http://ncadac.globalchange.gov/

Effects of Climatic Variability and Change on Forest Ecosystems: a Comprehensive Science Synthesis for the U.S.

http://www.treesearch.fs.fed.us/pubs/42610

Midwest Technical Input Report for the National Climate Assessment (coordinated by the Great Lakes Integrated Science and Assessment [GLISA] Center)

glisa.msu.edu/great_lakes_climate/nca.php

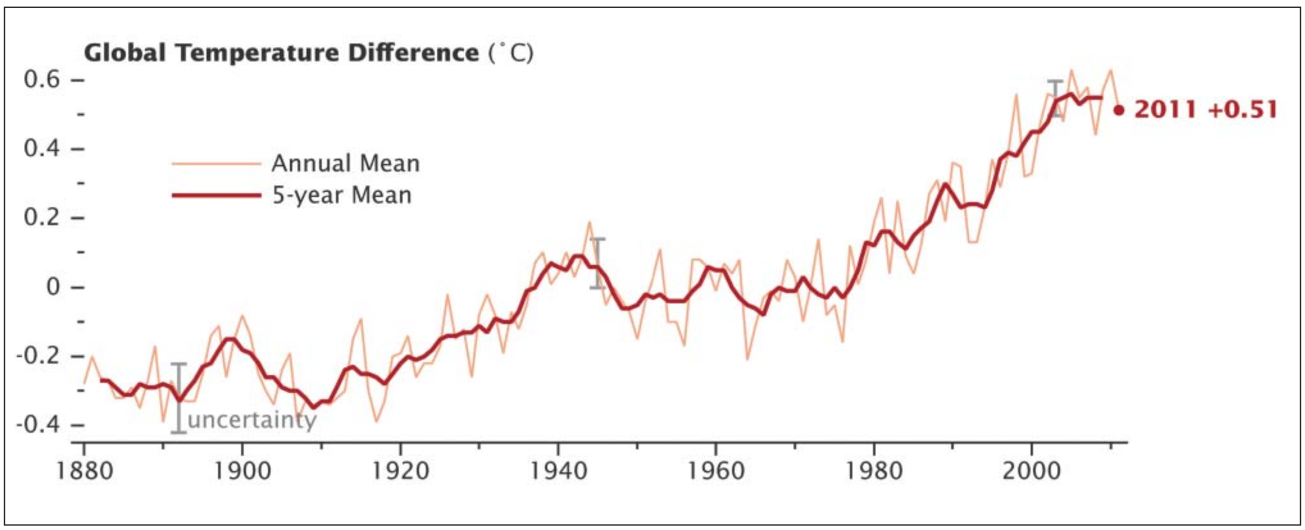


Figure 11.—Trends in global temperature compared to the 1951 through 1980 mean. Data source: NASA Goddard Institute for Space Studies. Image credit: NASA Earth Observatory, Robert Simmon; www.giss.nasa.gov/research/news/20120119/.

days, cold nights, and frosts has decreased for many regions of the world while the frequency of hot days and nights has increased (IPCC 2007). Within the United States, 356 all-time high temperature records were broken in 2012, compared to only 4 all-time low temperature records (NOAA National Climatic Data Center 2012b). There is also a strong indication that the frequency of heat waves and heavy precipitation events has increased during this period, with new records for both heat and precipitation in areas of the United States and Canada in 2007 (WMO 2008). Global rises in sea level, decreasing extent of snow and ice, and shrinking of mountain glaciers have all been observed over the past 50 years, and are consistent with a warming climate (IPCC 2007).

Average global temperature increases of a few degrees may seem small, but even small increases can result in large changes to the average severity of storms, the nature and timing of seasonal precipitation, droughts and heat waves, ocean temperature and volume, and snow and ice—all of which affect humans and ecosystems. Additionally, an average change of a few degrees means that some areas of the globe may experience much more change, while other areas experience very little change. The synthesis report of the International Scientific Congress on Climate Change concluded that “recent observations show that societies and ecosystems are highly vulnerable to even modest levels of climate change, with poor nations and communities, ecosystem services and biodiversity particularly at risk” (Richardson et al. 2009). Temperature increases of more than 3.6 °F (2.0 °C) above average will be difficult for contemporary societies to cope with, and are expected to cause major societal and environmental disruptions through the rest of the century and beyond (Richardson et al. 2009).

Scientists have been able to attribute these changes to human causes by using climate model simulations of the past, both with and without human-induced changes in the atmosphere, and then comparing those simulations to observational data. Overall, these studies have shown a clear human effect on recent changes in temperature, precipitation, and other climate variables due to changes in greenhouse gases and particulate matter in the air (Stott et al. 2010).

Chapter 3 provides specific information about observed climate trends for the assessment area in Michigan and the surrounding region, and Chapter 4 describes a range of anticipated future climate simulations.

The Greenhouse Effect

The greenhouse effect is the process by which certain gases in the atmosphere absorb and re-emit energy that would otherwise be lost into space (Fig. 12). This effect is necessary for human survival: without it, Earth would have an average temperature of about 0 °F (-18 °C) and would be covered in ice. Contributing to the greenhouse effect are several naturally occurring greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor. Water vapor is the most abundant greenhouse gas, but its residence time in the atmosphere is on the order of days as it quickly responds to changes in temperature and other factors. Carbon dioxide, CH_4, N_2O, and other greenhouse gases reside in the atmosphere for decades to centuries. Therefore, these long-lived gases are the primary concern with respect to long-term warming.

Human Influences on Greenhouse Gases

Human activities have increased CO_2, CH_4, and N_2O in the atmosphere since the beginning of the industrial era (Fig. 13), leading to an enhanced greenhouse effect. More CO_2 has been released by humans into the atmosphere than any other greenhouse gas. Carbon dioxide levels have been

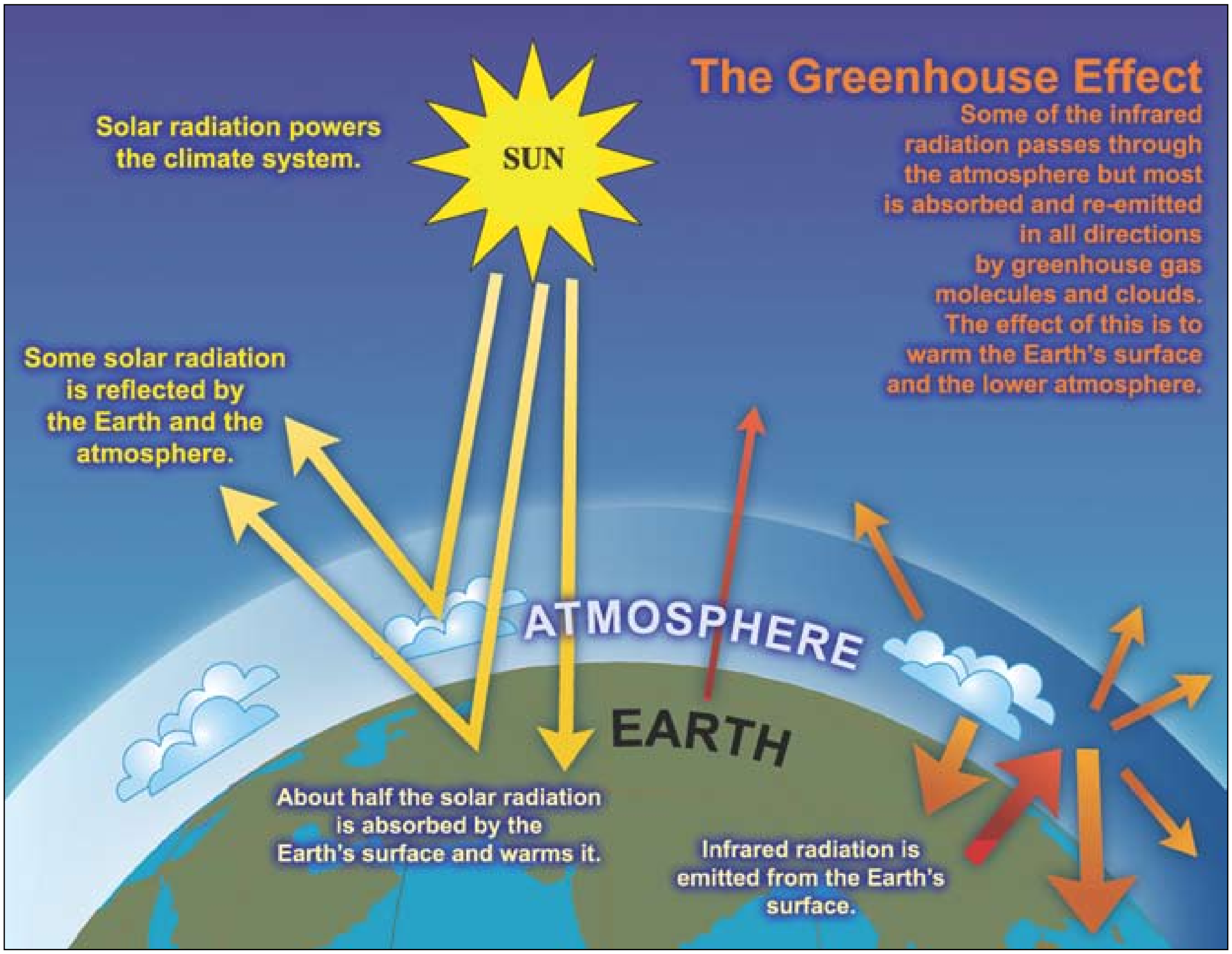


Figure 12.—Idealized model of the natural greenhouse effect. Figure courtesy of the Intergovernmental Panel on Climate Change (2007).

increasing at a rate of 1.4 parts per million (ppm) per year for the past 50 years (IPCC 2007), reaching 395 ppm in January 2013 (Tans and Keeling 2013). In recent decades, fossil fuel burning has been responsible for approximately 83 to 94 percent of the human-induced increase in CO_2. The remaining 6 to 17 percent of human-caused emissions has come primarily from deforestation of land for conversion to agriculture. However, increases in fossil fuel emissions over the past decade mean that the contribution from land-use changes has become a smaller proportion of the total (Le Quéré et al. 2009).

Methane is responsible for roughly 14 percent of greenhouse gas emissions (IPCC 2007). Concentrations of this gas have also been increasing as a result of human activities, including agricultural production of livestock and increases in rice production. Livestock production is a contributor to CH_4 emissions, primarily from fermentation in the guts of cattle and other ruminants. Rice production requires wet conditions that are also ideal for microbial CH_4 production. Other sources of CH_4 include biomass burning, microbial emissions from landfills, fossil fuel combustion, and leakage of natural gas during mining and distribution.

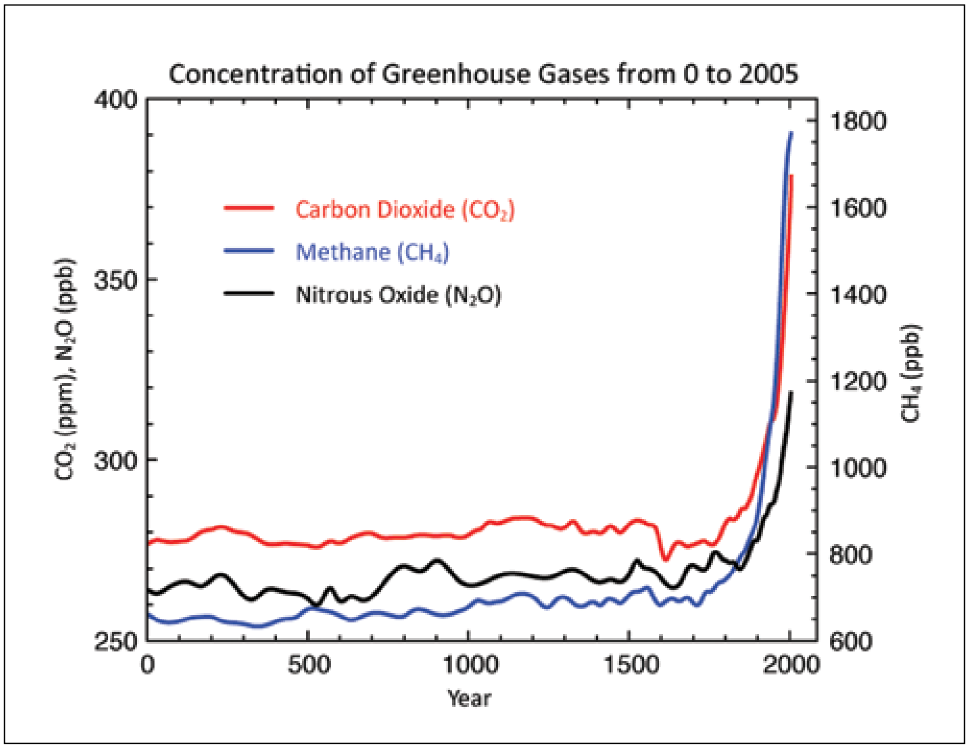


Figure 13.—Concentrations of greenhouse gases over the past 2005 years, showing increases in concentrations since 1750 attributable to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Figure courtesy of the Intergovernmental Panel on Climate Change (2007).

Nitrous oxide accounts for about 8 percent of global greenhouse gas emissions (IPCC 2007). The primary human source of N_2O is agriculture. Using more fertilizer increases N_2O emissions from soil as soil microbes break down nitrogen-containing products. In addition, converting tropical forests to agricultural lands increases microbial N_2O production. Other sources of N_2O from human activities include nylon production and combustion of fossil fuels.

Humans have also reduced stratospheric ozone through the use of chlorofluorocarbons (CFCs) in refrigeration, air conditioning, and other applications. Restrictions against the use of CFCs under the Montreal Protocol led to a decline in CFC emissions and reductions in ozone have subsequently slowed. After CFCs were banned, another class of halocarbons, hydrofluorocarbons (HFCs, also known as F-gases), largely replaced CFCs in refrigeration and air conditioning. Although HFCs do not deplete stratospheric ozone, many are powerful greenhouse gases. Currently, HFCs account for about 1 percent of greenhouse gas emissions (IPCC 2007).

CLIMATE MODELS

Scientists use models, which are simplified representations of reality, to simulate future climates. Models can be theoretical, mathematical, conceptual, or physical. General circulation models (GCMs), which combine complex mathematical formulas representing physical processes in the ocean, atmosphere, and land surface within large computer simulations, are important in climate science. These models are used in short-term weather forecasting as well as long-term climate projections.

General Circulation Models

General circulation models simulate physical processes on the Earth's surface, oceans, and atmosphere through time by using mathematical equations in three-dimensional space. They can work in time steps as small as minutes or hours in simulations covering decades to centuries. Because of their high level of complexity, GCMs require intensive computing power, and must be run on immense supercomputers.

Although climate models use highly sophisticated computers, limits on computing power mean that projections are limited to relatively coarse spatial scales. Instead of simulating climate for every single point on Earth, modelers divide the land surface, ocean, and atmosphere into a three-dimensional grid (Fig. 14). Each cell within the grid is treated as an individual unit, and able to interact with adjacent cells. Although each model is slightly different, each square in the grid is usually between 2° and 3° latitude and longitude, or for the middle latitudes, about the size of the assessment area in Michigan. These horizontal grids are stacked in interconnected vertical layers that simulate ocean depth or atmospheric thickness at increments usually ranging from 650 to 3,280 feet.

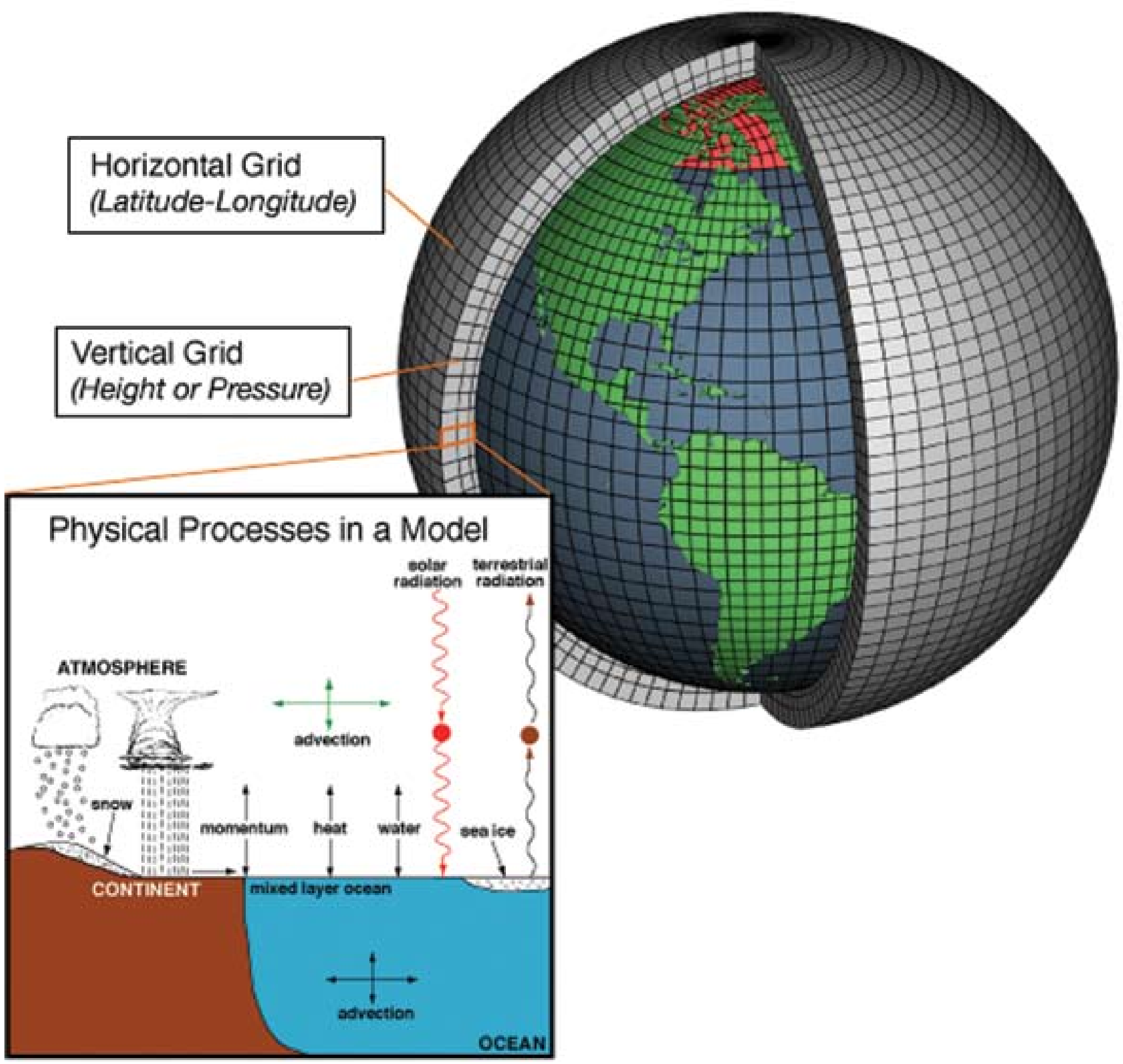


Figure 14.—Schematic describing climate models, which are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. The planet is divided into a three-dimensional grid that is used to apply basic equations and evaluate results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. Figure courtesy of the National Oceanic and Atmospheric Administration (2008).

Several GCMs have been used in climate projections for the IPCC reports and elsewhere (Box 5). These models have been developed by internationally renowned climate research centers such as NOAA's Geophysical Fluid Dynamics Laboratory (GFDL CM2) (Delworth et al. 2006), the United Kingdom's Hadley Centre (HadCM3) (Pope et al. 2000), and the National Center for Atmospheric Research (PCM) (Washington et al. 2000). These models use slightly different grid sizes and ways of quantitatively representing physical processes. They also differ in sensitivity to changes in greenhouse gas concentrations, which means that some models will tend to project higher increases in temperature than others under increasing greenhouse gas concentrations (Winkler et al. 2012). In some instances, the choice of GCM can have a larger influence on the projected climate trends than the choice of greenhouse gas emissions scenario.

Like all models, GCMs have strengths and weaknesses (Box 6). They are useful and reliable tools because they are based on well-understood physical processes. In general, GCM simulations of past climates correspond well with measured and proxy-based estimates of ancient climates (Maslin and Austin 2012). These models are judged in part by their ability to accurately simulate past climate against proxy estimates. But GCM projections are not perfect (Maslin and Austin 2012). Climate scientists' understanding of some climate processes is incomplete, and some influential climate processes occur at spatial scales that are too small to be modeled given current computing power. Additionally, GCM projections are impossible to validate perfectly, because the projections are driven by future conditions that have never previously occurred. Finally, future climate projections may be unable to capture the frequency of extreme weather events or large climate shifts. Technological advances in computing along with scientific advances in our understanding of Earth's physical processes will lead to continued improvements in GCM projections. Projections may still have a considerable range of future values, however, because adding greater modeling complexity introduces new sources of uncertainty (Maslin and Austin 2012).

Box 5: More Resources on Climate Models and Emissions Scenarios

U.S. Forest Service

Climate Projections FAQ
www.treesearch.fs.fed.us/pubs/40614

U.S. Global Change Research Program

Climate Models: an Assessment of Strengths and Limitations
http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products

Intergovernmental Panel on Climate Change

Chapter 8: Climate Models and Their Evaluation
www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8.html

Special Report on Emissions Scenarios: Summary for Policymakers
http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

Great Lakes Integrated Science and Assessment (GLISA) Center

Midwest Technical Input Report for the National Climate Assessment
glisa.msu.edu/great_lakes_climate/nca.php

Box 6: Model Limitations and Uncertainty

"All models are wrong, some are useful."
–George Box (Box and Draper 1987)

Models are conceptual representations of reality, and any model output must be evaluated for its accuracy to simulate any biological or physical response or process. The overall intention is to provide the best information possible for land managers given the uncertainty and limitations inherent in models.

Model results are not considered standalone components of this vulnerability assessment because there are many assumptions made about the processes simulated by GCMs and impact models, uncertainty in future greenhouse gas concentrations, and limits on the numbers of inputs that a model can reliably handle. Precipitation projections usually have much more variability among future climate projections than temperature. Regions with complex topography contain much more diversity in microclimates than many models can capture. Many nonclimate stressors, such as insect pests or pathogens, can overshadow the impact of climate on a species or community, especially in the short term. Therefore, model results are best interpreted by local experts to identify regional caveats and limitations of each model, and are best considered with additional knowledge and experience in the forest ecosystems being assessed.

We integrated fundamentally different types of impact models into our assessment of forest vulnerability to climate change. These models operate at different spatial scales and provide different kinds of information. The DISTRIB model projects the amount of available suitable habitat for a species. The LANDIS-II model projects changes in biomass and species distribution. The PnET-CN model projects ecosystem productivity. There are similarities between some inputs into these models—downscaled climate models and scenarios, simulation periods, and many of the same species—but because of the fundamental differences in their architecture, their results are not directly comparable. Their value lies in their ability to provide insights into how various interrelated forest components may respond to climate change under a range of possible future climates.

Models can be useful, but they are inherently incomplete. For that reason, an integrated approach using multiple models and expert judgment is needed. The basic inputs, outputs, and architecture of each model are summarized in this chapter with clear descriptions of the limitations and caveats of each model. Limitations of these models with specific applicability to forest ecosystems are discussed in more detail in Chapter 5.

Emissions Scenarios

General circulation models require significant amounts of information to project future climates. Some of this information, like future greenhouse gas concentrations, is not known and must be estimated. Although human population growth, economic circumstances, and technological developments will certainly have dramatic effects on future greenhouse gas concentrations, these developments cannot be completely foreseen. One common approach for dealing with uncertainty about future greenhouse gas concentrations is to develop alternative storylines about how the future may unfold and then calculate the potential greenhouse gas concentrations for each storyline. The IPCC's set of standard emissions scenarios is a widely accepted set of storylines (IPCC 2007). In GCMs, the use of different emissions scenarios results in different climate projections.

Emissions scenarios are a quantitative representation of alternative storylines given certain demographic, technological, or environmental developments. None of the scenarios includes any changes in national or international polices directed specifically at greenhouse gas mitigation such as the Kyoto Protocol. However, some of the scenarios that include a reduction in greenhouse gases via other means suggest what we could expect if these policies were implemented. Six different emissions scenarios are commonly used in model projections (Fig. 15).

The A1FI scenario is the most fossil-fuel intensive storyline, and thus results in the highest projected future greenhouse gas concentrations. GCM simulations using the A1FI scenario predict the most future warming. On the other end of the spectrum, the B1 scenario represents a future where alternative energies are developed and there is decreasing reliance on fossil fuels, resulting in the lowest rise in greenhouse gas concentrations. GCM simulations using the B1 scenario predict the least future warming. Although these scenarios were designed to describe a range of future emissions over the coming decades, it is important to note that the future could conceivably be different from any of the developed scenarios. It is highly improbable that future greenhouse gas emissions will be less than described by the B1 scenario even if national or international policies were implemented immediately. In fact, current emissions more closely track the greenhouse gas emissions of the A1FI scenario, and global emissions since 2000 have even exceeded the A1FI scenario values in some years (NOAA National Climatic Data Center 2012a, Raupach et al. 2007).

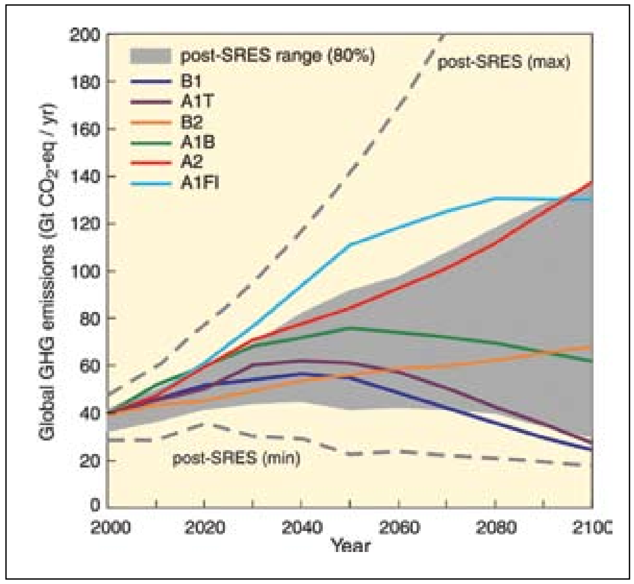


Figure 15.—Projected global greenhouse gas emissions (in gigatons [Gt] of carbon dioxide equivalent per year) assuming no change in climate policies under six scenarios (B1, A1T, B2, A1B, A2, and A1FI) originally published in the Special Report on Emissions Scenarios (SRES) (IPCC 2000), and the 80th-percentile range (gray shaded area) of recent scenarios published since SRES. Dashed lines show the full range of post-SRES scenarios. Figure courtesy of the Intergovernmental Panel on Climate Change (IPCC 2007).

Downscaling

As mentioned previously, GCMs simulate climate conditions only for relatively large areas. To examine the future climate of areas within northern Michigan, a smaller grid scale is useful. One method of projecting climate on smaller spatial scales is to use statistical downscaling, a technique by which statistical relationships between GCM model outputs and on-the-ground measurements are derived for the past. These statistical relationships are then used to adjust large-scale GCM simulations of the future for much smaller spatial scales. Grid resolution for downscaled climate projections is typically about 6.2 miles. Although it is useful to have more localized projections, users must consider that downscaling introduces further uncertainty to the future GCM projections, so it is important to pay attention to general trends rather than individual pixels or clusters of pixels.

Statistical downscaling has several advantages and disadvantages (Daniels et al. 2012, Maslin and Austin 2012) (Box 6). It is a relatively simple and inexpensive way to produce smaller-scale projections using GCMs. One limitation is that downscaling assumes that past relationships between modeled and observed temperature and precipitation will remain consistent under future change. This assumption may or may not be true. Another limitation is that downscaling depends on local climatological data. If there is no weather station in the area of interest, it may be difficult to obtain a good downscaled estimate of future climate for that area. Finally, local influences on climate that occur at finer scales (such as land cover type or topography) also add to uncertainty when downscaling climate projections.

Another approach, dynamical downscaling, uses a regional climate model (RCM) embedded within a GCM (Daniels et al. 2012). Like GCMs, RCMs simulate physical processes through mathematical representations on a grid. However, RCMs operate on a finer resolution than GCMs, typically ranging from 15.5 to 31.0 miles, but can be as fine as 6.2 miles or less. Thus, they can simulate the effects of topography, land cover, lakes, and regional circulation patterns that operate on smaller scales.

As with statistical downscaling, dynamical downscaling has pros and cons (Daniels et al. 2012). It is advantageous for simulating the effects of climate change on processes such as lake-effect snow or extreme weather. However, like GCMs, RCMs require a lot of computational power and they are not necessarily more accurate at projecting change than GCMs (Kerr 2013). Therefore, dynamically downscaled data are usually available only for one or two GCMs or scenarios, and for limited geographic areas. Because dynamically downscaled data are limited for the assessment area, we use statistically downscaled data in this report.

Downscaled Climate Projections Used in this Assessment

In this assessment, we report statistically downscaled climate projections for two GCM-emissions scenario combinations: GFDL A1FI and PCM B1. Both models and both scenarios were included in the IPCC Fourth Assessment Report (IPCC 2007). The latest version of the National Climate Assessment, which is currently in development, also draws on statistically downscaled data based on IPCC models and scenarios but uses the A2 scenario as an upper bound, which projects lower emissions compared to A1FI. The IPCC Assessment includes

Douglas Lake at the University of Michigan Biological Station. Photo by Stephen Handler, U.S. Forest Service.

several other models, which are represented as a multi-model average in its reports. The National Climate Assessment takes a similar approach in using a multi-model average. For this assessment, we instead selected two models that had relatively good skill at simulating climate in the eastern United States and that bracketed a range of temperature and precipitation futures. This approach gives readers a better understanding of the level of agreement among models and provides a set of alternative scenarios that can be used by managers in planning and decisionmaking.

The National Oceanic and Atmospheric Administration's GFDL model is considered moderately sensitive to changes in greenhouse gas concentrations (Delworth et al. 2006). In other words, any change in greenhouse gas concentration would lead to a change in temperature that is higher than some models and lower than others. By contrast, the National Center for Atmospheric Research's model, PCM, is considered to have low sensitivity to greenhouse gas concentrations (Washington et al. 2000). As mentioned above, the A1FI scenario is the highest greenhouse gas emissions scenario used in the 2007 IPCC assessment, and is the most similar to current trends in greenhouse gas emissions globally. The B1 scenario is the lowest greenhouse gas emissions scenario used in the 2007 IPCC assessment, and is thus much lower than the trajectory for greenhouse gas emissions during the past decade. Therefore, the GFDL A1FI and PCM B1 scenarios span a large range of possible futures. Although both projections are possible, the GFDL A1FI scenario represents a more realistic projection of future greenhouse gas emissions and temperature increases (Raupach et al. 2007). It is important to note that actual emissions and temperature increases could be lower or higher than these projections.

This assessment relies on a statistically downscaled climate data set (Hayhoe 2010a). Daily mean, maximum, and minimum temperature and total daily precipitation were downscaled to an approximately 7.5-mile grid across the United States. This data set uses a modified statistical asynchronous quantile regression method to downscale daily GCM output and historical climate data (Stoner et al. 2013). This approach is advantageous because GCM and historical data do not need to be temporally correlated, and it is much better at capturing extreme temperatures and precipitation events than a linear regression approach (Hayhoe 2010b). This is a different statistically downscaled data set than used in the National Climate Assessment, which uses a simpler "delta" approach (Kunkel et al. 2013). This data set was chosen for several reasons. First, the data set covers the entire United States, and thus allows a consistent data set to be used in this and other regional vulnerability assessments. Second, it includes downscaled projections for the A1FI emissions scenario, which is the scenario that most closely matches current trends in global greenhouse gas emissions (Raupach et al. 2007). Third, the data set includes daily values, which are needed for some impact models used in this report. Finally, the 7.5-mile grid scale was fine enough to be useful for informing land management decisions.

Summarized projected climate data are shown in Chapter 4. To show projected changes in temperature and precipitation, we calculated the average daily mean, maximum, and minimum temperature for each month for three 30-year periods (2010 through 2039, 2040 through 2069, 2070 through 2099). The monthly averages were grouped into seasonal and annual values. Mean monthly precipitation was also calculated and summed seasonally and annually for the same periods. We then subtracted these values from the corresponding 1971 through 2000 average to determine the departure from current climate conditions. Historical climate data used for the departure analysis were taken from ClimateWizard (Girvetz et al. 2009). Chapter 3 includes more information about the observed climate data from ClimateWizard.

Importantly, the downscaled future climate projections were also used in each of the forest impact models described below. This consistency in future climate data allows for more effective comparison across different model results. The models also operate on grid scales that may be larger or smaller than the grid scale of the downscaled data set, and grid scales were adjusted accordingly.

MODELS FOR ASSESSING FOREST CHANGE

Downscaled climate projections from GCMs provide us with important information about future climate, but they tell us nothing about how climate change might affect forests and other ecosystems. Other models, commonly called impact models, are needed to project impacts on trees, animals, and ecosystems. Impact models use GCM projections as inputs, as well as information about tree species, life history traits of individual species, and soil types. Many different models are used to simulate impacts on species and forest ecosystems. These models generally fall into one of two main categories: species distribution models (SDMs) and process models. In this assessment, we used one SDM, the Climate Change Tree Atlas (Prasad et al. 2007-ongoing), and two process models, LANDIS-II (Scheller et al. 2007) and PnET-CN (Aber et al. 1997). These models operate at different spatial scales and provide different kinds of information. We chose them because they have been used to assess climate change impacts on forests in our geographic area of interest, and have stood up to rigorous peer review in scientific literature.

A Kirtland's warbler in the northern Lower Peninsula of Michigan. Photo by U.S. Forest Service, Huron-Manistee National Forest.

Species distribution models establish a statistical relationship between the distribution of a species or community and key attributes of its habitat. This relationship is used to predict how the range of the species will shift as climate change affects those attributes. These models are much less computationally expensive than process models, so they can typically provide projections for the suitable habitat of many species over a larger area. There are some caveats that users should be aware of when using them, however (Wiens et al. 2009). These models use a species' realized niche instead of its fundamental niche. The realized niche is the actual habitat a species occupies given predation, disease, and competition with other species. A species' fundamental niche, in contrast, is the habitat it could potentially occupy in the absence of competitors, diseases, or predators. Given that a species' fundamental niche may be greater than its realized niche, SDMs may underestimate current niche size and future suitable habitat. In addition, species distributions in the future might be constrained by competition, disease, and predation in ways that do not currently occur. If so, SDMs could overestimate the amount of suitable habitat in the future. Furthermore, fragmentation or other physical barriers to migration may create obstacles for species otherwise poised to occupy new habitat. Therefore, a given species might not actually be able to enter the assessment area in the future, even if Tree Atlas projects it will gain suitable habitat. Additionally, SDMs like Tree Atlas do not project that existing trees will die if suitable habitat moves out of an area. Rather, these models indicate that trees will be living farther outside their ideal range and will be exposed to more climate-related stress.

In contrast to SDMs, process models such as LANDIS-II and PnET-CN simulate community and tree species dynamics based on interactive mathematical representations of physical and biological processes. Process models can simulate future change in tree species dispersal, succession, biomass, and nutrient dynamics over space and time. Because these models simulate spatial and temporal dynamics of a variety of complex processes, they typically require more computational power than a species distribution model. Therefore, fewer species or forest types can be modeled compared to an SDM. Process models have several assumptions and uncertainties that should be taken into consideration when applying results to management decisions. Process models rely on empirical and theoretical relationships that are specified by the modeler. Any uncertainties in these relationships can be compounded over time and space, leading to an erroneous result.

Although useful for projecting future changes, both process models and SDMs share some important limitations. They assume that species will not adapt evolutionarily to changes in climate. This assumption may be true for species with long generation times (such as trees), but some short-lived species may be able to adapt even while climate is rapidly changing. Both types of models may also magnify the uncertainty inherent in their input data. Data on the distribution of trees, site characteristics,

Planted jack pine seedling near Newberry, Michigan. Photo by Stephen Handler, U.S. Forest Service.

and downscaled GCM projections are estimates that add to uncertainty. No single model can include all possible variables, so there are important inputs that may be excluded from individual models, such as competition from understory vegetation, herbivory, and pest outbreaks. Given these limitations, it is important for all model results to pass through a filter of local expertise to ensure that results match with reality on the ground. Chapter 6 and Appendix 5 explain the approach used in this assessment for determining the vulnerability of forest ecosystems based on local expertise and model synthesis.

Climate Change Tree Atlas

The Climate Change Tree Atlas (Tree Atlas) incorporates a diverse set of information about potential shifts in the distribution of tree species' habitat in the eastern United States during the next century (Iverson et al. 2008, Prasad et al. 2007-ongoing). Tree Atlas is actually a set of different models and information that work together. The species distribution model DISTRIB measures relative abundance, referred to as importance values, for 134 eastern tree species. Inputs include tree species distribution data from the U.S. Forest Service Forest Inventory and Analysis (FIA) program and environmental variables (pertaining to climate, soil properties, elevation, land use, and fragmentation), which are used to model current species abundance with respect to current habitat distributions by using statistical techniques. DISTRIB then projects future importance values and suitable habitat for individual tree species using downscaled GCM data readjusted to a 12-mile grid (Prasad et al. 2007-ongoing).

Additionally, each tree species is further evaluated for additional factors not accounted for in the statistical models (Matthews et al. 2011b). These modifying factors (Appendix 4) are based on supplementary information about life history characteristics such as dispersal ability or fire tolerance as well as information on pests and diseases that have been having negative effects on the species. This supplementary information allows us to identify when an individual species may do better or worse than model projections would suggest.

For this assessment, the DISTRIB model uses the GFDL A1FI and PCM B1 model-scenario combinations. The results provided in Chapter 5 differ from online Tree Atlas results because they are specific to the assessment area and use the new statistically downscaled data set described above. Modifying factors are based on general species traits that are consistent across the entire range of a species, so the modifying factor values presented in the assessment are not unique to the assessment area.

LANDIS-II

The LANDIS-II model is an integrated modeling approach for simulating landscape changes that is process-driven and flexible to a variety of applications (Scheller et al. 2007). It is based on earlier versions of the LANDIS model (Mladenoff 2004). This model simulates disturbance, management, succession, and other processes in a grid-based framework that emphasizes spatial interactions across the landscape and among processes (e.g., climate change, harvesting, succession, fire, wind, and seed dispersal). This approach means that processes occur both within a given grid cell and between cells. LANDIS-II simulates age-based cohorts of individual tree species, rather than individual trees. It can run simulations for many decades and large spatial extents (greater than 1 million acres). Some processes are simulated to occur randomly based on probabilities and cell conditions, such as fire disturbance or seed dispersal. Specifically, the Biomass Succession (v3.1), Biomass Harvest (v2.0), Base Wind, and Base Fire extensions were used for all simulations (see www.landis-ii.org for further details on the options available).

Inputs to LANDIS-II include an initial conditions map with tree species assigned to age cohorts across all forested areas, soils information, and other spatial data. Climate change is incorporated by integrating specific species parameters to calculate maximum aboveground net primary productivity (Aber et al. 1997) and the probability of establishment (Xu et al. 2009) at every time step. LANDIS-II calculates these parameters by using monthly maximum and minimum temperature, precipitation, and solar radiation. Other inputs include foliar nitrogen (N) content, maximum foliar mass area, and soil water-holding capacity. LANDIS-II also requires modelers to specify timber harvest prescriptions (Ravenscroft et al. 2010) and rotation periods for fire and wind disturbances (White and Host 2008). More information on the harvest prescriptions used for this assessment can be found in Appendix 4. Outputs include maps of species distribution over time and time series graphs for aboveground biomass by species and for aggregated forest types.

For this assessment, two future climate scenarios, PCM B1 and GFDL A1FI, were used to simulate a range in potential future climate. A current climate scenario was also constructed as a baseline for comparison. The current climate scenario was designed by using climate data from 1970 through 1999 as a range of possible values. These data were accessed from the PRISM data set (Gibson et al. 2002), and values were randomly sampled from this range for all future years of the simulation. The simulations used a 4.9-acre grid and a 150-year time horizon from the year 2000 to 2150. The landscape in Michigan covered 6.4 million acres of forest across the northern Lower Peninsula, defined by Ecological Section VII (Albert 1995). LANDIS-II simulations included 26 common tree species within this landscape (Chapter 5). Forest management practices were described with a business-as-usual scenario, described in more detail in Appendix 4.

PnET-CN

The PnET-CN model is an ecosystem-level process model that simulates carbon (C), water, and N dynamics in forests over time (Aber et al. 1997, 2001; Ollinger et al. 2008; Peters et al. 2013). This model accounts for physiological and biogeochemical feedbacks, which allows C, water, and N cycles to interact with each other. This enables PnET-CN to simulate the effects of water and N limitation on forest productivity. A strength of the PnET-CN model is its ability to simulate forest responses over time to many simultaneously changing environmental factors, including climate, N deposition, tropospheric ozone, and atmospheric CO_2. Although PnET-CN can be applied to large geographical regions, it is not a spatially dynamic model and cannot represent ecological processes such as succession or migration. PnET-CN assumes forest composition does not change over time. Rather, the utility of PnET-CN is to assess the physiological response of existing forests to projected environmental change.

PnET-CN requires input information on climate, soil, and vegetation. Climate and atmospheric inputs include monthly air temperature, precipitation, photosynthetically active radiation, tropospheric ozone concentration, atmospheric CO_2 concentration, and atmospheric N deposition rate. Soils are defined by their water holding capacity. Vegetation inputs include a suite of parameters, such as specific leaf area or leaf lifespan, that define a particular forest type. Forest types used by PnET-CN in this assessment are similar to FIA forest-type groups, such as maple/beech/birch (Pugh et al. 2012). Output from PnET-CN includes many variables related to C, water, and N cycling, including key ecosystem processes such as net primary production, net ecosystem production, evapotranspiration, and N mineralization. Full information on the PnET-CN simulations used in this assessment, including inputs, methods, and results, can be found in Peters et al. (2013).

For this assessment, we ran PnET-CN from 1960 to 2100 across the assessment area in Michigan with a grid resolution of 0.6 miles. Two future climate scenarios, PCM B1 and GFDL A1FI, were used to simulate a range in potential future climate and atmospheric CO_2 concentration. Current tropospheric ozone concentrations and N deposition rates (data provided by the U.S. Environmental Protection Agency) were held constant into the future. Soil water-holding capacity was defined by using the National Resources Conservation Service's Soil Survey Geographic Database (Matthew Peters, personal comm.). Vegetation cover was defined by using a vegetation map based on FIA data and satellite imagery (Wilson et al. 2012), which included six forest-type groups (maple/beech/birch, elm/ash/cottonwood, oak/hickory, aspen/birch, spruce/fir, and pine). Although PnET-CN can account for discrete disturbance events, we did not include any harvest, fire, or wind-related disturbances for this assessment.

SUMMARY

Temperatures have been increasing in recent decades at global and national scales, and the overwhelming majority of scientists attribute this change to increases in greenhouse gases from human activities. Even if dramatic changes are made to help curtail greenhouse gas emissions, these greenhouse gases will persist in our atmosphere for decades to come. Scientists can model how these increases in greenhouse gases may affect global temperature and precipitation patterns by using general circulation models. These large-scale climate models can be downscaled to finer resolution and incorporated into other types of models that project changes in forest composition and ecosystem processes to inform local decisions. There are inherent uncertainties in what the future holds, but all of these types of models can help us frame a range of possible futures. This information can then be used in combination with the local expertise of researchers and managers to provide important insights about the potential effects of climate change on forests.

Horseback riders on the Hiawatha National Forest. Photo by U.S. Forest Service, Hiawatha National Forest.

CHAPTER 3: OBSERVED CLIMATE CHANGE

Climate is the long-term weather pattern for a region for a period of decades. As discussed in Chapter 1, climate is one of the principal factors that have determined the composition and extent of forest communities in northern Michigan during the past several thousand years.

This chapter describes the climate trends in the assessment area that have been observed over the past century, including documented patterns of climate-related processes and extreme weather events. Ecosystems in northern Michigan are already exhibiting signals that they are responding to shifts in temperature and precipitation. This chapter presents a few case studies to illustrate the effects of climate change on ecological indicators such as growing season length, wildlife populations, fish populations, and lake ice formation.

HISTORICAL TRENDS IN TEMPERATURE AND PRECIPITATION

Substantial changes in temperature and precipitation have been observed during the past 100 years. We used the ClimateWizard Custom Analysis tool to assess the changes in temperature and precipitation across the assessment area (ClimateWizard 2012, Girvetz et al. 2009). Data for the tool are derived from PRISM (Gibson et al. 2002), which models historical measured point data onto a continuous 2.5-mile grid over the entire United States. We examined long-term (1901 through 2011) trends for annual, seasonal, and monthly temperature (mean, maximum, and minimum) and total precipitation within the assessment area. Accompanying tables and figures present the change over the 110-year period estimated from the slope of the linear trend. In the following text we highlight increasing or decreasing trends which have high probability that they did not occur by chance. For more information regarding confidence in trends and the PRISM data, refer to Appendix 2.

Temperature

The mean annual temperature across the assessment area increased 1.7 °F (1.0 °C) between 1901 and 2011 (ClimateWizard 2012). Average annual temperatures fluctuated considerably during the 20th century, with almost 9 °F (5 °C) separating the hottest and coldest years on record (Fig. 16).

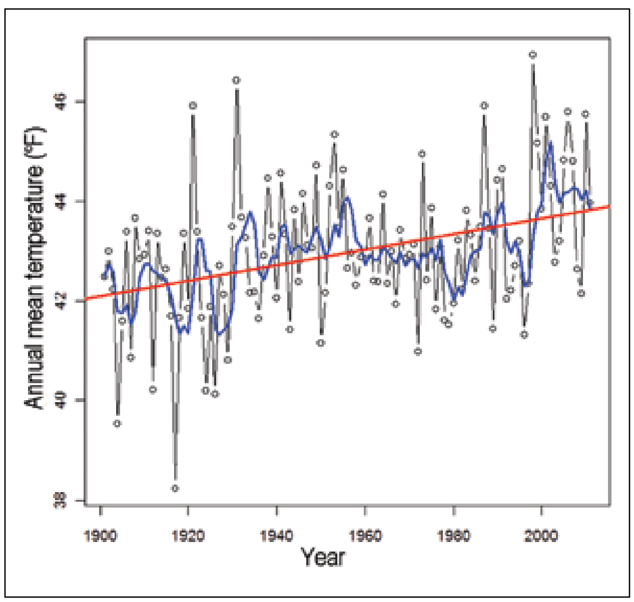


Figure 16.—Annual mean temperature (°F) within the assessment area from 1901 through 2011 (ClimateWizard 2012). The blue line represents the running 5-year mean. The red regression line shows the trend across the entire period.

Temperatures in the assessment area have increased across all seasons, but the magnitude of increase has varied from season to season (Table 12). The largest increase in average temperature occurred in winter (2.7 °F, 1.5 °C), and spring average temperatures increased by 2.6 °F (1.4 °C). Fall and summer mean temperatures have increased by smaller amounts. Average low temperatures increased at a faster rate than average high temperatures in winter and summer, but this pattern was reversed in spring and fall. The warming trends for the assessment area closely follow observed regional trends, which also show the greatest increases in winter low temperatures (Climate Change Science Program [CCSP] 2008). Data from 1971 through 2000 indicate that the winter warming trend in recent years has been roughly three times faster than the 20th-century trend (ClimateWizard 2012).

Observed temperature trends also vary by month within the assessment area (Fig. 17). Temperature increases were greatest during the winter and spring

Table 12.—Increase in mean annual and seasonal temperatures (°F) from 1901 through 2011 in the assessment area (ClimateWizard 2012)

Season	Average temperature increase	Average high temperature increase	Average low temperature increase
Annual	1.7	1.6	1.8
Winter (Dec.-Feb.)	2.7	2.2	3.2
Spring (Mar.-May)	2.6	3.1	2.1
Summer (June-Aug.)	1.2	0.8	1.6
Fall (Sept.-Nov.)	0.4	0.5	0.3

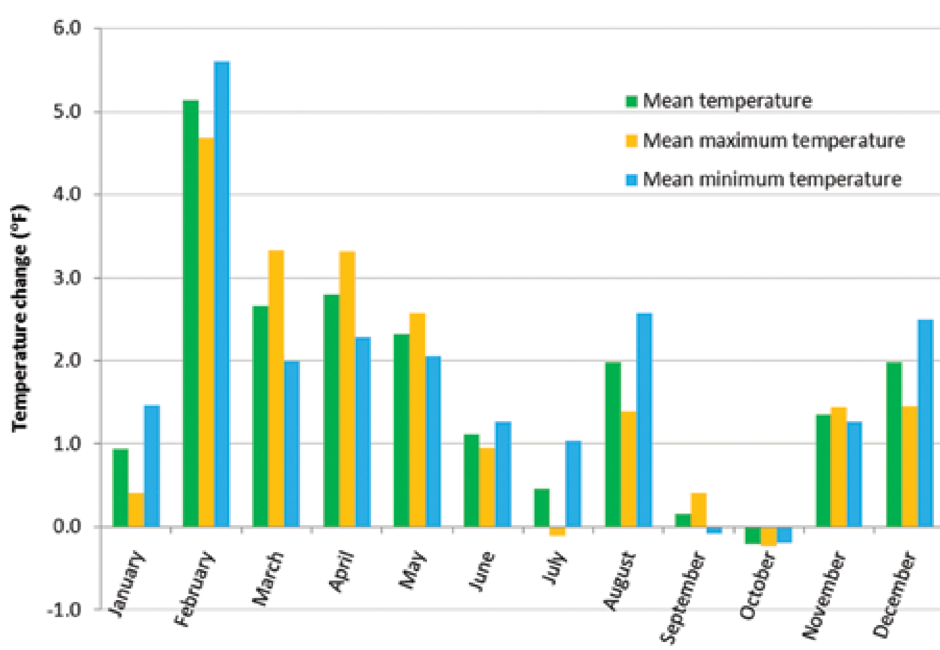


Figure 17.—Change in mean monthly temperatures (°F) from 1901 through 2011 within the assessment area (ClimateWizard 2012).

months, peaking in February with an increase of 5.1 °F (2.9 °C) in monthly mean temperature from 1901 through 2011. March, April, May, August, and December also warmed more than the annual mean increase. October was the only month when average temperature declined during this period, although this decline was very slight (-0.2 °F, -0.1 °C). Records for individual months correspond with the seasonal trends for minimum and maximum temperature increases. For example, average low temperatures increased by greater amounts than average high temperatures for all winter and summer months.

Temperature trends varied geographically across the assessment area (Fig. 18). In winter, the increase in average temperature was between 2 and 5 °F (1.1 and 2.8 °C) across most of the assessment area, with areas along the Great Lakes coasts generally warming faster than interior areas. The greatest winter warming occurred throughout Alger, Delta, and Schoolcraft Counties in the Upper Peninsula, and Cheboygan and Presque Isle Counties in the northern Lower Peninsula. Spring temperature patterns were similar, with the largest average temperature increases observed in the Munising area in the Upper Peninsula. Summer temperatures also increased the most in the central Upper Peninsula in Alger, Delta, and Schoolcraft Counties. Summer temperature trends were more moderate across the northern Lower Peninsula, with increases in the eastern half of the peninsula. Fall spatial trends were similar to summer months, with increases and decreases of less than 1 °F (0.6 °C) across the assessment area. As mentioned above, fall temperatures held essentially constant during the 20th century. A slight but widespread cooling trend was observed in summer and fall for mean average and mean minimum temperature in an area around Wexford and Newaygo Counties. This decline was more pronounced during fall months.

Fall colors on the Hiawatha National Forest. Photo by Autumn Jauck, Hiawatha National Forest.

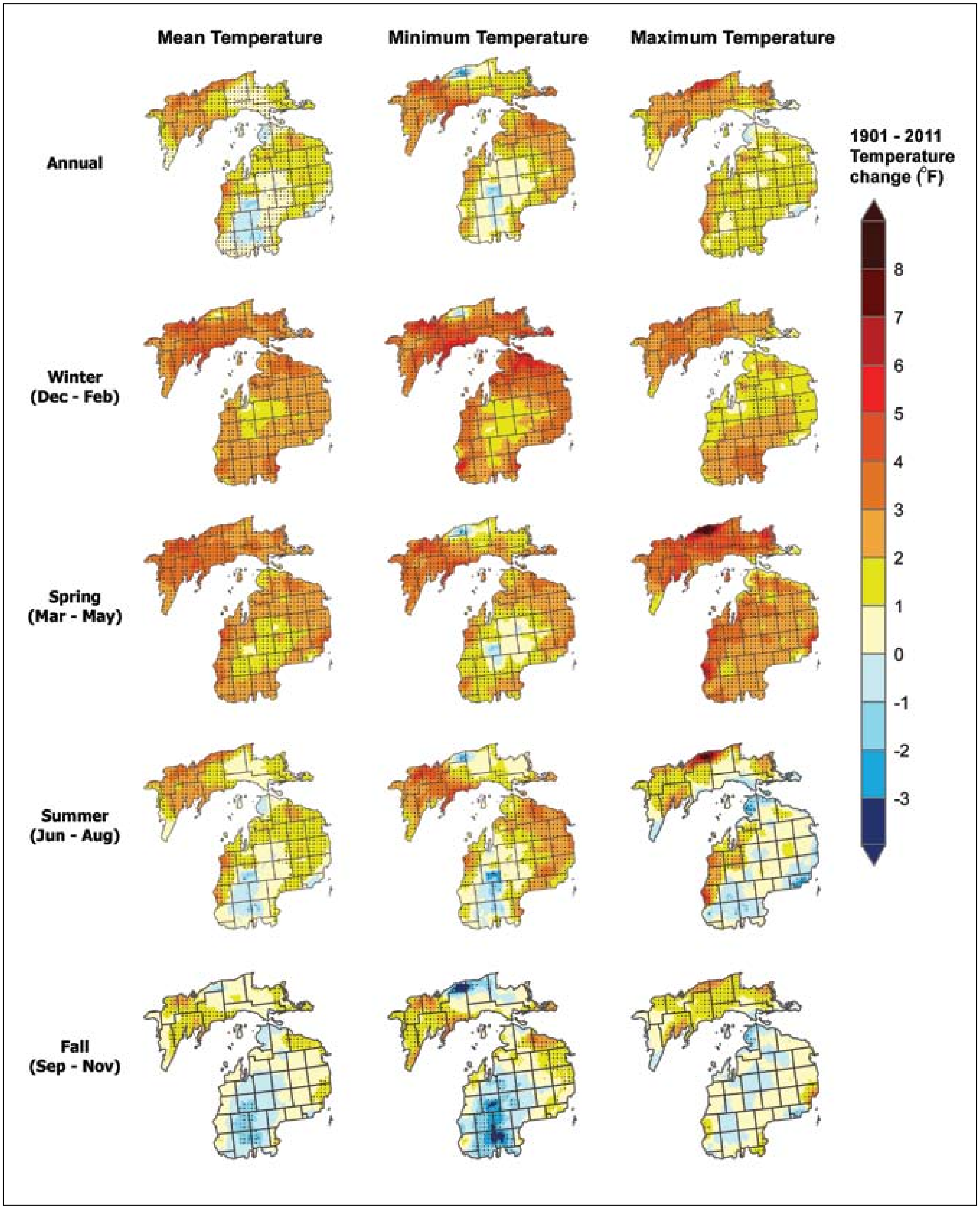


Figure 18.—Annual and seasonal observed temperature changes from 1901 through 2011 in the assessment area. Change is calculated from the slope of the regression line across the timeframe (ClimateWizard 2012). Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone.

Precipitation

From 1900 to 2011, mean annual precipitation increased by 4.9 inches across the assessment area (Table 13) (ClimateWizard 2012). The time series of annual precipitation for the assessment area displays a consistent upward trend despite wide year-to-year variability (Fig. 19). From 1950 to 2011, 7 years with greater than 35 inches of precipitation occurred in the assessment area, but from 1901 to 1950 the area never received this much precipitation.

The trend in the assessment area seems to be that summer and fall are getting much wetter, and winter and spring are getting only slightly wetter. The largest absolute increase in measured precipitation from 1901 through 2011 occurred in summer and fall (1.7 inches each). Compared to the 1971 through 2000 baseline period, the precipitation increases in these seasons were also proportionally larger than in the other seasons. Winter and spring exhibited smaller precipitation increases, less than 1 inch during each season. With regard to the trends in individual months from 1901 through 2011, slight declines in precipitation occurred only in February and May, although these declines were less than 0.2 inches for both months. Average precipitation in April, August, and October increased by more than 0.8 inches from 1901 through 2011.

There were also geographic differences in observed precipitation trends across the assessment area (Fig. 20). Across the entire year, the greatest precipitation increases occurred in an area bounded by Manistee, Oceana, Mecosta, and Wexford Counties. Precipitation increased between 6 and 10 inches in this area, which consistently received the largest precipitation increases across all seasons. The central portion of the Upper Peninsula and the eastern half of the Lower Peninsula received smaller precipitation increases throughout the year. In summer and winter, precipitation decreased less than 1 inch in the central Upper Peninsula from 1901 through 2011.

Table 13.—Increase in annual and seasonal precipitation (inches) from 1901 through 2011 in the assessment area (ClimateWizard 2012)

Season	Average precipitation increase
Annual	4.9
Winter (Dec.-Feb.)	0.7
Spring (Mar.-May)	0.9
Summer (June-Aug.)	1.7
Fall (Sept.-Nov.)	1.7

Interactions between Temperature and Precipitation

Observed temperature and precipitation trends in the assessment area correspond with larger regional climate patterns. Observed temperature and precipitation trends from 1950 through 2006 for the entire country show that areas that tended to get wetter during warm seasons also tended to have reduced high temperatures during those seasons

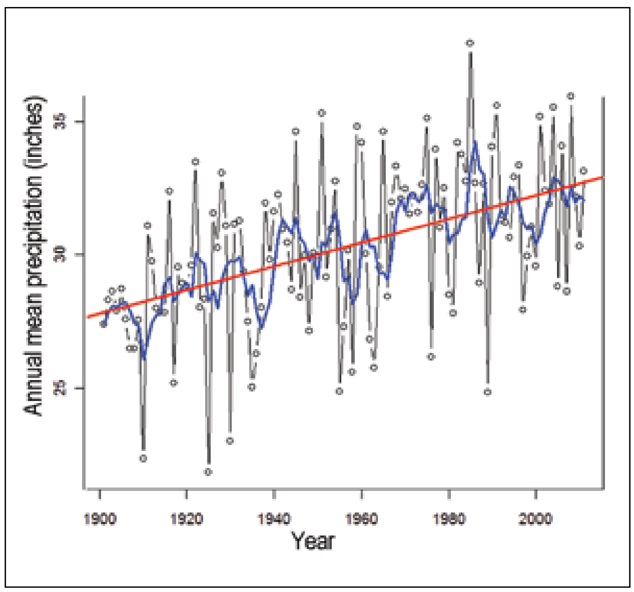


Figure 19.—Annual precipitation (inches) within the assessment area from 1901 through 2011 (ClimateWizard 2012). The blue line represents the running 5-year mean. The red regression line shows the trend across the entire period.

(Portmann et al. 2009). Conversely, areas of the country that are getting drier during warm seasons are also getting warmer. For the upper Midwest, this pattern was most evident during summer and fall.

Within the assessment area, summer and fall exhibited the smallest temperature increases within the assessment area (Table 12) and also the largest precipitation increases (Table 13). In these seasons, the largest average precipitation increases (Fig. 20) and the largest declines in average temperatures (Fig. 18) occurred in the southwestern portion of the assessment area. The causes of this relationship between precipitation and high temperatures are not yet fully explained, but it has been proposed that cloudiness, evaporation of surface moisture, organic aerosols from forests, and air pollution may all be involved (Portmann et al. 2009).

HISTORICAL TRENDS IN EXTREMES AND PHYSICAL PROCESSES

Although it can be very instructive to examine long-term means of climate and weather data, in many circumstances extreme events can have a greater impact on forests and the human communities that depend on them. Weather or climate extremes are defined as individual weather events or long-term patterns that are unusual in their occurrence or have destructive potential (CCSP 2008). These events can trigger catastrophic disturbances in forests, along with significant socioeconomic disasters. The distribution of individual species or forest types is often controlled by particular climatic extremes. Climate change has been estimated to have increased the likelihood of several kinds of extreme weather events, although it is difficult to directly attribute one particular event to climate change (Coumou and Rahmstorf 2012). Extreme events are difficult to analyze with standard statistical methods, so long-term studies of weather and climate trends are necessary.

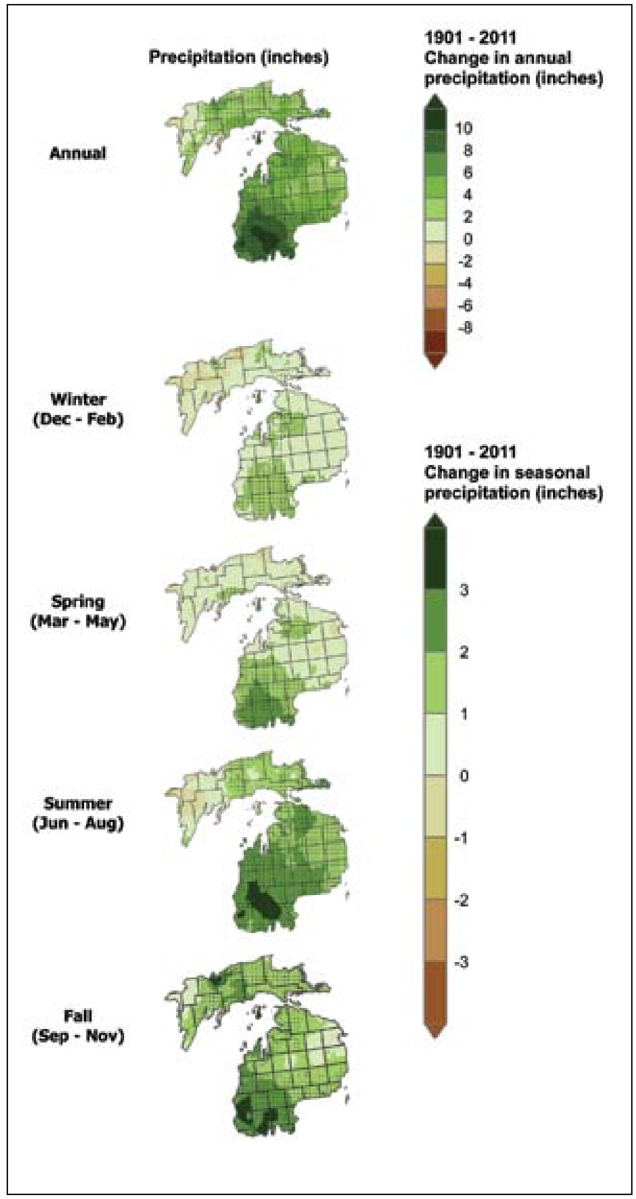
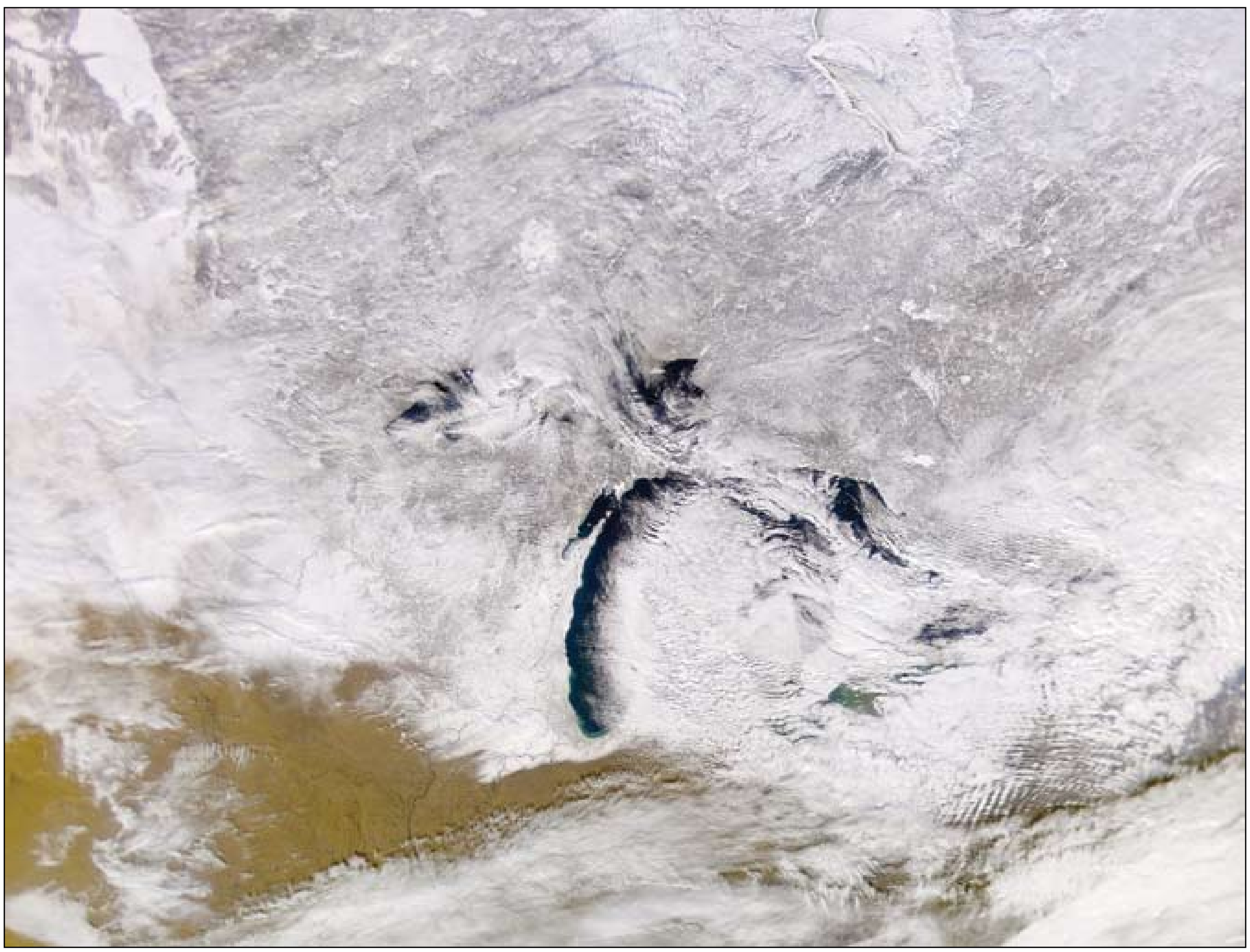


Figure 20.—Annual and seasonal precipitation changes (inches) from 1901 through 2011 in the assessment area (ClimateWizard 2012). Change is calculated from the slope of the regression line across the timeframe. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone.

Many physical processes important for forest ecosystems are also driven by climate and weather patterns. These processes, such as snowpack and soil frost, can regulate annual phenology, nutrient cycling, and other ecosystem dynamics. Changes to these physical processes can result in impacts and stress that might not be anticipated from mean climate values alone. This section presents a few key trends that have been observed in Michigan or throughout the broader region.

Snow and Winter Storms

Cold and snowy winters are characteristic of northern Michigan. The state experiences more snowstorms than nearby Wisconsin or Minnesota, and both the Upper and Lower Peninsulas have significant lake-effect snowfall (Changnon and Changnon 2007). Among all the eastern states, Michigan ranked second in the number of 6-inch snowstorms in the 20th century (Changnon and Changnon 2007). There are clear winter precipitation gradients across the assessment area, decreasing from north to south in the eastern Upper Peninsula and decreasing from west to east in the northern Lower Peninsula (ClimateWizard 2012). These trends are dictated by the prevailing wind direction, topography, and lake-effect snow from Lake Superior and Lake Michigan. For the assessment area, winter precipitation increased 0.7 inches during the 20th century, and the most notable increase occurred in the southwestern corner of the assessment area (Table 13, Fig. 20).



Lake-effect snowfall over Michigan. Image courtesy of the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE.

Annual snowfall amounts have been increasing between 1 and 6 percent per decade in northern Michigan over the 20th century (Kunkel et al. 2013). Regional trends indicate that snowfall is quite variable from year to year, but few heavy snowfall years have occurred in the most recent 30 years (Kunkel et al. 2013). Individual snowfall events have been more intense, however. From 1900 to 1990, there was an increase in snowstorms of 6 inches or more across the upper Midwest (CCSP 2008). The four-state region including Michigan had a decreasing trend of extreme low-snow years during the 20th century (Kunkel et al. 2009), which corresponds with the slight increase in winter precipitation across the assessment area and the wider region. Long-term records from across the Great Lakes indicate that lake-effect snow increased gradually across the region during the 20th century due to the warming of these water bodies and the decreasing trend in lake-ice cover (Burnett et al. 2003, Kunkel et al. 2013). When the Great Lakes are free of ice during the winter, cold continental air masses can pick up warm water vapor and deposit this moisture as snowfall. This effect is reduced as Great Lakes are increasingly covered with ice.

Soil Frost

Soil frost dynamics are important for forest ecosystems because soil temperatures can affect water infiltration rates, nutrient cycling, and tree growth. Research has shown that deeper snow depth results in shallower soil frost depth in northern forests, and thinner snowpack results in colder soil temperatures and deeper soil frost (Hardy et al. 2001). Long-term data indicate that winter soil temperatures decreased over the 20th century across northern Michigan and northern Wisconsin, even as temperatures increased (Isard et al. 2007). A similar study also found evidence for decreasing winter soil temperatures within the assessment area in recent decades (Sinha et al. 2010). Therefore, even as winter temperatures have risen in the assessment area (Table 12), frost depth may have increased as snowpack conditions became more variable. Warmer winter air temperatures have led to more snowmelt between snowfall events.

During the entire 20th century, trends in the duration and timing of soil frost have been different for the Upper and Lower Peninsulas of Michigan. There appears to have been a 12- to 24-day decline in the annual number of soil frost days across most of the northern Lower Peninsula, whereas there has been a corresponding increase in the annual number of soil frost days in the eastern Upper Peninsula. These findings suggest that reductions in winter precipitation in the eastern Upper Peninsula have exposed the soil to more prolonged cold temperatures, even as winter temperatures have risen. The increased winter precipitation in the northern Lower Peninsula may also have resulted in more snowfall to insulate soils from frost in this part of the assessment area. Compared to the early 20th century, one to two more freeze-thaw cycles occur per winter across the assessment area. These events indicate more variable winter conditions (Sinha et al. 2010). Freeze-thaw cycles can damage roots of frost-intolerant tree species and affect the timing of nutrient release in forest soils (Auclair et al. 2010, Tierney et al. 2001).

Intense Precipitation

Intense precipitation events have become more frequent across much of the continental United States (Kunkel et al. 2008). In the upper Midwest, there was a 50-percent increase in the frequency of days with rainfall of 4 inches or more during the 20th century (CCSP 2008). A recent study across the central United States also supports this trend, noting that moderately heavy rainfall events (0.5 to 1.0 inches) became less frequent while rainfall events of at least 1 inch became more common (Groisman et al. 2012). Heavy precipitation events that used to occur only once every 12 months are now occurring every 9 months across the upper Midwest, an increase of roughly 35 percent over the past 60 years (Madsen and Willcox 2012).

This trend is exemplified in Michigan, where a 180-percent increase in rainstorms of 3 inches or more occurred between 1960 and 2011 (Fig. 21) (Saunders et al. 2012). The northern Lower Peninsula in particular had a larger increase in heavy rainfall events than surrounding states, with 50- to 100-percent increases in the frequency of large precipitation events from 1931 to 1996 (Kunkel et al. 1999). A change in heavy precipitation events has not been observed in the Upper Peninsula during this timeframe.

Flooding and Streamflow

Long-term data on flooding is difficult to interpret because of the variety of measures used to describe floods. From 1961 to 1979, the National Weather Service reported no severe flood years in the four-state region including Michigan, and there were 4 such years between 1983 and 2001 (Cartwright 2005). There are several complicating factors in explaining this trend. In particular, anthropogenic land-use change over the past century has had a considerable influence on flooding frequency in the upper Midwest. Increased flood peaks in the upper Midwest may be driven by land use practices, agricultural practices, and dam construction (Villarini et al. 2011). After accounting for these factors, however, Midwestern watersheds still exhibited increased discharge during the past several decades and this trend has been attributed to climate change (Tomer and Schilling 2009).

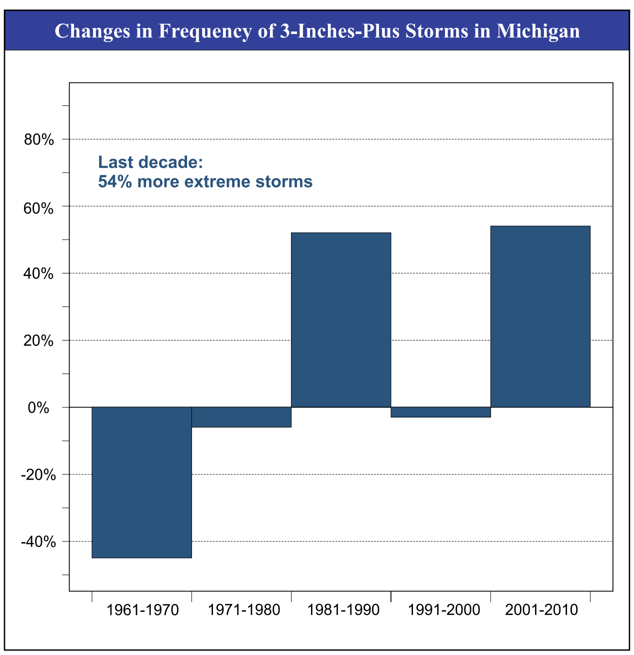


Figure 21.—Changes in the frequency of rainfall events of 3 inches or more in Michigan from 1961 through 2011, compared to the baseline years 1961 through 1990. Figure from Saunders et al. (2012) and used with permission of the authors.

Extreme Temperatures

High temperatures can influence forests in a variety of ways, and some tree species are limited by hot growing-season temperatures. Extreme temperatures may also be associated with disturbance events like droughts and wildfire. Long-term records indicate that extreme hot weather has become more frequent across the Midwest region over the second half of the 20th century (Kunkel et al. 2013, Perera et al. 2012). Recent heat waves have been characterized by very high humidity levels as well as high nighttime temperatures (Kunkel et al. 2013). Additionally, multi-day heat waves have become more common during the past 60 years (Perera et al. 2012). Summer cool days have become less frequent over this same period. These trends correspond to global patterns of increasing occurrence of extreme hot weather and decreasing occurrence of extreme cool weather (Hansen et al. 2012). A study across the entire Midwest found that intense cold waves (4-day durations of temperatures below a 1-in-5-year recurrence threshold) have been less frequent during the past 17 years, but there has not been a clear trend across the 20th century (Perera et al. 2012).

Soil Moisture and Drought

Droughts are among the greatest stressors on forest ecosystems, and can often lead to secondary effects of insect and disease outbreaks on stressed trees and increased fire risk. In North America and the Midwestern United States in particular, there has been a trend toward wetter conditions since 1950, and there is no detectable trend for increased drought based on the Palmer Drought Severity Index (Dai et al. 2004, Karl et al. 2009). Another study of hydrologic trends in the United States over the last century (1915 through 2003) also observed reduced duration and severity of droughts across the upper Midwest as a result of increased precipitation (Andreadis and Lettenmaier 2006).

Data from the past century indicate that drought trends have been diverging between the Upper and Lower Peninsulas in Michigan. Between 1895 and 2013, the trend in the northern Lower Peninsula has been toward slightly less common and less severe droughts during the growing season, with the years between 1910 and 1940 representing the most extreme droughts during the period of record (National Oceanic and Atmospheric Administration National Climatic Data Center 2013). Conversely, droughts have occurred more frequently in the eastern Upper Peninsula, particularly since 1980. The western Upper Peninsula (outside the assessment area) has also undergone frequent and multi-year droughts in the past 30 years (National Drought Mitigation Center 2013).

Thunderstorms and Tornadoes

Strong thunderstorms occur most frequently in the summer months in northern Michigan, and these weather events can be particularly damaging if they generate tornadoes. Based on long-term data from 1896 through 1995, the assessment area in Michigan averaged 25 to 35 thunderstorm days per year (Changnon 2003). There is a clear south-to-north gradient of decreasing thunderstorm frequency across the assessment area and the entire state.

An average of 17 tornadoes occurred in Michigan each year from 1981 through 2010, and tornado frequency appears to have remained stable in recent decades (National Weather Service 2012). The U.S. Annual Tornado Maps from 1950 to 2009 show that very few of these tornadoes occurred within the assessment area in northern Michigan, with only occasional occurrences in the northern Lower Peninsula and exceedingly rare tornadoes in the eastern Upper Peninsula (National Weather Service 2012). Michigan made national news in March 2012 for an unusual outbreak of tornadoes across the Lower Peninsula, setting new records for the earliest observed tornadoes across the state (Erdman 2012). These events were also some of the northernmost tornadoes ever observed for March.

Windstorms

In warm months of the year the assessment area occasionally experiences very powerful windstorms, often called derechos. These events can result in substantial windthrow disturbances. A recent example from the upper Midwest was the 1999 storm that passed through neighboring Minnesota along the Canadian border. This single storm blew down roughly 665,000 acres of forest within the Boundary Waters Canoe Area Wilderness and the Quetico Provincial Park (Price and Murphy 2002). Smaller-scale wind disturbances also introduce complexity in forest stands throughout the region (Schulte and Mladenoff 2005, White and Host 2008). The frequency of derechos decreases with increasing latitude in Michigan, and these events are quite rare in the eastern Upper Peninsula (Coniglio and Stensrud 2004). Our understanding of historical trends in derecho frequency and geographic location is limited by a lack of long-term data in the first half of the 20th century (Peterson 2000).

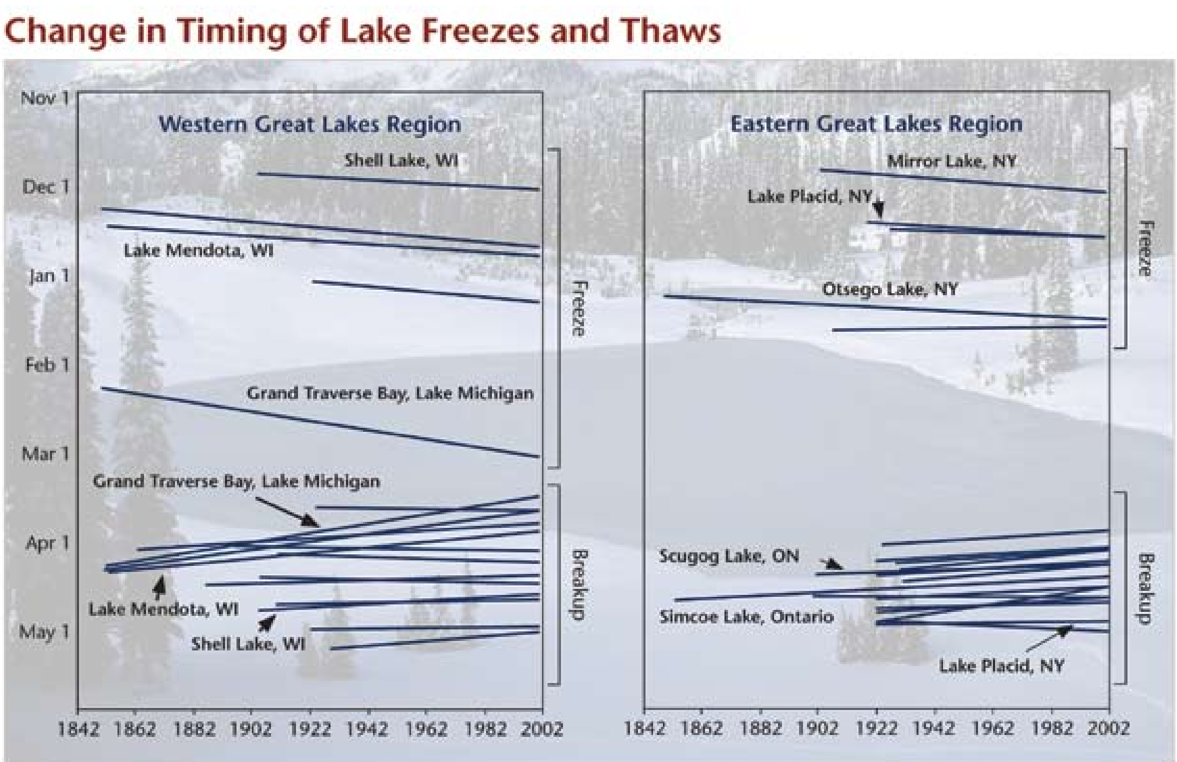
ECOLOGICAL INDICATORS OF CLIMATE CHANGE

The following case studies present some examples of early indications of climate change within northern Michigan. This list is by no means comprehensive, but is intended to highlight a few of the ways that shifts in temperature, precipitation, and other factors may be influencing natural communities in Michigan. A list of suggested resources for further reading is provided at the end of this chapter.

Lake Ice

Across Michigan and the entire Great Lakes region, long-term records have shown that lake ice is breaking up earlier in the spring and forming later in the fall (Fig. 22). The combined effect of these trends is a longer ice-free period for lakes across the region and the assessment area.

A long-term simulation of historical lake ice trends across Michigan, Minnesota, and Wisconsin



	Freeze		Breakup	
	Western Great Lakes	Eastern Great Lakes	Western Great Lakes	Eastern Great Lakes
Long term data 80 or more years lake sample=5	mean=1.2 range=0.7 to 2.5 lake sample=5	mean=0.3 range=-0.1 tp 0.6 lake sample=13	mean=0.7 range=-0.3 to 2.9 lake sample=13	mean=0.5 range=0 to 1.5
Last 2 decades	mean=3.4 range=-2.7 to 13.5 lake sample=24	mean=0.3 range=-5.4 to 5.4 lake sample=25	mean=2.8 range=-1.1 to 15.2 lake sample=38	mean=0.1 range=-3.8 to 8.4 lake sample=34

Freeze and breakup change in days per decade. Positive change indicates a later freeze date and an earlier breakup date. Negative change indicates an earlier freeze date and later breakup date.

Source: Data courtesy of T.B. Clark, J.J. Magnuson, R.A. Assel, V. Card, M. Futter, P.A. Soranno, and K.M. Stewart.

Figure 22.—Lake ice trends from across the Great Lakes region. Figure from Kling et al. (2003) and used with permission of the Union of Concerned Scientists.

estimated that breakup dates are occurring earlier and freeze dates are occurring later, both by about 1.4 days per decade (Mishra et al. 2011). The assessment area showed more gradual changes than southern portions of the state, and Michigan in particular showed more change than other states. These state and regional patterns of lake ice duration correspond with observed trends across the entire northern hemisphere (Johnson and Stefan 2006, Kling et al. 2003, Magnuson et al. 2000). Within the region of Michigan, Minnesota, and Wisconsin, observed changes in lake ice duration indicate that breakup and freeze dates have been shifting three to four times more rapidly since 1980 than over the entire 20th century (Kling et al. 2003). Therefore, the total duration of lake ice is shrinking at an accelerating rate, which long-term trends may underestimate. Ice cover on the Great Lakes is also declining substantially, with an average decrease of 71 percent in ice coverage between 1973 and 2010 (Wang et al. 2012). Reduced ice cover exposes more of the lake's surface to radiation, allowing the lake to absorb and retain more heat. Increased lake temperatures can contribute to shifts in ice formation and coverage, which can strongly influence near-shore climates and weather events, such as lake-effect snow.

Tree Phenology and Growth

Certain aspects in the annual life cycle of trees are governed by seasonal cues that are relatively constant from year to year, like day length. Other aspects are controlled by cues that can vary substantially from year to year, like temperature. For sugar maple, a common northern hardwood species across the assessment area, leaf expansion in the spring is triggered by temperature. Rather than sending out new leaves on the first warm day, sugar maples adjust the date of leaf-out based on aggregated temperature. Growing degree days, an indicator of heat accumulation above a species-specific base temperature, can be used to predict the progress of sugar maple leaf expansion and development. Leaf expansion marks the beginning of a tree's growing season, and growing season length can help dictate how much trees grow over time.

Researchers have been measuring leaf phenology and tree growth in sugar maple stands across a latitudinal gradient in northern Michigan for more than 20 years (Fig. 23) (Burton et al. 1996). Annual growing season across the gradient of study sites differs by about 3 weeks, being longer in the southern portion of the assessment area where annual temperatures are warmer by more than 5 °F (2.8 °C). Mean annual temperatures increased by 2.3 °F (1.3 °C) across the study sites from 1989 through 2009 (A.J. Burton, Michigan Technological University, unpublished data). This change had a corresponding influence on growing season length, which increased by an average of 11.5 days over the study period. The growing season seems to be shifting earlier into the spring for sugar maple, as leaf-out dates advanced more rapidly than leaf-fall dates were delayed (Fig. 24). Tree growth increased at each of the study sites in the Lower Peninsula,

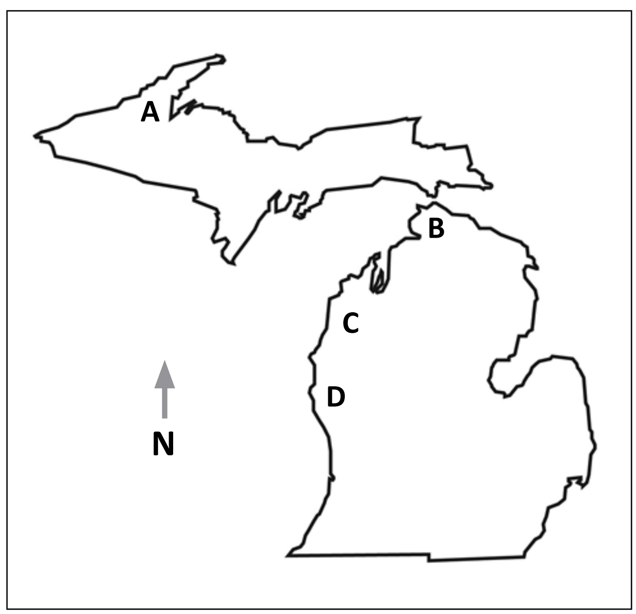


Figure 23.—Map of four long-term study sites (A, B, C, D) tracking phenology in hardwood forests in northern Michigan (Burton et al. 1996). © Canadian Science Publishing or its licensors.

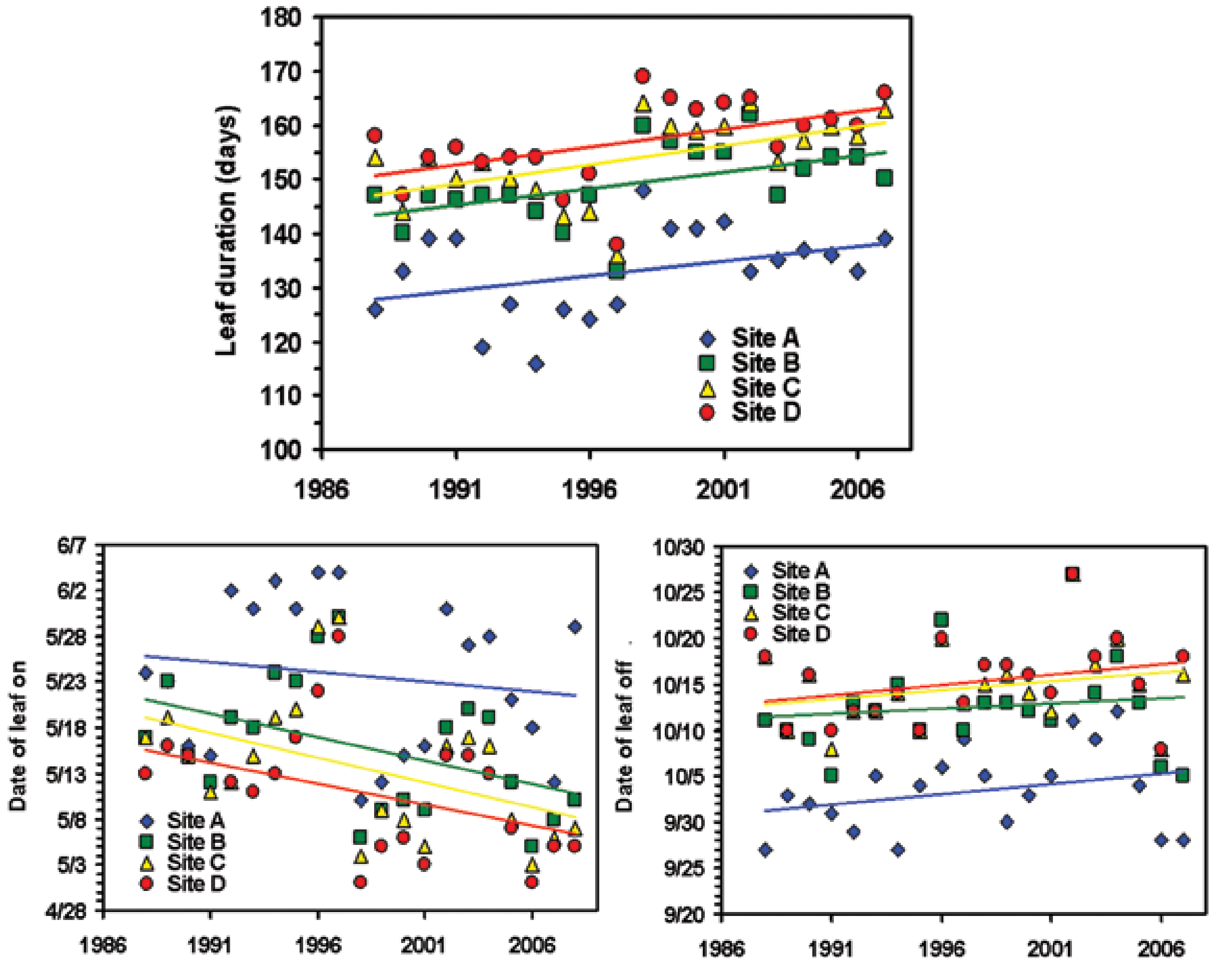


Figure 24.—Leaf phenology trends across four northern hardwood study sites in Michigan. Leaf duration is the number of days between leaf-out and leaf-drop (A.J. Burton, Michigan Technological University, unpublished data).

with an average 26-percent gain in aboveground biomass. The study site in the Upper Peninsula appears to have been limited by late-season droughts for most of the years from 2001 through 2009, and therefore sugar maple in this location was unable to take advantage of the extended growing season.

These phenology and growth trends highlight the influence that shifting temperatures can have on northern Michigan forests. This work also shows that forest productivity may be limited by moisture availability, even as temperatures rise and growing seasons lengthen.

Small Mammal Populations and Range Shifts

Changes in wildlife populations observed in northern Michigan also may be taken as further evidence of climate change. Small mammals like mice, voles, and chipmunks are important actors in forest communities. They are dispersers of seeds and fungi; prey for many animals; and consumers of seeds, eggs, and insects. Therefore, these small animals have cascading influences throughout forests they inhabit.

A study of small mammal populations across northern Michigan documented large range shifts among nine species that have northern or southern range limits within the assessment area (Myers et al. 2009). Southerly species such as white-footed mice, eastern chipmunks, southern flying squirrels, and common opossums were found to be expanding their ranges northward across the assessment area since 1980, in some cases by as much as 150 miles. Northern species such as woodland deer mice, southern red-backed voles, woodland jumping mice, least chipmunks, and northern flying squirrels declined in relative abundance across the assessment area. In many cases, the proportion of southern mammal species appears to have increased substantially during the 20th century, replacing their northern counterparts in some locations.

Similar studies have also documented a rapid northward range expansion for southern small mammals in Ontario (Garroway et al. 2011) and Minnesota (Jannett et al. 2007). The steadily warming climate across the assessment area seems to be an underlying cause for these changes in wildlife distribution and abundance. A change in small mammal populations has the potential to affect the function and composition of forest communities throughout northern Michigan.

SUMMARY

Several notable shifts have been observed in climate, climate-driven processes, and extreme weather events within the assessment area. In general, the assessment area is experiencing warmer weather across all seasons, particularly with respect to winter and summer temperatures. Precipitation has increased over the 20th century and the precipitation regime has intensified, resulting in more large precipitation events. Characteristic winter conditions are diminishing, and growing seasons have been lengthening. These trends are consistent with regional, national, and global observations related to anthropogenic climate change. Ecological indicators are beginning to reflect these changes as well, as evidenced by changing ranges of wildlife species and changing phenology. For more information on observed climate trends, see the resources suggested in Box 7.

Box 7: More Information on Observed Climate Trends and Ecological Indicators

Much more information on historical climate trends and ecological indicators for northern Michigan exists than was possible to present in this chapter. Interested readers will be able to find more information from the following resources:

- Michigan State Climatology Office: climate.geo.msu.edu/
- Michigan Department of Environmental Quality "Climate Change and Global Warming" Web page: www.michigan.gov/deq/0,4561,7-135-50990--,00.html
- National Phenology Network: www.usanpn.org/
- ClimateWizard: www.climatewizard.org/
- Great Lakes Integrated Science and Assessments Center: glisa.msu.edu/
- National Climatic Data Center: www.ncdc.noaa.gov/

CHAPTER 4: PROJECTED CHANGES IN CLIMATE, EXTREMES, AND PHYSICAL PROCESSES

This chapter describes climate projections for the assessment area over the 21st century, including projections related to patterns of extreme weather events and other climate-related processes. Temperature and precipitation projections are derived from downscaled climate models. Chapter 2 more fully describes the models, data sources, and methods used to generate these downscaled projections, as well as the inherent uncertainty in making long-term projections. We focus on two plausible climate scenarios for the assessment area, chosen to bracket a range of possible climate futures. Information related to future weather extremes and other impacts is drawn from published research.

PROJECTED TRENDS IN TEMPERATURE AND PRECIPITATION

To represent the range of plausible climate futures in the assessment area, we report projected changes in temperature and precipitation for three 30-year periods during the next century (2010 through 2039, 2040 through 2069, 2070 through 2099) (Hayhoe 2010a, Stoner et al. 2013). For each of these periods, we calculated the average mean, maximum, and minimum temperature for each season and across the entire year. We also calculated mean annual and seasonal precipitation for the same periods. We use the 1971 through 2000 average as a contemporary "baseline" to determine future departure from current climate conditions. Observed climate data for the baseline period are from ClimateWizard (Girvetz et al. 2009), based on the PRISM dataset (see Chapter 3 and Appendix 2).

For all climate projections, we report values for two general circulation model (GCM)-emissions scenario combinations: GFDL A1FI and PCM B1 (see Chapter 2). The GFDL A1FI model-scenario combination projects greater changes in terms of future temperature increases and precipitation decreases, and PCM B1 projects less change. Although both projections are plausible, GFDL A1FI may be more realistic based on our current global greenhouse gas emissions trajectory (Raupach et al. 2007). The future will probably be different from any of the developed scenarios, so we encourage readers to consider the range of possible climate conditions over the coming decades rather than one particular scenario.

Temperature

The assessment area in Michigan is projected to warm substantially during the 21st century (Figs. 25 through 28). Compared to the 1971 through 2000 baseline period, the average annual temperature is projected to increase 2.2 °F (1.2 °C) under the PCM B1scenario and 8.1 °F (4.5 °C) under the GFDL A1FI scenario by the end of the century. The projected temperature increase is not consistent across all seasons. Both models project that winter months (December through February) will show dramatic warming by the end of the century (PCM B1: 2.5 °F, 1.4 °C; GFDL A1FI: 7.3 °F, 4.1 °C), but spring months (March through May) will experience less warming (PCM B1: 1.7 °F, 0.9 °C; GFDL A1FI: 6.0 °F, 3.3 °C). The GFDL A1FI scenario also projects an increase of 11.2 °F (6.2 °C) in summer temperatures by the end of the century. Summer warming is much milder under PCM B1 (2.2 °F, 1.2 °C). See Appendix 3 for a table of temperature projections for the assessment area, as well as maps of projected change in the early century (2010 through 2039) and mid-century (2040 through 2069).

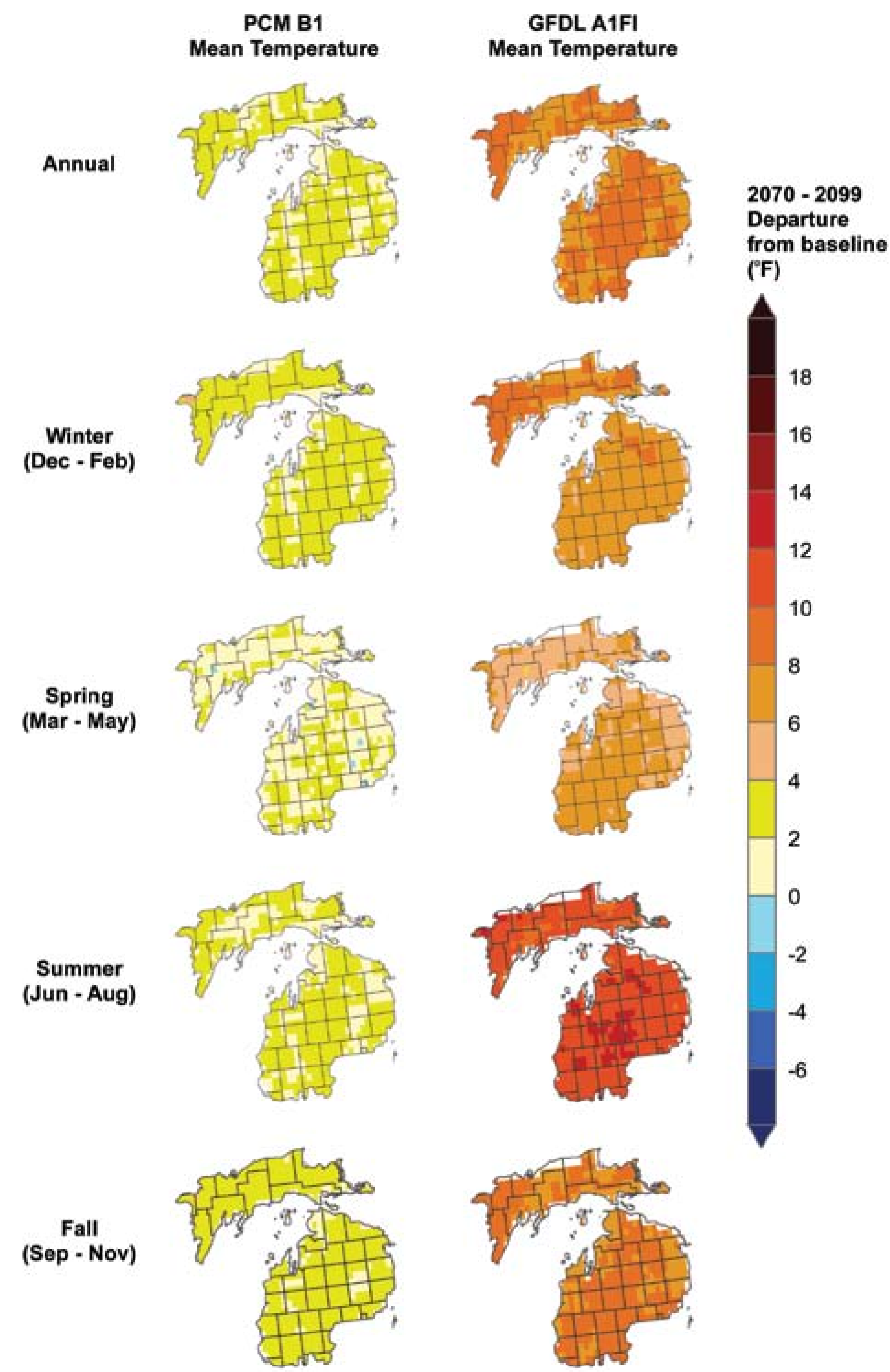


Figure 25.—Projected difference in mean daily temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

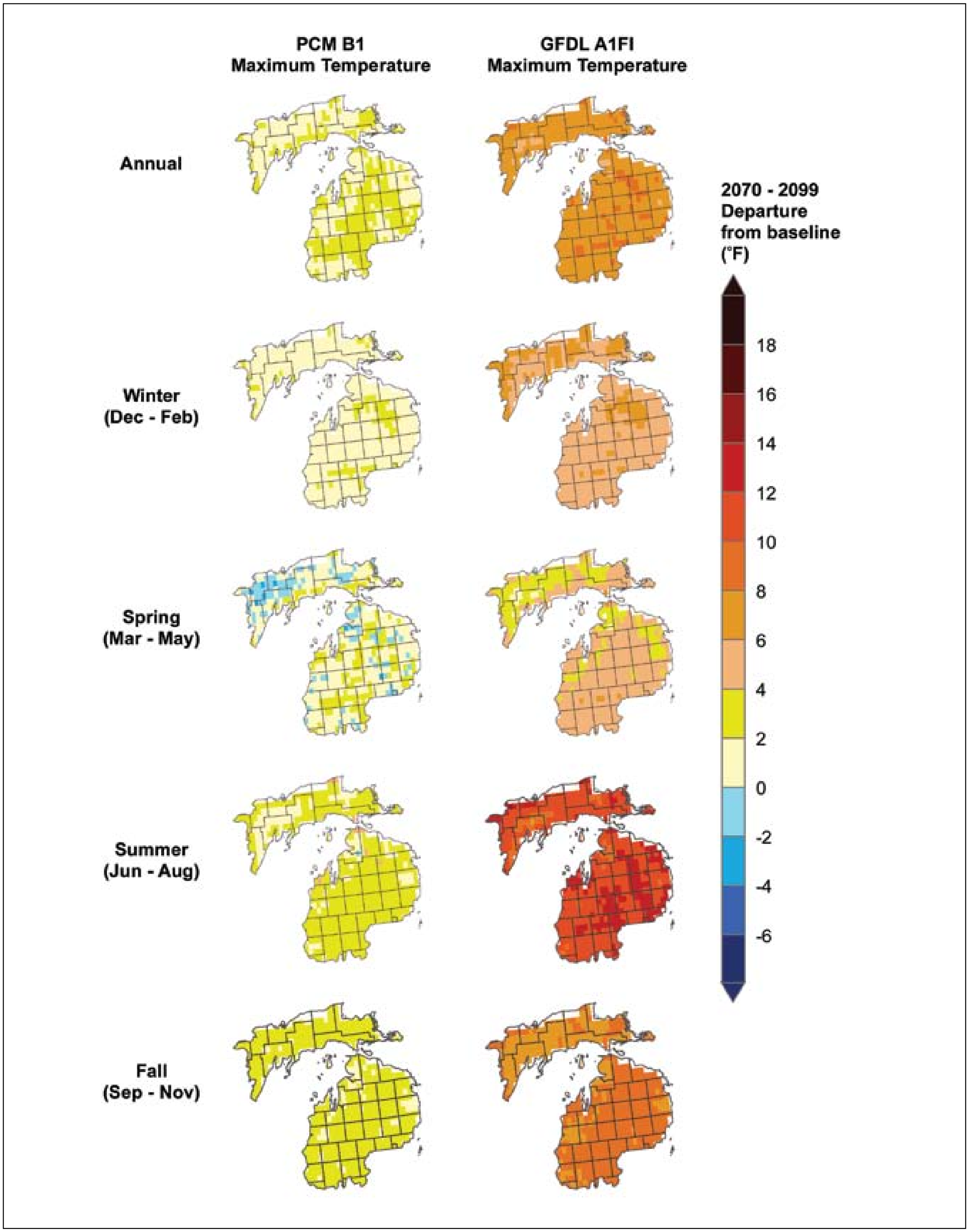


Figure 26.—Projected difference in mean daily maximum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

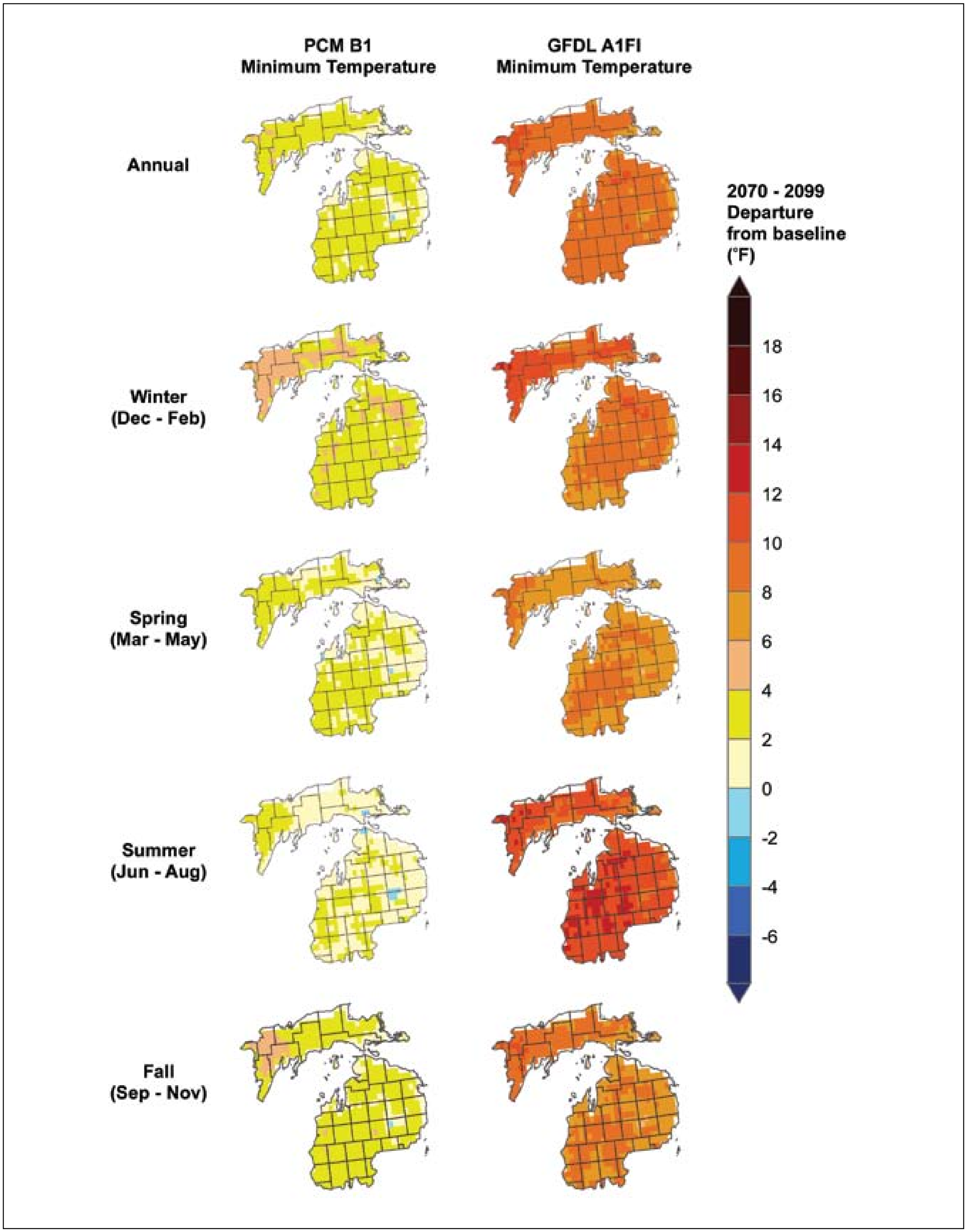


Figure 27.—Projected difference in mean daily minimum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

Minimum temperatures are projected to increase more than maximum temperatures under both scenarios across nearly all seasons. Summer is the exception to this trend, with maximum temperature increases projected to be slightly greater than the projected increases in minimum temperatures under both scenarios. By the end of the century, winter minimum temperatures are expected to increase 3.5 °F (1.9 °C) under PCM B1 and 9.0 °F (5.0 °C) under GFDL A1FI.

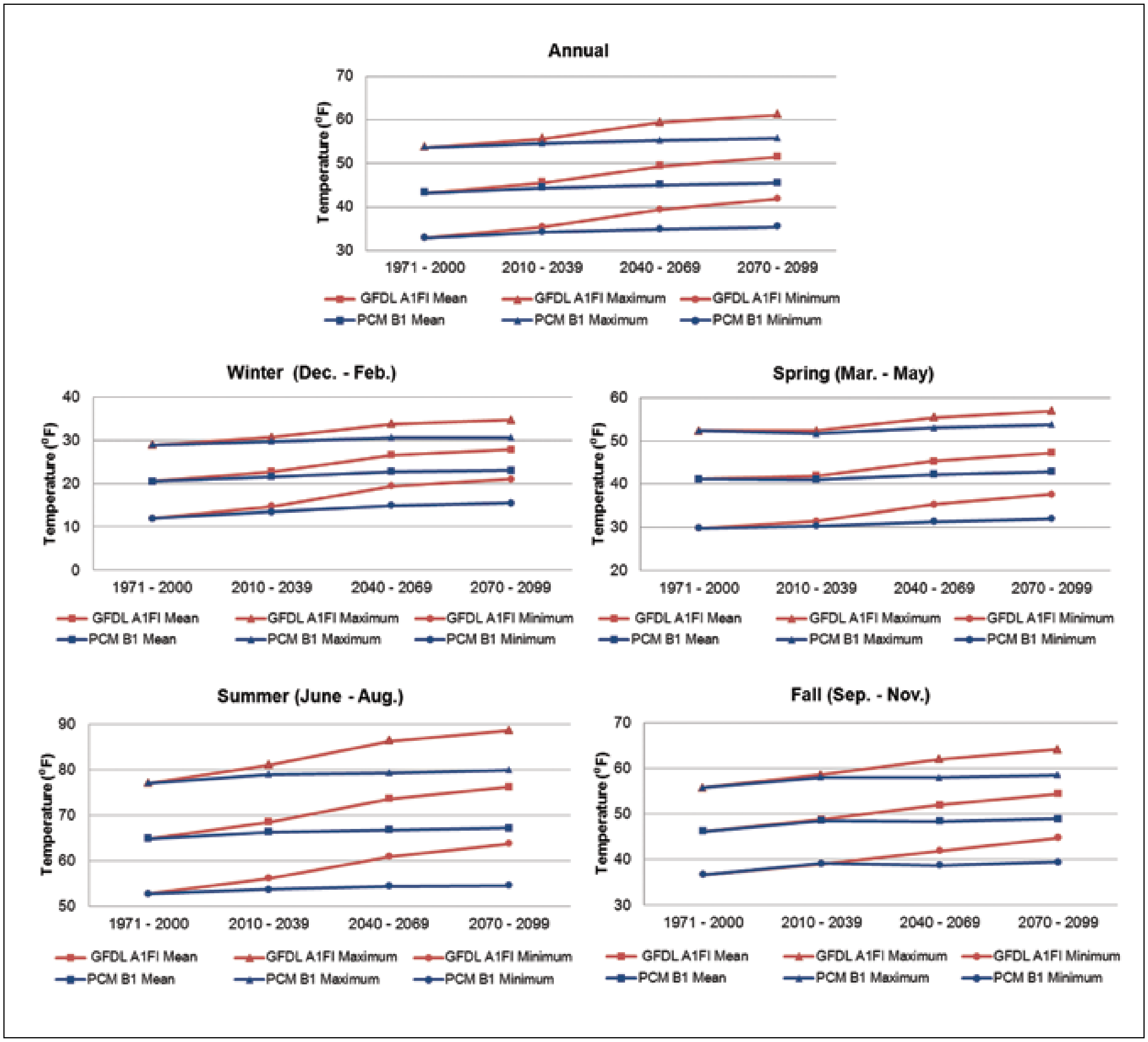


Figure 28.—Projected mean, maximum, and minimum temperatures (°F) in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 through 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values.

Temperature increases are projected to be relatively minor between the 1971 through 2000 baseline period and the 2010 through 2039 period (Fig. 28). Spring, in particular, is projected to show short-term decreases under both scenarios for average and maximum mean temperatures. These initial decreases are generally reversed by mid-century. Additionally, the projections under the two future scenarios do not diverge substantially until mid-century. The GFDL A1FI scenario leads to much larger temperature increases, with the greatest amount of change expected to occur mid-century. Alternatively, PCM B1 projections indicate a substantially smaller increase in temperature, with relatively constant increases during the 21st century.

Interesting spatial patterns occur within the future temperature projections across the assessment area (Figs. 25 through 27). Projections of mean temperature change are relatively consistent across the assessment area under both scenarios. The central Upper Peninsula, near the western boundary of the assessment area is projected to show reduced spring maximum temperatures by about 2 °F (1.1 °C) compared to the surrounding area under PCM B1. This regional difference does not appear in the GFDL A1FI projections. Compared to the assessment area as a whole, this area is also expected to experience larger minimum temperature increases across all seasons. In the northern Lower Peninsula, minimum temperatures are generally projected to increase more rapidly in the interior areas compared to the coastal areas.

Although the two climate scenarios project different amounts of warming, they are in agreement that mean, maximum, and minimum temperatures will increase in the assessment area across all seasons. The two models display the most difference for summer months, with the PCM B1 scenario projecting very little warming and the GFDL A1F1 scenario projecting most of the assessment area will warm between 10 and 12 °F (5.6 and 6.7 °C).

Precipitation

The two climate scenarios we chose for this assessment describe a range of future precipitation for the assessment area (Figs. 29 and 30), but it is important to keep in mind that other GCM and emissions scenario combinations could project values outside of this range. Substantial differences exist among projections of precipitation across the Midwest (Kunkel et al. 2013, Winkler et al. 2012). For the assessment area in Michigan, the PCM B1 scenario projects that the assessment area will receive 2.7 inches more annual precipitation at the end of the next century compared to the baseline years of 1971 through 2000. The GFDL A1F1 scenario projects an annual precipitation increase of around 1 inch for this same period. See Appendix 3 for a table of precipitation projections for the assessment area, as well as maps of projected change in the early century and mid-century.

The seasonal precipitation trends show even more departure between the two scenarios. In particular, most of the difference between these two climate scenarios exists in spring and summer. Under the PCM B1 scenario, spring months are projected to receive 0.8 inches more precipitation over the 21st century, with all of the increase coming by mid-century. Summer precipitation under this scenario is projected to increase around 1 inch by mid-century. The GFDL A1FI scenario projects a much sharper distinction between these seasons, with spring precipitation gaining 2.7 inches and summer precipitation declining by 3.8 inches. Those projections represent a 37-percent increase from baseline spring precipitation, followed by a 39-percent decrease from baseline summer precipitation. Winter precipitation is expected to increase slightly for both scenarios. Fall precipitation is expected to decline slightly by the end of the century under the PCM B1 scenario (-0.3 inches), and fluctuate during the century under GFDL A1FI.

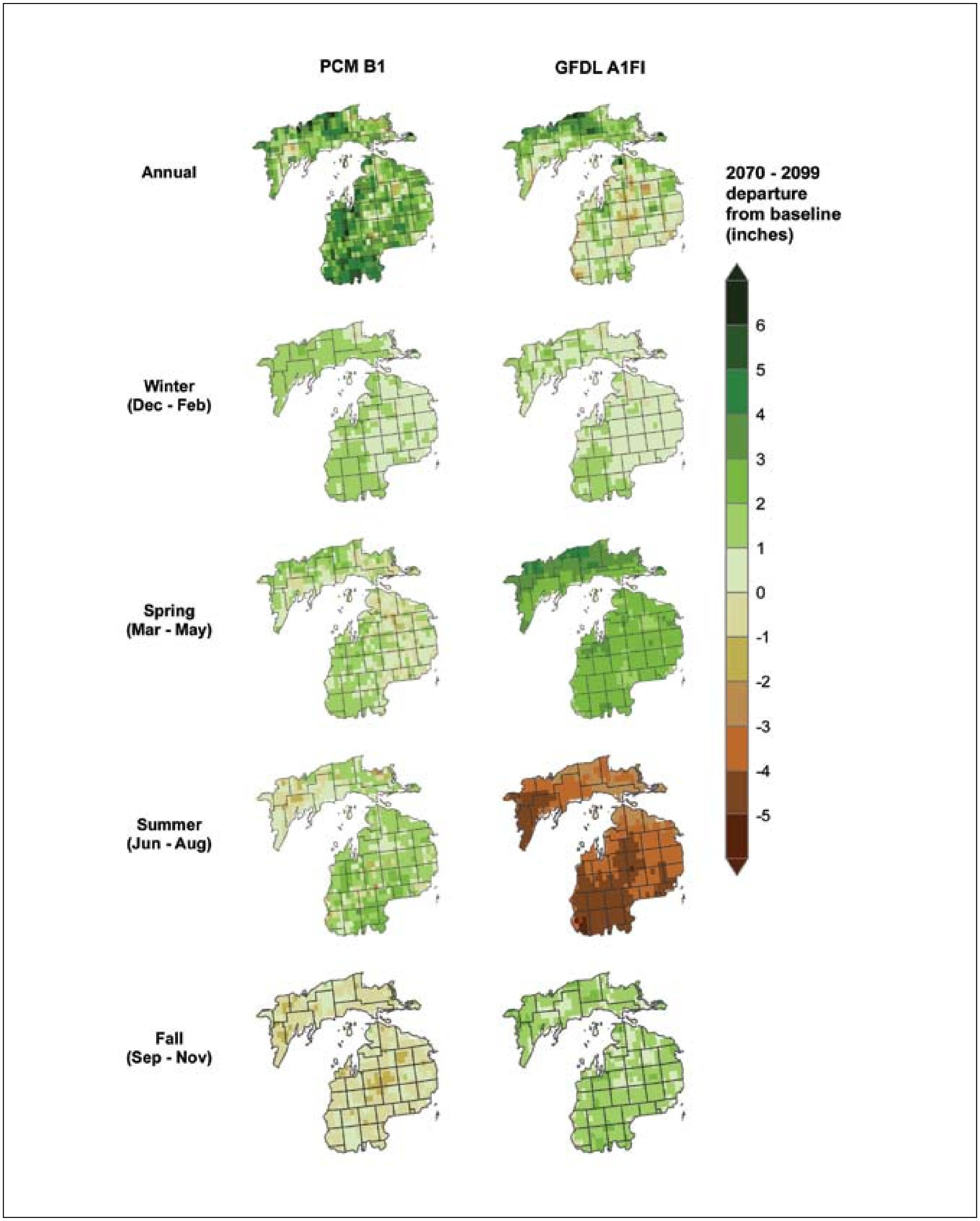


Figure 29.—Projected difference in mean precipitation (inches) at the end of the century (2070 through 2099) compared to baseline (1971 to 2000) for two climate scenarios.

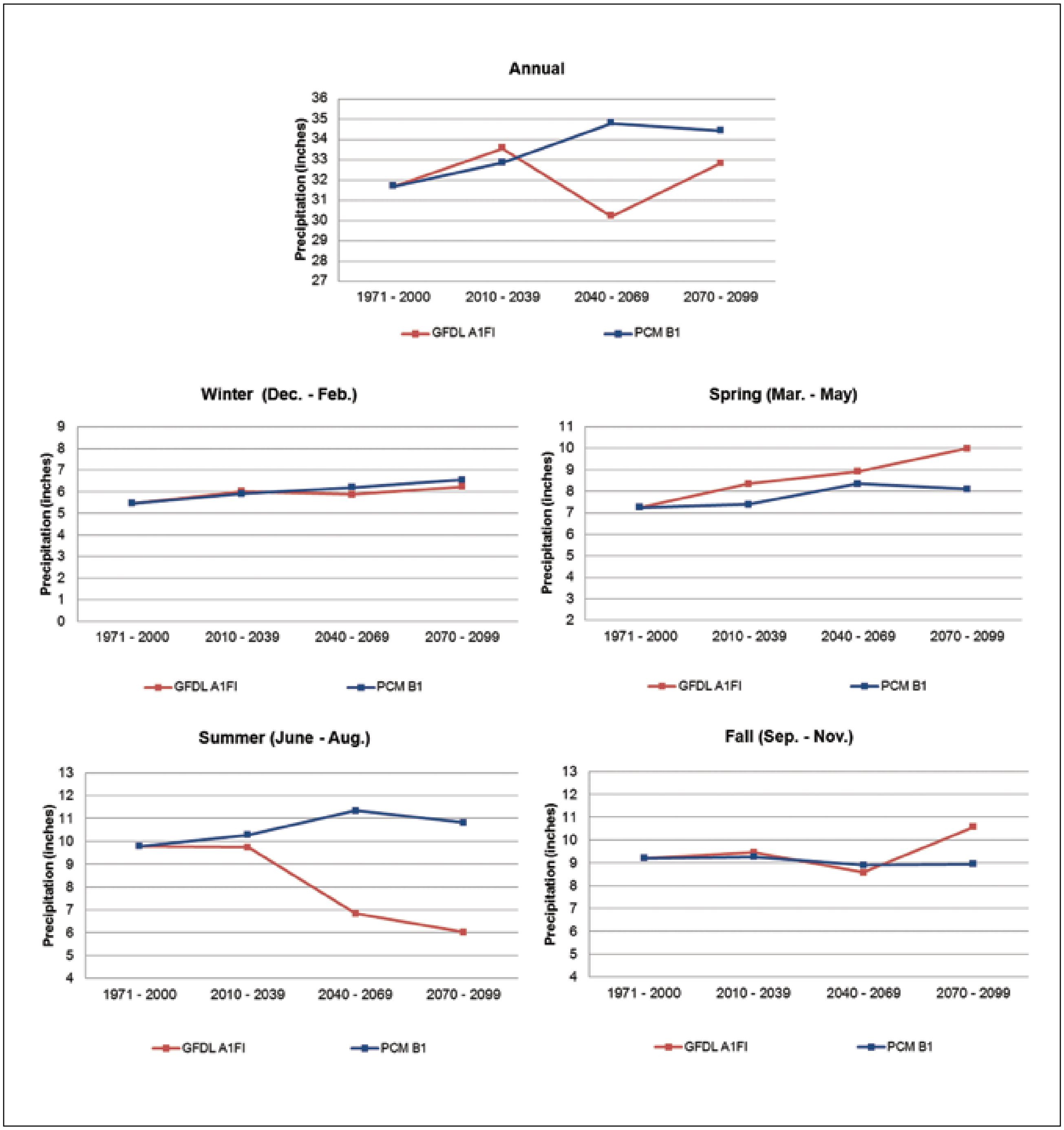


Figure 30.—Projected trends in average precipitation (inches) in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 through 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values.

Similar to the future temperature projections, precipitation across the assessment area is expected to change only slightly between the baseline period and the early century. The greatest change in precipitation projections under GFDL A1FI occur mid-century, driven by a 3-inch decline in summer precipitation. The PCM B1 scenario also shows larger changes by mid-century than by the end of the century, as precipitation in spring increases by 1.0 inches and in summer by 1.5 inches.

The projected shifts in precipitation are not distributed evenly across the assessment area (Fig. 29). The PCM B1 scenario projects that precipitation increases will occur mostly in the western half of the northern Lower Peninsula, and that these increases will be delivered across winter, spring, and summer. The central Upper Peninsula is expected to decline in precipitation during summer, and the eastern Lower Peninsula is projected to receive less rainfall during spring. Precipitation declines in fall are widespread across the assessment area under PCM B1. The spatial patterns of projected precipitation are more even across the assessment area under GFDL A1FI (Fig. 29). Winter, spring, and fall increases are distributed evenly across the assessment area. During summer months, the central Upper Peninsula and southern and central Lower Peninsula are projected to have the most severe precipitation decreases (4 to 6 inches). The maps of precipitation departure from baseline conditions for the GFDL A1FI scenario also highlight the sharp contrast between projected spring increases and summer decreases.

Evapotranspiration and Precipitation Ratios

Temperature and precipitation values are both important climatic factors governing forest ecosystems, and it is projected that both will continue to change within the assessment area over the century. A given amount of change in temperature or precipitation may be ecologically significant, but it is difficult to know how changes in one value might buffer or amplify changes in the other. For example, a given increase in temperature may not result in significant ecological change if precipitation also increases, but the same increase in temperature could result in a severe change if accompanied by reduced precipitation. As temperatures increase, the atmosphere is able to hold larger quantities of water, which causes evaporation and transpiration to increase. Increasing evaporation and transpiration both lead to drier soils and vegetation (Drever et al. 2009). Therefore, precipitation generally needs to increase significantly to compensate for even moderate temperature increases. One way to examine the potential interaction between temperature and precipitation shifts is to consider changes in the ratio of evapotranspiration (ET) to precipitation (P). This ratio, ET:P, is essentially a metric to describe how completely a forest is using the available water. Changes in this ratio indicate whether a forest is experiencing relatively drier or wetter conditions.

We used the ecosystem model PnET-CN to calculate projected changes in ET:P for the assessment area, comparing the 1971 through 2000 baseline period to the years 2070 through 2099. Evapotranspiration is an output of PnET-CN, so these values also incorporate projected changes in forest productivity due to changes in temperature and precipitation, growing season length, CO_2 fertilization, and other factors. Chapter 2 more fully describes the PnET-CN model, and further results from this model are presented in Chapter 5. Figure 31 displays the projected annual and seasonal changes in ET:P for both PCM B1 and GFDL A1FI. Positive values indicate that ET is increasing relative to available moisture and that forests would be undergoing more moisture stress. Conversely, negative values indicate that more moisture is available. It is important to note that PnET-CN projects major water savings under elevated CO_2, which is an area of considerable uncertainty.

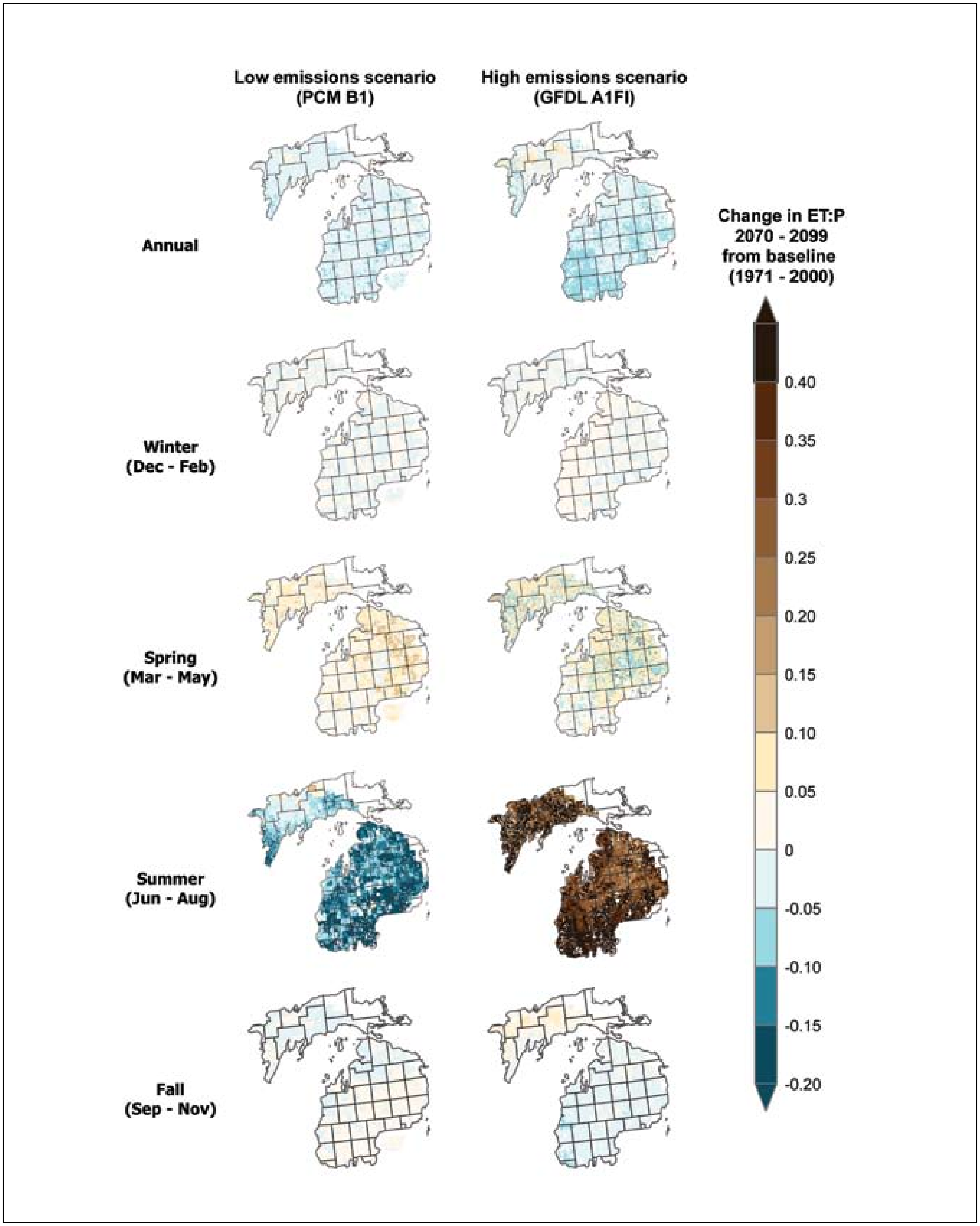


Figure 31.—Projected changes in the ratio of evapotranspiration to precipitation (ET:P) under two future climate scenarios for the assessment area over the next century. Data from Stoner et al. (2013) and Peters et al. (2013). Positive values indicate that ET is increasing relative to available moisture and that forests would be experiencing more moisture stress. Negative values indicate that more moisture is available.

Both scenarios project slightly wetter total annual conditions (decrease in annual ET:P) across the entire assessment area by the end of the century, indicating greater water availability to forests. Spring values are mixed across the assessment area under both scenarios, with drier conditions projected under PCM B1 (increasing ET:P) and more pronounced moisture increases under GFDL A1FI (decreasing ET:P). Summer months display the largest departure between the two projected scenarios, with PCM B1 projecting slightly wetter conditions (slightly decreasing ET:P) and GFDL A1FI projecting much drier conditions (large increase in ET:P). This overall trend is consistent with the precipitation trends discussed above.

The ET:P values highlight that the GFDL A1FI scenario may result in a much higher degree of moisture stress in summer months than indicated by precipitation values alone. The projected increase in summer temperatures of 11.2 °F (6.2 °C) results in higher evapotranspiration for forests across the assessment area, which essentially intensifies the projected precipitation decline. There is high spatial variation for spring months under this scenario, but the overall ET:P ratio for spring is also slightly positive under GFDL A1FI. This result means that in some areas evapotranspiration increases may outweigh the projected precipitation increase.

Additionally, forests across the assessment area are projected to be more moisture limited (increasing ET:P) in spring months under PCM B1, despite projected increases in precipitation. This outcome indicates that productivity increases and longer growing seasons could lead to increases in ET that outpace the projected increases in precipitation. This pattern is strongest in the eastern Lower Peninsula and central Upper Peninsula.

As mentioned above, ET:P values projected by PnET-CN include the effects of CO_2 fertilization, which results in significantly higher water-use efficiency and lower evapotranspiration for forest communities (Ollinger et al. 2002). Projections not including the effects of higher atmospheric CO_2 concentrations resulted in substantially higher ET:P ratios for the assessment area during the growing season (not shown). These results suggest that forests could have more frequent and extreme moisture stress in the future if water-use efficiency benefits from CO_2 fertilization are less significant than modeled by PnET-CN. Chapter 5 includes more information on the potential for CO_2 fertilization to influence forest productivity and water-use efficiency.

PROJECTED CHANGES IN EXTREMES AND PHYSICAL PROCESSES

Mean temperature, precipitation, and ET:P ratios are not the only climatic factors that are important for regulating forest ecosystems. Other examples include extreme weather events, soil frost, and snowfall. Extremes are by their very nature difficult to forecast and model reliably, and climate-mediated processes often involve several interacting factors. Nevertheless, the scientific community is developing a clearer sense of how climate change may alter some of these weather events and physical processes (Kunkel et al. 2013). Below, we present a summary of current evidence on how climate change may affect other climate-related factors in the assessment area.

Snow and Freezing Rain

Studies have shown that across much of the Midwest, an increasing percentage of winter precipitation is being delivered as rain rather than snow (Feng and Hu 2007, Notaro et al. 2011). This shift from snowfall to rainfall is strongly correlated with winter wet-day temperatures. As winter temperatures increase across the assessment area, it is projected that more winter precipitation in northern Michigan will also be delivered as rain (Sinha and Cherkauer 2010). Total snow water equivalent (the amount of water contained in the snowpack) is projected to decrease between 40 and 80 percent by the end of the century under a range of climate scenarios (Sinha and Cherkauer 2010).

A study of neighboring Wisconsin presents several projected snowfall trends that may be applicable to the assessment area (Notaro et al. 2011). Researchers anticipate snowfall across Wisconsin to decline 31 percent under a low climate scenario and 47 percent under a high climate scenario by the end of the century. The largest reductions occurred in the early and late portions of the snow season, in November, March, and April. Under the same range of climate projections, the frequency of snowfall days is expected to decline between 41 and 54 percent. Finally, snow depth throughout the winter is expected to decline even more than snowfall amounts, because snow depth will also be reduced by warm temperatures between snowfall events.

Areas that typically receive lake-effect snow may receive increased snow during the early part of the 21st century while winter temperatures remain cold enough and ice cover on the Great Lakes continues to decrease (Burnett et al. 2003, Wright et al. 2013). As temperatures continue to warm through the 21st century, the potential exists for increasingly warm winter temperatures to negate the effect of decreased lake ice, leading to lake-effect rain events (Kunkel et al. 2002).

Additionally, modeling studies have projected that climate change will result in less frequent freezing rain events across the assessment area (Lambert and Hansen 2011). The projected decreases were slight (2.5 to 10 fewer events per decade over the 21st century), but this trend corresponds with the projected increase in wintertime temperatures and the overall shift from snowfall to rain.

Shifts in winter precipitation and temperature will generally advance the timing of snowmelt runoff earlier into the year. The ability of soils to absorb this moisture will depend on infiltration rates and the soil frost regime. If soils are able to absorb and retain more of this moisture, soil moisture could be higher at the outset of the growing season. If this moisture is instead lost to runoff, forests in the assessment area could enter the growing season with a moisture deficit.

Soil Frost

Winter temperatures are projected to increase across the assessment area under both PCM B1 and GFDL A1FI, which would be expected to increase soil temperatures. Snow cover typically insulates forest soils, however, so reduced snowpack under climate change could also leave the soil surface more exposed to fluctuations in air temperature and result in deeper soil frost (Isard et al. 2007). A study that attempted to integrate these opposing trends found that cold-season soil temperatures may increase between 1.8 and 5.4 °F (1 and 3 °C) and that there would be approximately 30 to 50 fewer soil frost days per winter on average across the assessment area by the end of the 21st century (Sinha and Cherkauer 2010). The projected trends for soil frost across the region are shown in Figure 32. Total frost depth is projected to decline by 40 to 80 percent across the assessment area. Therefore, it appears that warmer winter air temperatures may more than counteract the loss of snow insulation, and that soil frost will generally be reduced across the assessment area. The northern Lower Peninsula is also projected to have two to three more freeze-thaw cycles per winter by the end of the century (Sinha and Cherkauer 2010). These projections are generally consistent with studies of snowpack and soil frost in New England forests (Campbell et al. 2010).

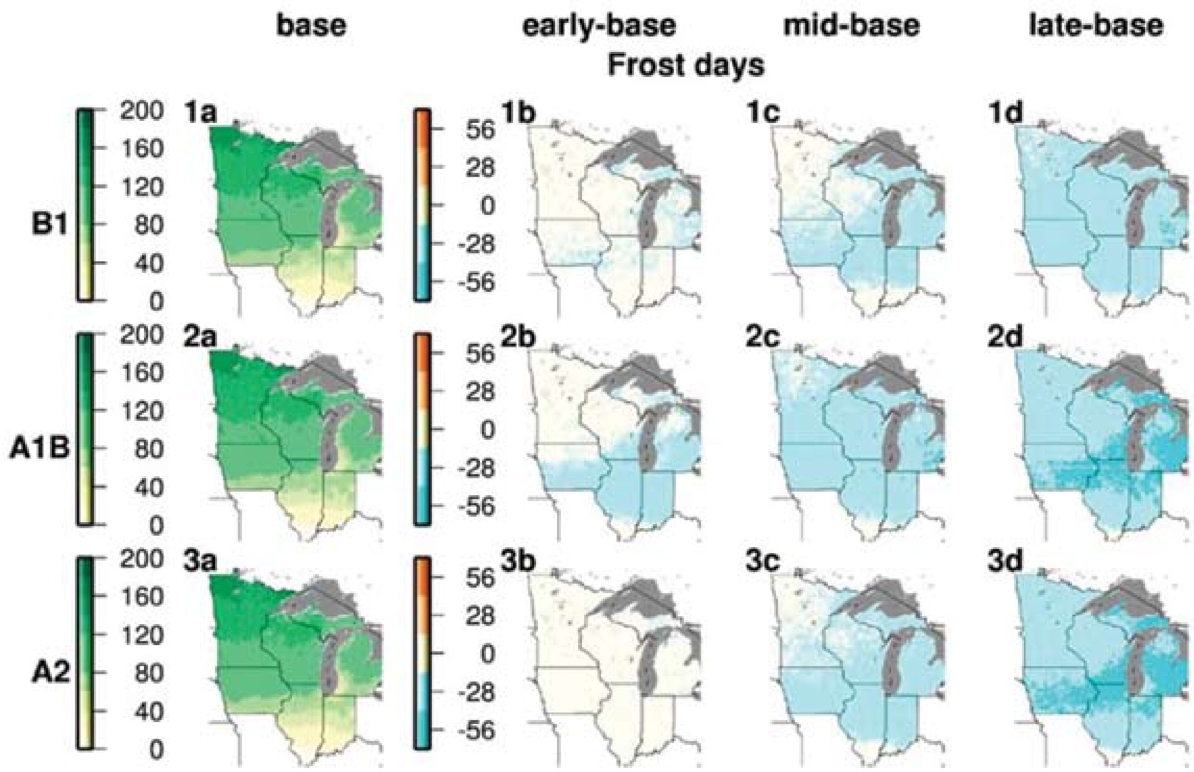


Figure 32.—Baseline and projected number of annual soil frost days for the Midwest under a range of climate scenarios, from Sinha and Cherkauer (2010). Base refers to the average annual number of soil frost days, 1977 through 2006. Early-base, mid-base, and late-base refer to the difference in mean soil frost days from the baseline period for 2010 through 2039, 2040 through 2069, and 2070 through 2099. The A2 emissions scenario is roughly equivalent to the A1FI scenario in terms of greenhouse gas emissions, and the A1B scenario is approximately a middle range between A1FI and B1.

Growing Season Length

The growing season has shifted in the assessment area during the past century, as noted in Chapter 3. Growing seasons are dictated by a variety of factors, including day length, air temperatures, soil temperatures, and dates of first and last frost (Linderholm 2006). Therefore, a variety of metrics can describe how growing seasons may continue to change under a range of climate scenarios. A study covering the entire Midwest examined the changes in dates for the last spring frost and first fall frost under a range of climate scenarios (Wuebbles and Hayhoe 2004). This study projected that the growing season will be extended by 30 days under the B1 emissions scenario and 70 days under the A1FI scenario by the end of the century (Fig. 33). The last spring frost dates are projected to shift earlier into the year at approximately the same rate that first fall frost dates will retreat later into the year. Another study across the Midwest region projected that the assessment area in Michigan will have 22 to 25 fewer frost days by the middle of the 21st century, under the A2 emissions scenario (Kunkel et al. 2013). The A2 emissions scenario is comparable to the A1FI scenario presented in this chapter, although it has a more gradual emissions increase through the 21st century (Chapter 2).

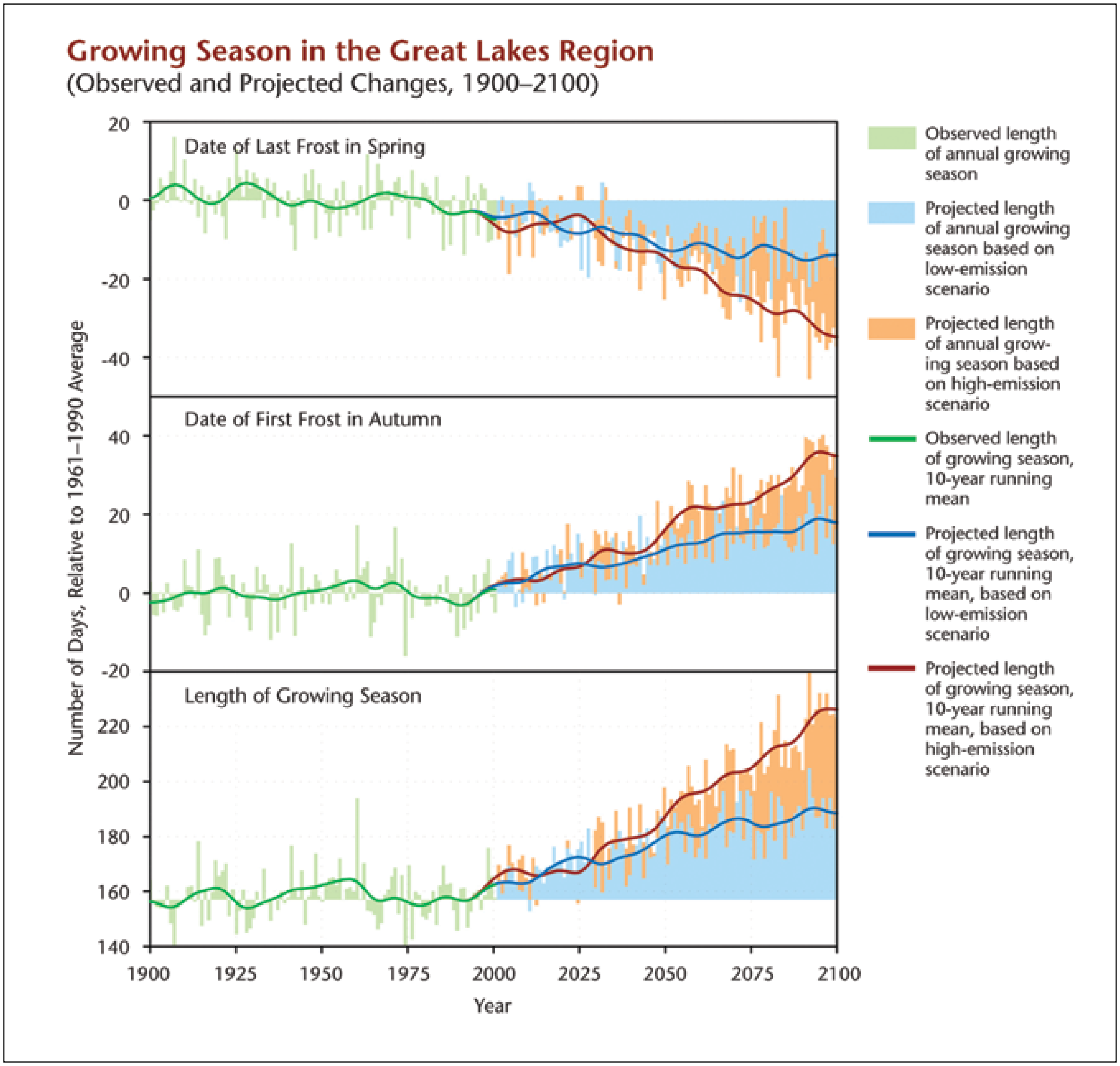


Figure 33.—Changes in length of frost-free season and dates of last spring and first autumn frost over the Midwest states. Historical data on the frost-free season are shown from 1900 through 2000, based on observed data. Projections from 2001 through 2099 are shown in orange for the higher A1FI scenario and blue for the lower B1 scenario. Bars show year-to-year variability and solid lines indicate 10-year running means. From Kling et al. (2003), modified from Wuebbles and Hayhoe (2004), and reprinted with the permission of the authors.

As the climatic growing season changes, not all species will track these changes equally with their own phenology. For example, if native tree species are adapted to respond to day length changes at their particular latitude for leaf-drop in the fall, they may not be able to extend their growing seasons later in the year. If invasive species or southern migrants are adapted to a different day length regime or to frost dates, they may be more able to take advantage of the longer climatic growing season.

Intense Precipitation

As described in Chapter 3, there is a clear trend toward more extreme precipitation events in Michigan and throughout the Midwest (Kunkel et al. 2008, Saunders et al. 2012). Rainfall from these high-intensity events is representing a larger proportion of the total annual and seasonal rainfall, meaning that the precipitation regime is becoming more episodic. An assessment covering the entire Great Lakes region projected that the frequency of single-day and multi-day heavy rainfall events could double by 2100 (Kling et al. 2003). More recent assessments across a combination of climate projections suggest that the Midwest will experience 23 percent more rainfall events of at least 1 inch by 2100, with larger events increasing by progressively larger amounts (Kunkel et al. 2013). Other future climate projections indicate that the assessment area may have 2 to 4 more days of extreme precipitation (95th percentile or greater) by the end of the century (Diffenbaugh et al. 2005).

It is important to consider this trend in combination with the projected increases or decreases in mean precipitation over the 21st century. A given increase or decrease in precipitation may not be distributed evenly across a season or even a month. Additionally, large-scale modeling efforts have suggested that climate change will increase the year-to-year variation of precipitation across the northern United States (Boer 2009). Therefore, the assessment area may have more extreme wet and dry years in the future. Further, ecological systems are not all equally capable of holding moisture that comes in the form of extreme events. Areas with shallow soils may not have the water holding capacity to retain moisture received in intense rainstorms, and areas with fine-textured soils might not have fast enough infiltration rates to absorb water from these kinds of storms. Therefore if rainfall becomes more episodic, these areas may suffer from additional drought stress even if overall moisture or precipitation increases. Landscape position will also influence the ability of a particular location to retain moisture from extreme events.

Flooding and Streamflow

High-intensity rainfall events are linked to both flash flooding and widespread floods, depending on soil saturation and stream levels at the time of the event. As noted in Chapter 3, there has been a trend toward more frequent flooding in river systems across the Midwest. A modeling study examining climate change effects on streamflow across the Midwest projected that runoff and streamflow may shift substantially across the assessment area in Michigan (Cherkauer and Sinha 2010). Researchers project that total winter runoff values may increase by more than 100 percent across the assessment area by the end of the 21st century, with the most dramatic increases occurring in the eastern Upper Peninsula as a result of winter melt events and winter rain (Fig. 34). Spring total runoff is also projected to increase across a range of climate scenarios, and fall total runoff is projected to decline by 8 to 32 percent across the assessment area. Additionally, summer low flow levels may decrease even further, summer high flows may increase, and overall flashiness may increase in summer (Cherkauer and Sinha 2010).

Temperature Extremes

In addition to projecting mean temperatures, downscaled daily climate data can also be used to estimate the frequency of extreme high and low temperatures in the future. Studies from across the Midwest point to an increasing frequency of hot days across the assessment area, with roughly 20-30 more days per year above 95 °F (35 °C) and a greater frequency of multi-day heat waves by the end of the century (Diffenbaugh et al. 2005, Perera et al. 2012, Winkler et al. 2012). Downscaled climate scenarios also project that the Midwest will experience between 25 and 38 fewer days below

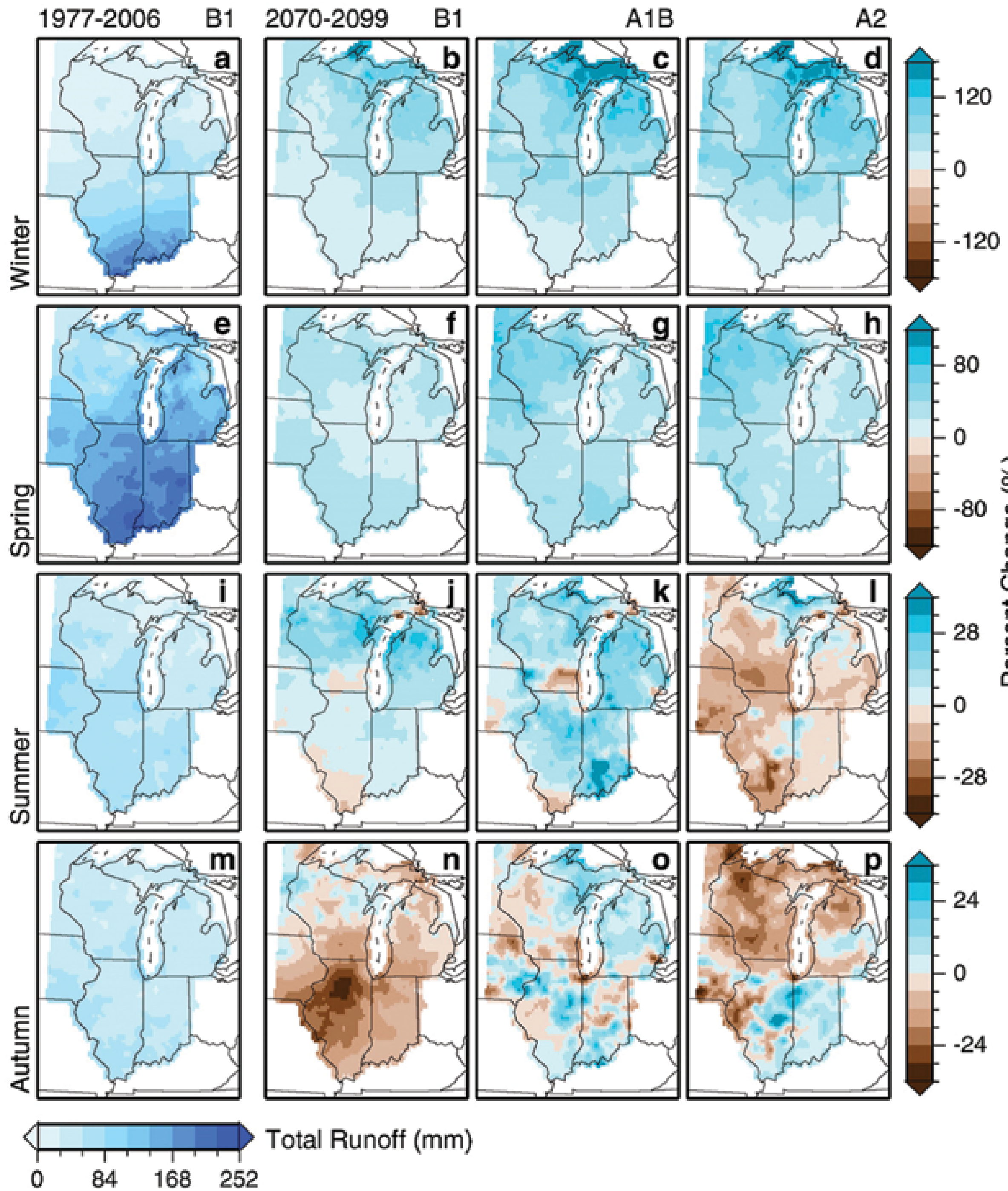


Figure 34.—Past (1977 to 2006) seasonal cumulative runoff values and projected (2070 through 2099) changes (percent) under a range of climate scenarios (Cherkauer and Sinha 2010). The A2 emissions scenario is roughly equivalent to the A1FI scenario in terms of greenhouse gas emissions, and the A1B scenario is approximately a middle range between A1FI and B1.

freezing by the end of the 21st century (Sinha and Cherkauer 2010), and 12 to 15 fewer days that are colder than the current 95th percentile cold event (Diffenbaugh et al. 2005). These trends are consistent with another assessment covering the entire Midwest, which projected that northern Michigan could have up to 10 more days above 95 °F (35 °C) and 15 to 25 fewer days below 10 °F (-12 °C) by the middle of the 21st century (Kunkel et al. 2013).

Thunderstorms and Windstorms

An increasing frequency of strong convective storms has been observed across the entire Midwest in recent decades (Changnon 2011a, 2011b; Diffenbaugh et al. 2008). Modeling studies indicate that there will be more days with weather conditions that support severe thunderstorms in the assessment area, particularly in summer months (Trapp et al. 2007). This pattern is primarily due to an increase in atmospheric water vapor during summer months. Modeling studies also suggest that weather conditions in the upper Midwest could lead to more storms that result in extreme rainfall but without strong convective winds (Trapp et al. 2007). This concept is supported by other research that forecasts a decrease in the frequency of severe tornadoes across Minnesota, Wisconsin, and Michigan (Lee 2012). The timing of tornado season may continue to shift under future conditions, and tornadoes may occur farther north in areas where they have historically been uncommon.

As mentioned in Chapter 3, a general lack of long-term data on straight-line wind storms limits our understanding of the trends for these events (Peterson 2000). Straight-line wind storms are prompted by different conditions than convective storms such as thunderstorms and tornadoes. There is a great deal of inherent annual and decadal variability for extreme wind events, and any shift in these events due to climate change is projected to be small over the next century (Winkler et al. 2012).

SUMMARY

The assessment area is projected to undergo profound changes in climate by the end of the century. Direct changes include shifts in mean temperature and precipitation as well as altered timing and extremes. Projected changes also extend to more indirect climate-controlled factors such as an increasing frequency of extreme rainstorms and decreased soil frost during winter. In general, by the end of the 21st century northern Michigan is projected to experience a climate that is hotter and more variable, with more moisture stress towards the end of the growing season and less characteristic winter weather. In the next chapter, we examine the ecological implications of these anticipated changes for forest ecosystems.

CHAPTER 5: FUTURE CLIMATE CHANGE IMPACTS ON FORESTS

In this chapter, we describe the potential effects of climate change on forest ecosystems in the assessment area during the next century. These effects include the direct impacts of climate change, as well as indirect impacts due to forest pests, invasive species, altered disturbance regimes, and other interacting factors. To gain a better understanding of how forests in northern Michigan may respond to climate change, we rely on forest impact models as well as scientific literature. This information provides us with the foundation to assess the potential vulnerability of forest ecosystems in the assessment area (Chapter 6).

MODELED PROJECTIONS OF FOREST CHANGE

Forest ecosystems in the assessment area may respond to climate change in a variety of ways. Potential changes include shifts in the spatial distribution, abundance, and productivity of tree species. For this assessment, we rely on a combination of three forest modeling efforts to describe these potential changes. Researchers using the Climate Change Tree Atlas, LANDIS-II, and PnET-CN models contributed results to this assessment (Table 14). Tree Atlas uses statistical techniques to model changes in suitable habitat for individual species over broad geographic areas. LANDIS-II is a spatially dynamic simulation model that includes migration, natural disturbances, timber harvest, and competition to project the abundance and distribution of individual tree species. PnET-CN simulates the movement of carbon (C), water, and nitrogen (N) in forest ecosystems and calculates the productivity of aggregated forest types. No single model offers a perfect projection of future change, but each tool is valuable for a particular purpose or set of questions. Complementary patterns across models are reinforced, and differences between model projections provide opportunities to better understand the nuances of ecological responses given the strengths and limitations of the models. For a more thorough description of the different models, and specifically how they were applied for this assessment, see Chapter 2.

These model results are best used to describe trends across large areas and over long time scales. Models are not designed to deliver precise results for individual forest stands or a particular year in the future, despite the temptation to examine particular data points or locations on a map.

Importantly, all of these modeling investigations relied on a consistent set of future climate data. Research teams used the same two combinations of general circulation models (GCMs) and emissions scenarios described in detail in Chapter 4: GFDL A1FI and PCM B1. The GFDL A1FI model-scenario combination is on the higher end of the spectrum for future temperature increases and precipitation decreases, and PCM B1 represents a milder projection. This consistency in the climate data used as inputs means that the forest impact models are describing potential forest changes for the same range of plausible future climates. See Chapter 2 for a more complete description of GCMs and emissions scenarios.

Table 14.—Overview of impact models used for this assessment and the different features included in simulations of future conditions[a]

Feature	Tree Atlas	LANDIS-II	PnET-CN
Summary	Suitable habitat distribution model (DISTRIB) + supplementary information (Modifying Factors)	Spatially dynamic process model	Ecosystem level carbon, water, and nitrogen process model
Primary outputs for this assessment	Area-weighted importance values and modifying factors by species	Aboveground biomass by species and distribution maps by forest type	Aboveground Net Primary Productivity by forest type
Analysis area	Albert's Ecological Sections VII & VIII (full assessment area)	Albert's Ecological Section VII (northern lower MI)	Albert's Ecological Sections VII & VIII (full assessment area)
Migration	No[b]	Yes	No
Competition, survival, and reproduction	No	Yes	No
Forest management	No	Yes	No[b]
Disturbances	No (but addressed through modifying factors)	Yes (fire, wind, and timber harvest)	No[b]
Tree physiology feedbacks	No	No	Yes
Succession or community shifts	No	Yes	No
Biogeochemical feedbacks	No	No[b]	Yes

[a] See Chapter 2 for model descriptions, parameters, and scenarios used for this assessment.
[b] This parameter can be an output for this model, but was not investigated in this assessment.

Tree Atlas

Importance values of 134 eastern tree species were modeled for potential habitat suitability in the assessment area by using DISTRIB, a component of the Tree Atlas toolset (Iverson et al. 2008). Importance value is an index of the relative abundance of a species in a given community. For an individual 12.4-mile grid cell, the importance value for a species can range from 0 (not present) to 100 (completely covering the area). Cell-by-cell importance values are then summed across the assessment area to reach the area-weighted importance value for a species, so area-weighted importance values can be well above 100. This analysis was completed for the entire assessment area, and 75 of the 134 species have or are projected to have suitable habitat in the area. Chapter 2 contains more detail on the Tree Atlas methods.

The projected change in potential suitable habitat for the 75 species was calculated for the years 2070 through 2099 by comparing the GFDL A1FI and PCM B1 scenarios to present values (Table 15). Species were categorized based upon whether the results from the two climate-emissions scenarios projected an increase, decrease, or no change in suitable habitat compared to current conditions, or if the model results were mixed. Further, some tree species that are currently not present in the assessment area were identified as having potential suitable habitat in the future under one or both scenarios. See Appendix 4 for complete results from the DISTRIB model, including both model-scenario combinations for 2010 through 2039, 2040 through 2069, and 2070 through 2099.

Table 15.—Potential changes in suitable habitat for 75 tree species in the assessment area for the PCM B1 and GFDL A1FI climate scenarios, from the Tree Atlas model

Common name	PCM B1	GFDL A1FI
Declines under Both Scenarios		
Balsam fir (-)	Decrease	Large Decrease
Balsam poplar	Decrease	Decrease
Black spruce	Large Decrease	Large Decrease
Jack pine	Decrease	Large Decrease
Mountain maple (+)	Large Decrease	Large Decrease
Northern white-cedar	Decrease	Large Decrease
Paper birch	Decrease	Large Decrease
Quaking aspen	Decrease	Large Decrease
Tamarack (-)	Decrease	Large Decrease
White spruce	Large Decrease	Large Decrease
Mixed Results Between Scenarios		
American basswood	No Change	Increase
American beech	Increase	No Change
Bigtooth aspen	No Change	Large Decrease
Bitternut hickory (+)	No Change	Large Increase
Black ash (-)	No Change	Decrease
Black cherry (-)	Increase	No Change
Boxelder (+)	Decrease	Large Increase
Bur oak (+)	Decrease	Large Increase
Chestnut oak (+)	No Change	Increase
Chokecherry	No Change	Large Decrease
Eastern cottonwood	No Change	Large Increase
Eastern hemlock (-)	No Change	Large Decrease
Eastern hophornbeam (+)	No Change	Increase
Eastern white pine	No Change	Large Decrease
Green ash	Decrease	Increase
Northern pin oak (+)	No Change	Large Increase
Northern red oak (+)	Increase	No Change
Ohio buckeye	No Change	Increase
Peachleaf willow	Large Decrease	No Change
Pin cherry	No Change	Large Decrease
Pin oak (-)	No Change	Large Increase
Red maple (+)	No Change	Decrease
Red pine	No Change	Large Decrease
River birch	Decrease	Increase
Rock elm (-)	Decrease	Increase
Striped maple	No Change	Decrease
Sugar maple (+)	No Change	Large Decrease
Swamp white oak	No Change	Large Increase
Sweet birch (-)	No Change	Increase
Yellow birch	No Change	Large Decrease
Increases under Both Scenarios		
American elm	Increase	Large Increase
American hornbeam	Increase	Large Increase
Black locust	Large Increase	Large Increase
Black oak	Increase	Large Increase
Black walnut	Large Increase	Large Increase
Black willow (-)	Increase	Large Increase
Blackgum (+)	Increase	Large Increase
Eastern redcedar	Increase	Large Increase
Flowering dogwood	Increase	Large Increase
Honeylocust (+)	Increase	Increase
Sassafras	Large Increase	Large Increase
Scarlet oak	Increase	Increase
Shagbark hickory	Large Increase	Large Increase
Silver maple (+)	Increase	Large Increase
Slippery elm	Increase	Large Increase
Sycamore	Increase	Increase
White ash (-)	Increase	Increase
White oak (+)	Increase	Large Increase
Species Gaining New Habitat		
Black hickory	NA	New Habitat
Blackjack oak (+)	NA	New Habitat
Chinquapin oak	NA	New Habitat
Common persimmon (+)	NA	New Habitat
Eastern redbud	NA	New Habitat
Hackberry (+)	New Habitat	New Habitat
Mockernut hickory (+)	New Habitat	New Habitat
Osage-orange (+)	New Habitat	New Habitat
Pawpaw	NA	New Habitat
Pignut hickory	New Habitat	New Habitat
Post oak (+)	NA	New Habitat
Red mulberry	New Habitat	New Habitat
Shellbark hickory	NA	New Habitat
Shingle oak	NA	New Habitat
Sugarberry	NA	New Habitat
Wild plum	NA	New Habitat
Yellow-poplar (+)	New Habitat	New Habitat

Species are assigned to change classes based on the comparison between end-of-century (2070-2099) and current figures for area-weighted importance value. Species with particularly high and low modifying factors are marked with plus (+) or minus (-) signs. See Appendix 4 for complete results, including classification rules, model reliability, and current, early-century, mid-century, and late-century importance values.

Modifying factors have also been incorporated into the Tree Atlas to provide additional information on potential forest change. Modifying factors include life history traits and environmental factors that make a species more or less able to persist on the landscape (Matthews et al. 2011b). These factors are not explicitly included in the DISTRIB outputs, and are based on a review of a species' life-history traits, known stressors, and other factors. Examples of modifying factors are drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases. Modifying factors are highly related to a species' adaptive capacity (see Chapter 6). Information on modifying factors is included in the summary of projected changes in habitat (Table 15), where a plus (+) or minus (-) sign after a species name indicates that certain modifying factors could lead it to do better or worse, respectively, than DISTRIB model results indicate. As an example, the species with the five highest and five lowest modifying factor scores are displayed in Table 16. Appendix 4 contains more information on the specific modifying factors for each species.

When examining these results, it is important to keep in mind that model reliability is generally higher for more common species than for rare species. When model reliability is low, less certainty exists for the model results. See Appendix 4 for specific rankings of model reliability for each species.

Declining Species

For the assessment area in Michigan, 10 of the 75 modeled species are projected to decline in suitable habitat under both the PCM B1 and GFDL A1FI scenarios. The projected declines in importance values are more severe for these species under GFDL A1FI than under PCM B1. Many of the species projected to decline are boreal or northern species near the southern limit of their range in the assessment area. Many of these species are widespread across the landscape, including characteristic species such as balsam fir, black spruce, jack pine, quaking aspen, and tamarack. Therefore, the reduction of suitable habitat for these species may affect a large portion of forested landscape in northern Michigan. Black spruce and

Table 16.—Species with the five highest and five lowest adaptive capacity potential, based on Tree Atlas modifying factors[a]

Species	Factors that affect rating
Highest adaptive capacity	
1. Red maple	high seedling establishment rate, wide range of habitats, shade tolerant, high dispersal ability
2. Boxelder	high seedling establishment rate, shade tolerant, high dispersal ability, wide range of temperature tolerances, drought tolerant
3. Bur oak	drought tolerant, fire tolerant
4. Eastern hophornbeam	shade tolerant, wide range of temperature tolerances, wide range of habitats
5. Osage-orange	wide range of habitats
Lowest adaptive capacity	
1. Black ash	emerald ash borer susceptibility, poor light competitor, limited dispersal ability, poor seedling establishment, fire intolerant, dependent on specific hydrological regime
2. Balsam fir	spruce budworm and other insect pests, fire intolerant, drought intolerant
3. White ash	emerald ash borer, drought intolerant, fire intolerant
4. Eastern hemlock	hemlock wooly adelgid, drought intolerant
5. Rock elm	narrow range of soil requirements, low ability to regenerate from seed

[a] See Appendix 4 for a complete listing of modifying factors for each species.

white spruce are projected to have the most dramatic reductions in suitable habitat.

Balsam fir, black ash, paper birch, and tamarack also have low modifying factor scores, suggesting that there are life-history traits or biological stressors that may cause these species to lose even more suitable habitat than the model results indicate. Appendix 4 contains more information on the specific modifying factors for each species.

A projected reduction in suitable habitat at the end of the 21st century does not imply that these species will be extirpated or that mature, healthy trees will die. What this result indicates is that these species will be living farther outside their ideal climatic envelope and that these conditions may expose these species to greater stress. Living outside a suitable range also raises the risk of regeneration failure due to climatic factors.

Species with Mixed Results Between Scenarios

Thirty of the 75 total species are projected to have mixed results between the two climate scenarios, with different combinations of increases, decreases, and no change. In some cases, the results indicate that a species is expected to gain more suitable habitat under the GFDL A1FI scenario than under PCM B1 (e.g., American basswood, bur oak, green ash, and northern pin oak). This subset of species could be favored by hotter, drier conditions and is typically more common to the south of the assessment area. In other cases, the results indicate that many species are expected to gain suitable habitat or remain stable under PCM B1 and decline under GFDL A1FI (e.g., American beech, bigtooth aspen, black ash, eastern hemlock, eastern white pine, red maple, sugar maple, and yellow birch). This subset of species is more characteristically northern and generally projected to undergo large declines in suitable habitat under GFDL A1FI. This outcome suggests that there may be a climate-driven “tipping point” somewhere within this range of future climates for these species; beyond a certain amount of change in temperature and precipitation, suitable habitat is projected to decline in the assessment area.

Some of the species with mixed results occur at very low densities (e.g., chokecherry and swamp white oak) and could essentially be considered new entries to the assessment area. A few common species such as black ash and eastern hemlock have low modifying factor scores, suggesting that these species could lose more suitable habitat than the model indicates. Anticipated emerald ash borer infestations are expected to result in declines for black ash across northern Michigan. For American beech, the continued threat of beech bark disease also presents future challenges for this species. Conversely, bitternut hickory, boxelder, bur oak, northern red oak, northern pin oak, red maple, and sugar maple all have high modifying factor scores. Oak wilt may still be a future concern for oak species in Michigan. Appendix 4 contains more information on the specific modifying factors for each species.

Increasing Species

Suitable habitat is projected to increase for 18 species by the end of the century under both the PCM B1 and GFDL A1FI scenarios. Most of these are temperate deciduous species such as black oak, black walnut, white ash, and white oak. Additionally, most of these species are projected to gain more suitable habitat under GFDL A1FI than under PCM B1, suggesting that hotter conditions at the end of the century in northern Michigan may be suitable for an array of southern species.

All of the species in this category are already present within northern Michigan. Several of these species occur at very low densities (e.g., black locust, shagbark hickory, and sycamore) and could essentially be considered new entries to the assessment area. Overall, the potential increases in suitable habitat for temperate species raise the possibility of a large shift within forest communities in the assessment area. Several species common to the south of the assessment area may become more widespread, assuming higher regeneration success under future forest conditions. Because many of the species projected to lose suitable habitat are still expected to persist in the assessment area by the end of the century, forests in northern Michigan potentially could contain a higher overall diversity of species in the future, with a blend of temperate and boreal species.

Importantly, DISTRIB results indicate only a change in suitable habitat, not necessarily the ability of a given species to migrate to newly available habitat and colonize successfully. A few species projected to gain suitable habitat, such as white ash and black willow, have low modifying factor scores which suggest that they may be less able to take advantage of increasing suitable habitat. White ash is threatened by emerald ash borer, so it is not expected to fully occupy its projected suitable habitat across the assessment area. Similarly, Dutch elm disease will continue to limit American elm. This category also contains several species with high modifying factor scores, such as white oak, silver maple, and honey locust.

Species Gaining New Habitat

DISTRIB also projects that 17 species not already present will gain new suitable habitat within the assessment area by the end of the 21st century. A given species will not necessarily be able to migrate to newly available habitat and colonize successfully, however. Species not currently present in the assessment area would require long-distance migration, whether intentional or unintentional, to occupy suitable habitat in the assessment area. Because the Great Lakes and the Straits of Mackinac present substantial barriers to migration, southern species may be even less able to occupy suitable habitat in the eastern Upper Peninsula. Habitat fragmentation and the limited dispersal ability of seeds could also hinder the northward movement of the more southerly species, despite the increase in habitat suitability (Ibáñez et al. 2008). Most species can be expected to migrate more slowly than their habitats will shift (Iverson et al. 2004a, 2004b). Of course, human-assisted migration is a possibility for some species and is expected to become tested and used during the next decades (Pedlar et al. 2012).

Of the 17 species in this category, only 6 are projected to gain new suitable habitat under both climate scenarios (hackberry, mockernut hickory, Osage-orange, pignut hickory, red mulberry, and yellow-poplar). Under the GFDL A1FI scenario, 11 additional migrant species are projected to have an increase in suitable habitat within the assessment area, including 4 additional oak species and 2 more hickory species. Most of the species projected to gain suitable habitat in the assessment area only under the GFDL A1FI scenario are from ecological provinces far to the south. Seven of these species have high modifying factor scores, indicating that they possess life history traits that might help them be even more tolerant of future climatic conditions. For example, blackjack oak is rated highly because it is relatively drought tolerant, regenerates well after fire, and is readily established from seed. None of the species in this category have low modifying factor scores.

Geographic Trends

DISTRIB outputs can be visualized spatially, and these results can provide greater context for interpreting the projected changes in suitable habitat. Figures 35 through 37 display the changes in suitable habitat for three example species in three different change classes: quaking aspen, sugar maple, and white oak. These maps highlight that projected changes are not uniform across the assessment area, and that areas of suitable habitat are governed by soils, moisture gradients, and other factors. Quaking aspen appears to retain a large amount of suitable habitat in the assessment area under PCM B1, particularly in the eastern half of the Lower Peninsula. Under GFDL A1FI most of the suitable aspen habitat is confined to the far northeast corner of the eastern Upper Peninsula. Sugar maple is projected to lose areas of suitable habitat along the southern boundary of the assessment area under both climate scenarios, and under PCM B1 the potential distribution of this species is nearly equal to the current distribution. White oak is virtually absent from most of the assessment area today, occurring only sporadically in the northern Lower Peninsula. Under PCM B1 white oak is projected to gain suitable habitat throughout the Lower Peninsula, remaining largely absent from the eastern Upper Peninsula. Under GFDL A1FI, however, most suitable habitat for white oak is projected to occur within the eastern Upper Peninsula.

As mentioned above, DISTRIB results indicate only a change in suitable habitat, not necessarily the ability of a given species to migrate to newly available habitat. A species with large seeds like white oak may have a smaller likelihood of naturally migrating across northern Wisconsin or across the Straits of Mackinac. Suitable habitat maps for all the species addressed in this assessment are available online at the Climate Change Tree Atlas Web site (Appendix 4). As is the case for interpreting any spatial model outputs, local knowledge of soils, landforms, and other factors is necessary to determine if particular sites may indeed be suitable habitat for a given species in the future. These maps serve only as a guide of broad trends.

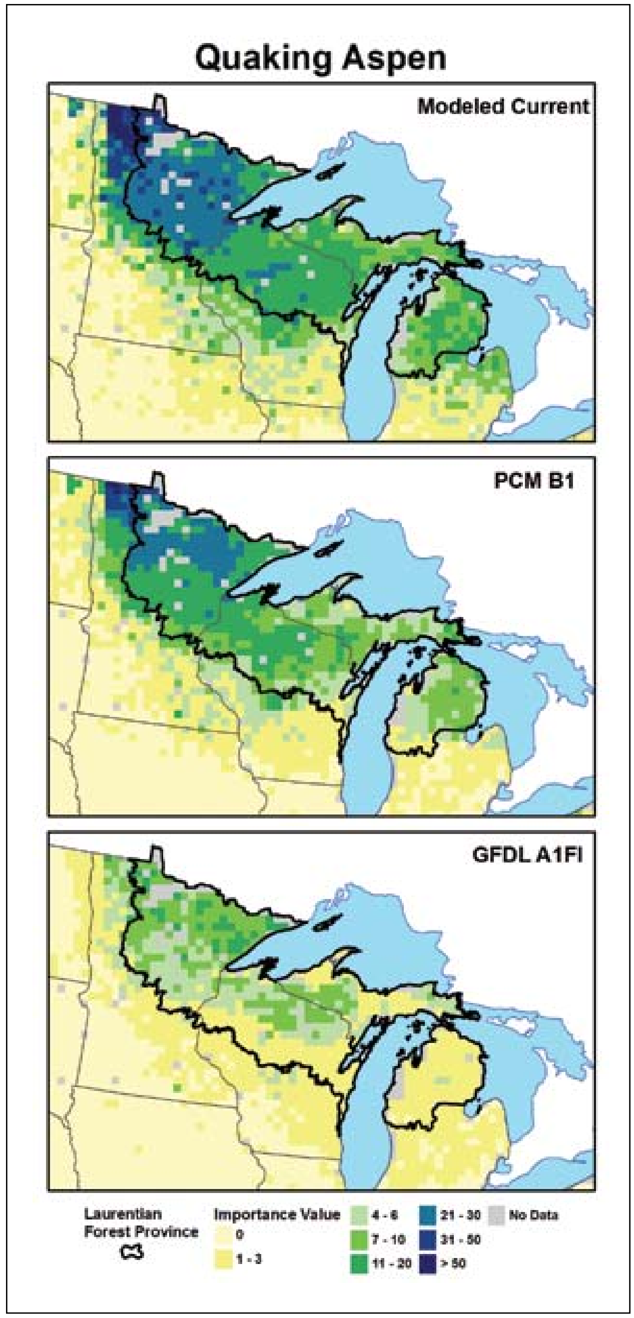


Figure 35.—Modeled importance values for quaking aspen across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present.

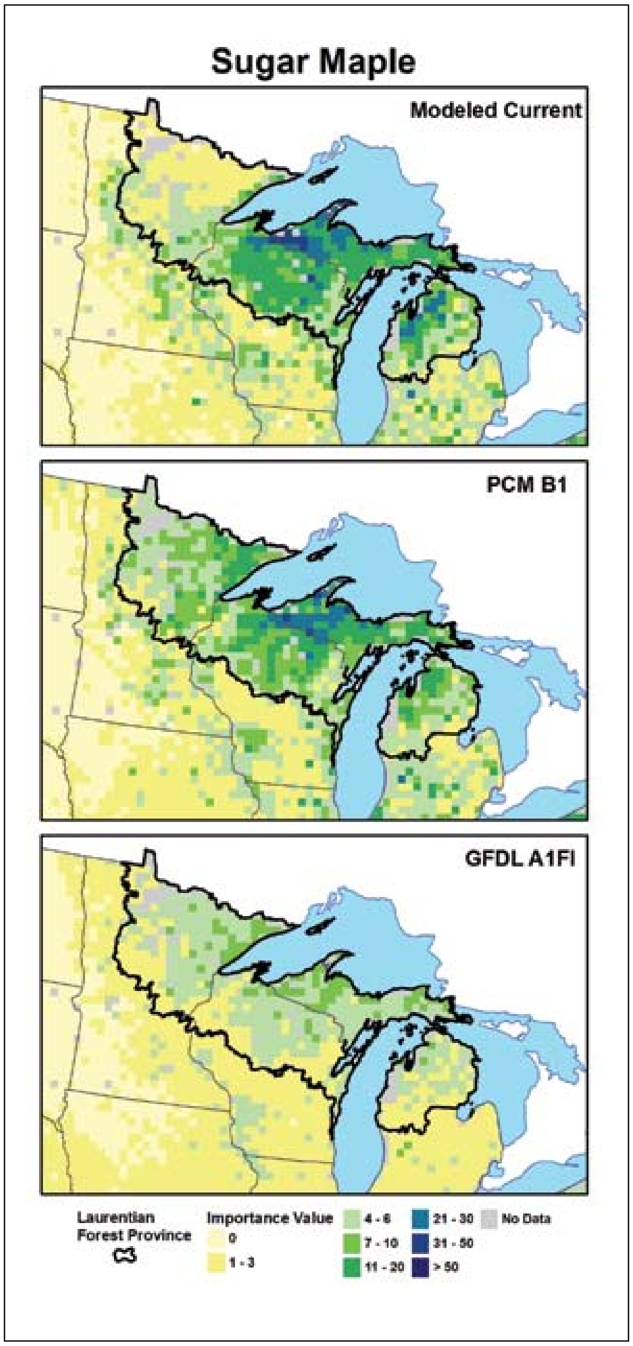


Figure 36.—Modeled importance values for sugar maple across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present.

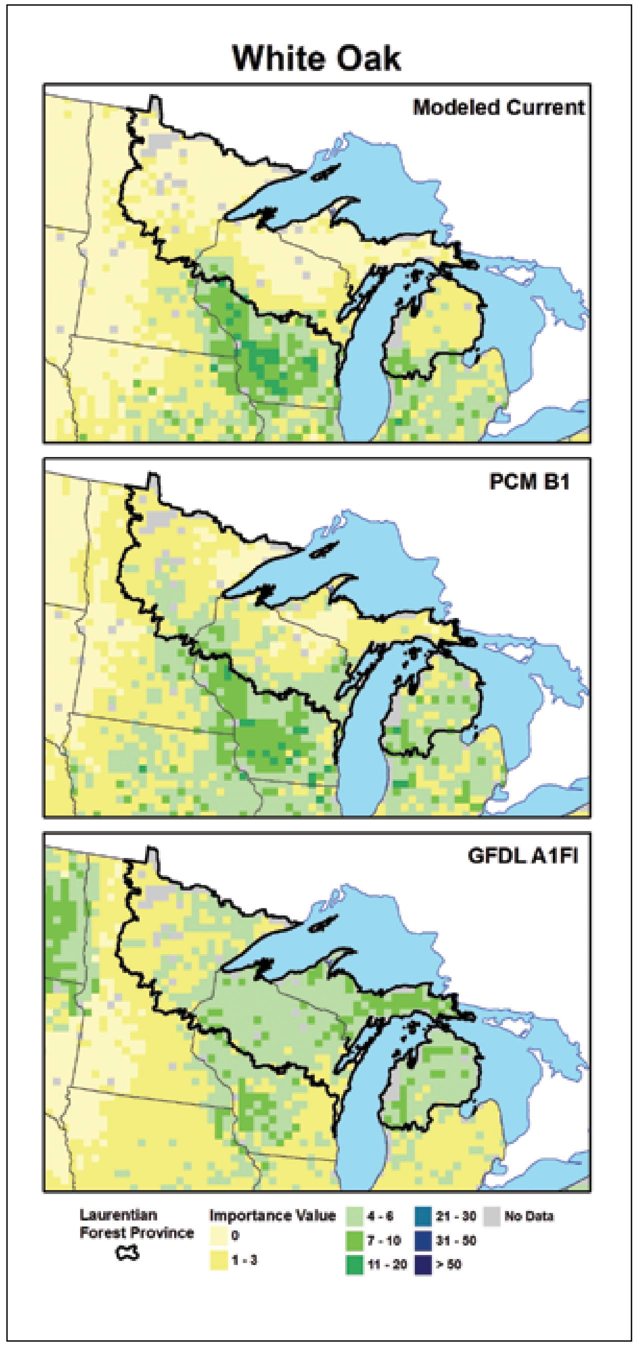


Figure 37.—Modeled importance values for white oak across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present.

LANDIS-II

Results from LANDIS-II include aboveground biomass (biomass) for 26 tree species and distribution maps for aggregated forest type communities. Importantly, the LANDIS-II model results described in this assessment cover only the northern Lower Peninsula (Ecological Section VII) (Fig. 38). The LANDIS-II analysis area includes the full diversity of forest types considered in this assessment, but the results are not assumed to represent the eastern Upper Peninsula. LANDIS-II is a computationally expensive model, and the authors contributing model results for this assessment were required to choose a smaller subset of the overall assessment area in order to complete the simulations (Chapter 2).

Aboveground Biomass

The LANDIS-II projections are plotted for each of 26 tree species over the 21st century for three climate scenarios (Fig. 39a and 39b). Species are limited to the most common tree species found within the LANDIS-II study area. Biomass values are averaged across the LANDIS-II analysis area. See Appendix 4 for a table of biomass values for all species assessed by LANDIS-II.

The current climate scenario is useful to highlight trends that might be expected if the climate were to remain stable during the next 100 years. This scenario highlights the effect of successional changes, such as the continued recovery of forests following historical periods of intensive logging.

Figure 38.—Analysis area modeled by LANDIS-II for this assessment.

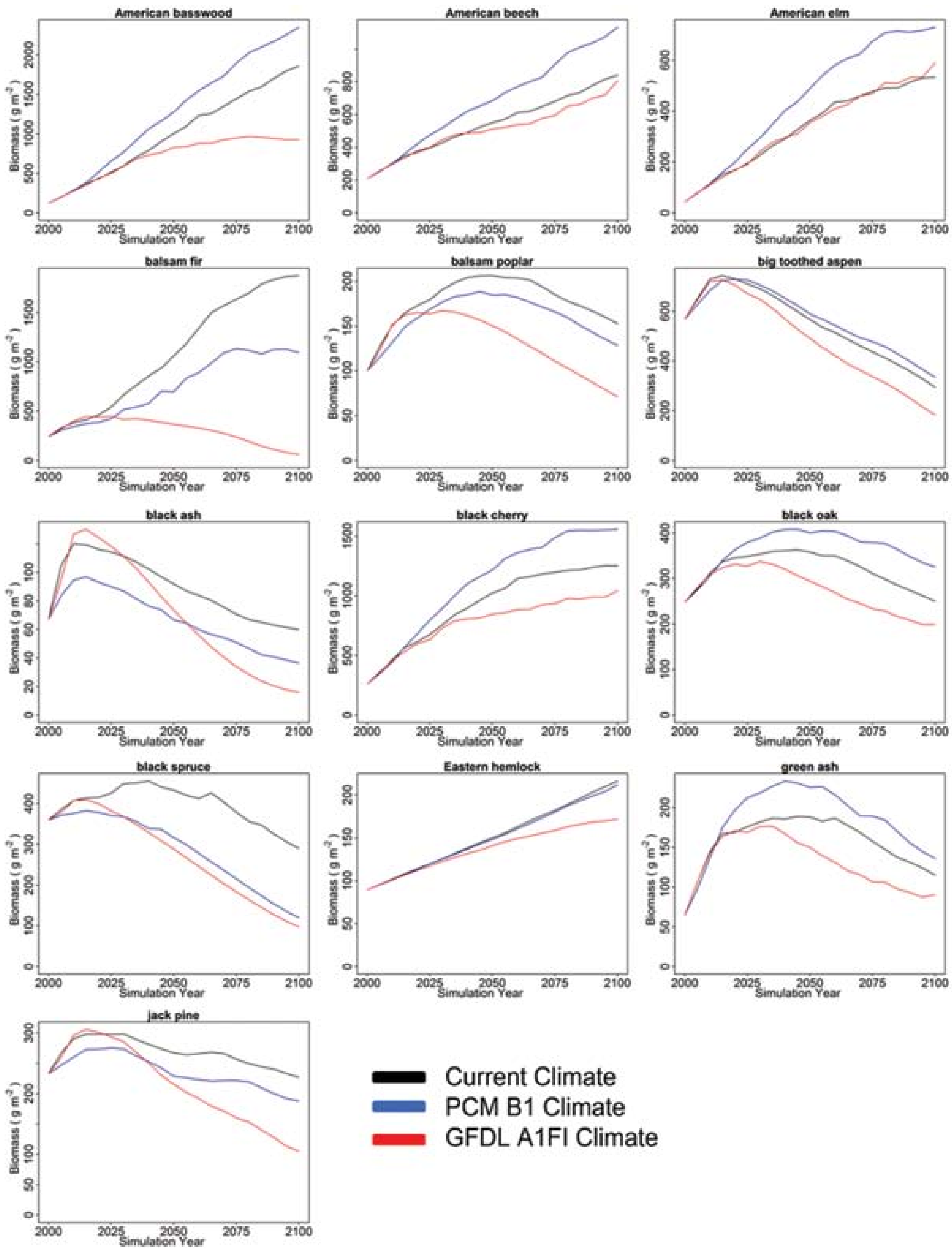


Figure 39a.—LANDIS-II biomass projections over the 21st century for the first 13 of 26 modeled tree species under three climate scenarios, presented in alphabetical order. Note that the Y-axis differs by species.

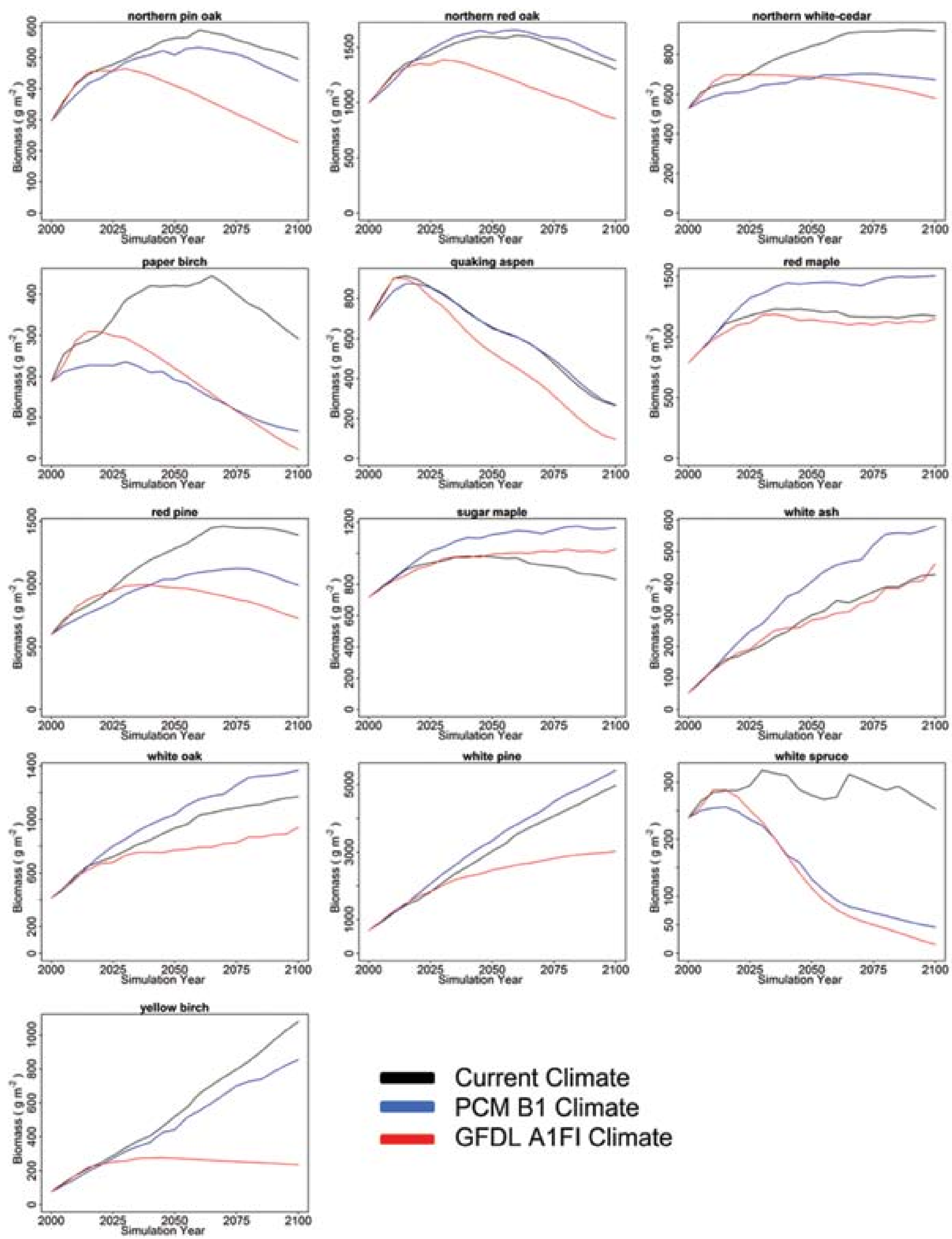


Figure 39b.—LANDIS-II biomass projections over the 21st century for the final 13 of 26 modeled tree species under three climate scenarios, presented in alphabetical order. Note that the Y-axis differs by species.

Although the current climate is not projected to remain the same over the next century (Chapter 4), this climate scenario is a useful reference to judge the relative increases or decreases in biomass under the two climate change scenarios (PCM B1 and GFDL A1FI). All scenarios in the LANDIS-II results incorporate natural disturbances (i.e., fire and wind), as well as timber harvest.

According to recent Forest Inventory and Analysis (FIA) inventory data for the assessment area, the annual net growth is more than double the harvest removals (Chapter 1: growth-to-removal ratio for the assessment area = 2.23). The ratio is even greater in the northern Lower Peninsula (Pugh et al. 2012). This finding helps explain the increasing trends for many of the species under the current climate scenario. The biomass projections of nearly all the species modeled for this assessment indicate at least a short-term biomass increase, regardless of climate scenario. All forested landscapes have a degree of "landscape inertia" in that recent trends are projected to continue into the near future (the next several decades). This momentum was built into the LANDIS-II simulations based on recent observed patterns of forest growth and regeneration, so that even species that are projected to eventually decline in biomass often show initial increases.

The 26 species modeled by LANDIS-II can be organized according to the proportional changes relative to the current climate scenario (Table 17). As mentioned above, the current climate scenario is essentially a control scenario, and the climate scenarios may either increase or decrease the landscape-scale biomass of a species relative to that control. LANDIS-II simulations may indicate that a given species may gain biomass across the analysis area compared to the year 2000, even if the projected biomass under the future climate scenarios is less than the current climate scenario. Red pine illustrates this pattern (Fig. 39b).

Table 17.—Potential changes in biomass for 26 tree species in the LANDIS-II analysis area[a]

Decrease - Both Scenarios	
Balsam fir (↓)	Northern pin oak (↓)
Balsam poplar (↓)	Northern white-cedar
Black ash (↓)	Paper birch (↓)
Black spruce (↓)	Red pine
Eastern hemlock	White spruce (↓)
Jack pine (↓)	Yellow birch (↓)
Increase PCM B1, Decrease GFDL A1FI	
American basswood (↓)	Eastern white pine
American beech	Green ash
Big toothed aspen	Northern red oak
Black cherry	Quaking aspen (↓)
Black oak	Red maple
Decrease PCM B1, Increase GFDL A1FI	
None	
Small Change	
White oak	
Increase - Both Scenarios	
American elm	White ash
Sugar maple	

[a] Species are grouped into change classes based on the proportional change between end-of-century (2100) biomass under the PCM B1 and GFDL A1FI scenarios and the end-of-century biomass under the current climate scenario. Up or down arrows (↑, ↓) indicate that the proportional change under one or both climate scenarios was greater than 50 percent. "Small Change" indicates that both scenarios projected less than 20-percent change in either direction. See Appendix 4 for complete results for all 26 species.

Declining Species

Twelve species are projected to decrease relative to the control scenario under both GFDL A1FI and PCM B1. These species include characteristic boreal species (e.g., balsam fir, black spruce, jack pine) as well as temperate species such as northern pin oak and black ash. For 10 out of the 12 decreaser species, projected declines were greater than

50 percent under one or both climate scenarios. The GFDL A1FI scenario resulted in larger biomass declines for all 12 of these species. In many cases, the proportional biomass decline under GFDL A1FI is double the expected decline under PCM B1. Jack pine illustrates this pattern (Fig. 39a). These trends indicate that climate-related shifts are driving the biomass projections for these species, and that the hotter, drier scenario amplifies the decline. Although oaks are generally expected to be favored by warmer, droughty conditions, northern pin oak is projected to decline under both future climate scenarios. Reduced seedling establishment under climate change is the main driver affecting the projected decline for this species.

Species with Mixed Results

Ten species are projected to increase relative to the control scenario under PCM B1, but projected to decline under GFDL A1FI. This list mostly includes temperate or northern hardwood species, such as American basswood, black cherry, eastern white pine, and northern red oak. White oak also displays this pattern, but the proportional changes are small enough (less than 20-percent increase and decrease), that this species was included in the small change category. Interestingly, no species are projected to decrease under PCM B1 and increase under GFDL A1FI.

These results suggest that slightly warmer temperatures and slightly wetter growing seasons under PCM B1 might benefit these species, but that a more severe change to hotter temperatures, wetter springs, and drier summers under GFDL A1FI may reduce the landscape-scale biomass of these species. White pine illustrates this pattern (Fig. 39b). This scenario also reduces the seedling establishment of northern red oak by the latter half of the 21st century. Northern red oak is also considered substantially less drought tolerant than bur oak, white oak, or northern pin oak. The biomass decline projected for black oak appears to be driven by reduced aboveground net primary productivity under GFDL A1FI. This outcome reinforces the dynamic nature of the LANDIS-II model, which projects the ability of species cohorts to grow, compete, reproduce, and disperse across the landscape. If climate influences one particular phase of this lifecycle, biomass trends will reflect that effect.

Increasing Species

Three species are projected to increase relative to the control scenario under both PCM B1 and GFDL A1FI (American elm, sugar maple, and white ash). For all species and climate scenarios, projected increases were less than 50 percent above the current climate scenario. Additionally, the proportional biomass increases for these species is larger under PCM B1 than GFDL A1FI, as illustrated by the projection of sugar maple (Fig. 39b). Importantly, these LANDIS-II simulations do not consider the full effects of pests and diseases. Dutch elm disease is expected to limit the biomass increases of American elm, and emerald ash borer may limit the future increase of white ash.

Patterns over Time

For many species that are projected to increase under PCM B1, there appears to be a late-century plateau or decline that could indicate the point at which a temperature or precipitation threshold has been crossed. Balsam fir, balsam poplar, black ash, eastern hemlock, green ash, paper birch, sugar maple and northern white-cedar all exhibit mid- or late-century biomass declines under PCM B1. When similar “tipping points” are evidenced under GFDL A1FI they seem to occur earlier, usually before 2050. Yellow birch illustrates this pattern (Fig. 39b). In these instances, the current climate trend line also increases initially, implying that the species had already been increasing across the northern Lower Peninsula before 2000. Trees take decades to grow, reproduce, and experience mortality, so climate-driven declines would take 20-50 years to appear in landscape-scale biomass figures.

The combined results for all species across the LANDIS-II analysis area tell an interesting story. For PCM B1, biomass across the northern Lower Peninsula is expected to increase quickly until 2075, more than doubling in that time. For the remainder of the simulation, the combined biomass of these 26 species more or less reaches a plateau. This trajectory closely tracks the combined results for the current climate scenario. The GFDL A1FI scenario projects a drastically different outcome, with an initial increase to 2040, followed by a steady decline until 2150. This combined result reflects the steep projected declines in boreal species, as well as in several mesic species. It appears that the few species projected to do well under GFDL A1FI may not be able to compensate for the overall biomass declines across the landscape. It is important to reiterate that LANDIS-II assesses only the 26 species listed in Table 17, and does not account for the potential of new migrants to enter the northern Lower Peninsula or for uncommon species to become more common.

Productivity

Simulations in LANDIS-II also require estimates of aboveground net primary productivity (productivity) as an input. For this assessment, productivity estimates were calculated via a version of the PnET model. These estimates of productivity used as inputs to LANDIS-II did not account for the potential effects of carbon dioxide (CO_2) fertilization, which will be discussed in more detail below. Compared to the year 2000, these simulations indicate an overall productivity decline of roughly 54 percent under GFDL A1FI by 2100. Alternatively, productivity is projected to remain fairly steady under PCM B1, declining by only 4 percent by 2100. Productivity is not the sole determinant of biomass but is an important regulator of potential biomass and recovery from disturbances.

Geographic Trends

The forest-type maps indicate the potential for landscape-level change under the two climate scenarios (Fig. 40). LANDIS-II allows for species cohorts to migrate, compete, reproduce, and undergo disturbances across the landscape, and these transitions are governed by a range of factors including soils and landform. To create these land cover maps, individual locations ("cells") in the LANDIS-II simulations were classified into six forest types based on characteristic species composition. These forest types are not perfectly correlated with the forest systems addressed in this assessment, and should not be cross-walked directly (Appendix 4). Because the LANDIS-II model does not effectively simulate lowland forest types or nonforested systems, the lowland conifer, lowland and riparian hardwoods, and barrens forest systems are not included in this classification. Additionally, LANDIS-II simulations account only for the 26 species modeled in this assessment. Therefore, these maps do not represent the potential for new species to migrate into the landscape or the potential for low-abundance species to increase within the assessment area, as suggested by Tree Atlas results.

Under the current climate scenario, the primary trend is a gradual 35-percent increase in the proportion of the landscape occupied by white pine- and red pine-dominated forests. This increase is matched by slight declines of the aspen-birch, oak, and spruce-fir forest types.

Under PCM B1, these trends are accentuated. A 10-percent increase in area occupied by northern hardwoods occurs across the landscape, and red pine-white pine forests also increase by roughly 20 percent. The northern Lower Peninsula in 2150 under PCM B1 looks like a hardwood-dominated landscape, particularly in the northwest portion of the Lower Peninsula area that currently contains most of the northern hardwood type. The virtual

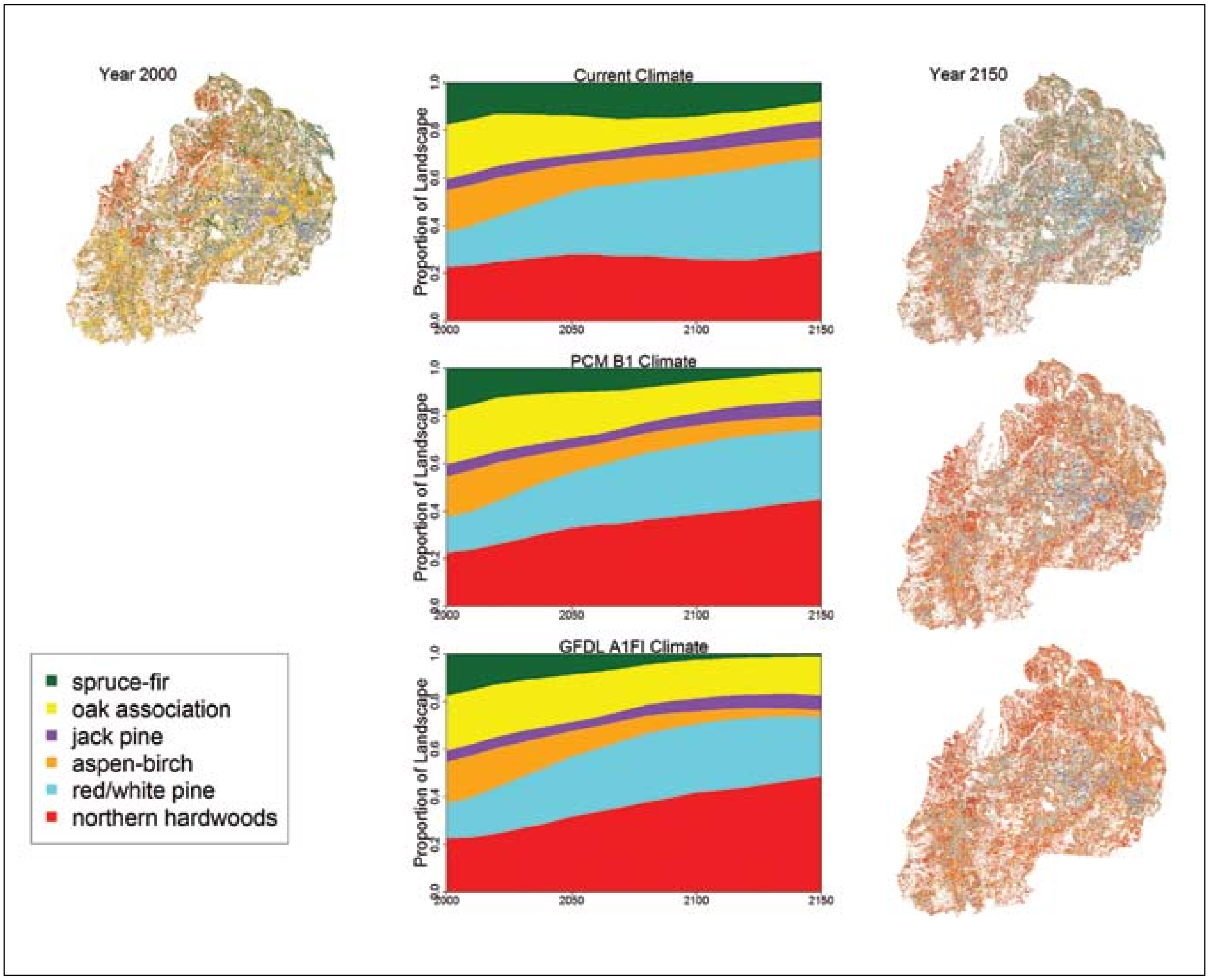


Figure 40.—Projected changes in land cover over the 21st century for six aggregated forest types under three different future climate scenarios, from the LANDIS-II model. Note that the simulations extend to 2150 for the graphs as well as for the resulting landscape maps.

absence of spruce-fir is also a noticeable change across the area, compared to the year 2000.

The GFDL A1FI scenario results in a similar compositional change across the landscape. Spruce-fir and aspen-birch forests are projected to decline more rapidly under this scenario, and northern hardwoods occupy more than 30 percent of the landscape by 2150. Red pine-white pine forests increase by roughly the same amount as under PCM B1, and oak forests maintain roughly the same proportion of overall land cover through time. The resulting landscape map of forest types looks similar to the projection for PCM B1. This forest-type map does not account for the differences in biomass described above.

Despite the large difference between the resulting forest-type maps under the two future climate scenarios, Figure 40 also shows the high degree of similarity between these projections for the first half of the 21st century. This is partially due to the simplified classification system used for the map, and the limited number of species used in the simulation. Tree species are relatively long-lived and there will be a lag time before changes in climate are translated into forest changes. As mentioned above, there will also be lags in community response due to species migration, establishment, competition, and reproduction. A certain amount of change during the first 50 years may be masked in these simulations because seedlings account for little biomass and a particular location may not be classified differently if the overstory remains intact. But the difference between the GFDL A1FI, PCM B1, and current climate simulations highlights the possibility for substantial landscape-level changes to occur under the two future climate scenarios.

PnET-CN

The PnET-CN model projects changes in aboveground net primary productivity (productivity). Productivity is commonly used as a measure of how well forests are photosynthesizing and accumulating biomass, which is essentially a way to describe overall ecosystem function. In this assessment, we report absolute productivity as well as relative percentage changes in productivity. The PnET-CN uses 1971 through 2000 as a baseline period, and simulates productivity changes from 2000 to 2099.

For this assessment, PnET-CN results describe six aggregated forest classifications rather than individual species. These classifications are based on FIA forest-type groups (Pugh et al. 2012), which are not perfectly matched with the nine forest communities considered in this assessment. The six FIA forest-type groups in the PnET-CN simulations are: aspen/birch, maple/beech/birch, oak/hickory, elm/ash/cottonwood, pine, and spruce/fir. These groups are assigned based only on tree species composition and they do not account for soils, disturbance processes, or other factors. Still, they are a useful way to describe broad forest categories in Michigan. Figure 41 shows the distribution of these forest-type groups across the assessment area.

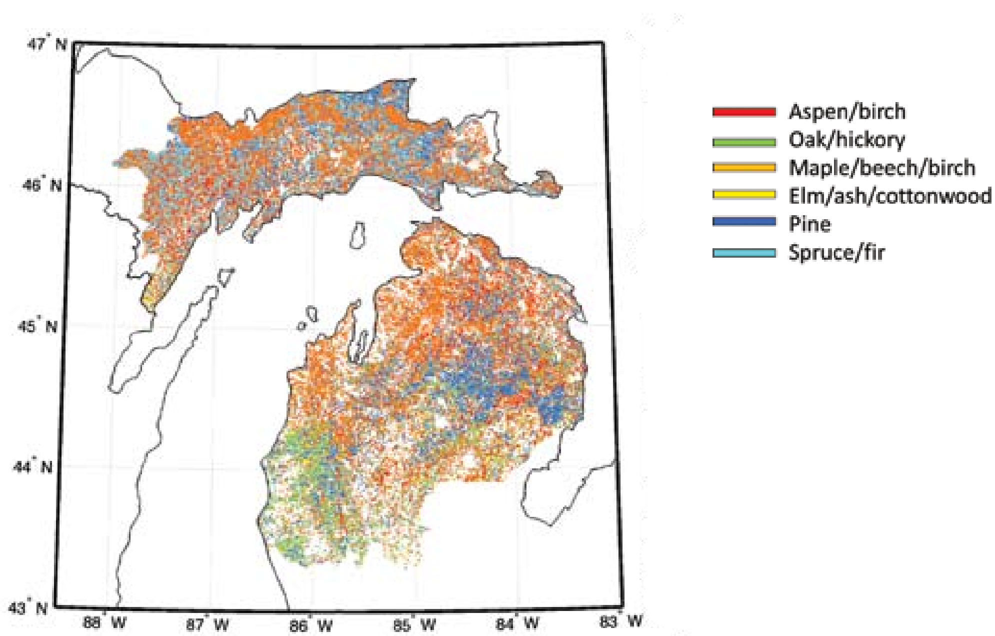


Figure 41.—Spatial distribution of the aggregated forest-type groups used in PnET-CN simulations. These forest-type groups remain fixed for the duration of the PnET-CN simulations.

Productivity Trends

As noted above, the PnET-CN and LANDIS-II simulations were run under different conditions. In particular, the LANDIS-II simulations presented above do not account for the effects of elevated atmospheric CO_2, but the PnET-CN simulations discussed here consider the effects of rising CO_2 on forest productivity. Under both PCM B1 and GFDL A1FI, PnET-CN projects that productivity will increase from the baseline period (1971 through 2000) through the end of the century (Fig. 42). All forest-type groups show increases in productivity, with greater absolute and relative increases in deciduous groups (aspen/birch, oak/hickory, maple/beech/birch, and elm/ash/cottonwood) compared to conifer forest-type groups (spruce/fir and pine). This trend is consistent for both climate scenarios. Under PCM B1, deciduous forest-type groups appear to peak around an 80-percent increase in productivity and the pine and spruce/fir groups are projected to plateau around 40 percent.

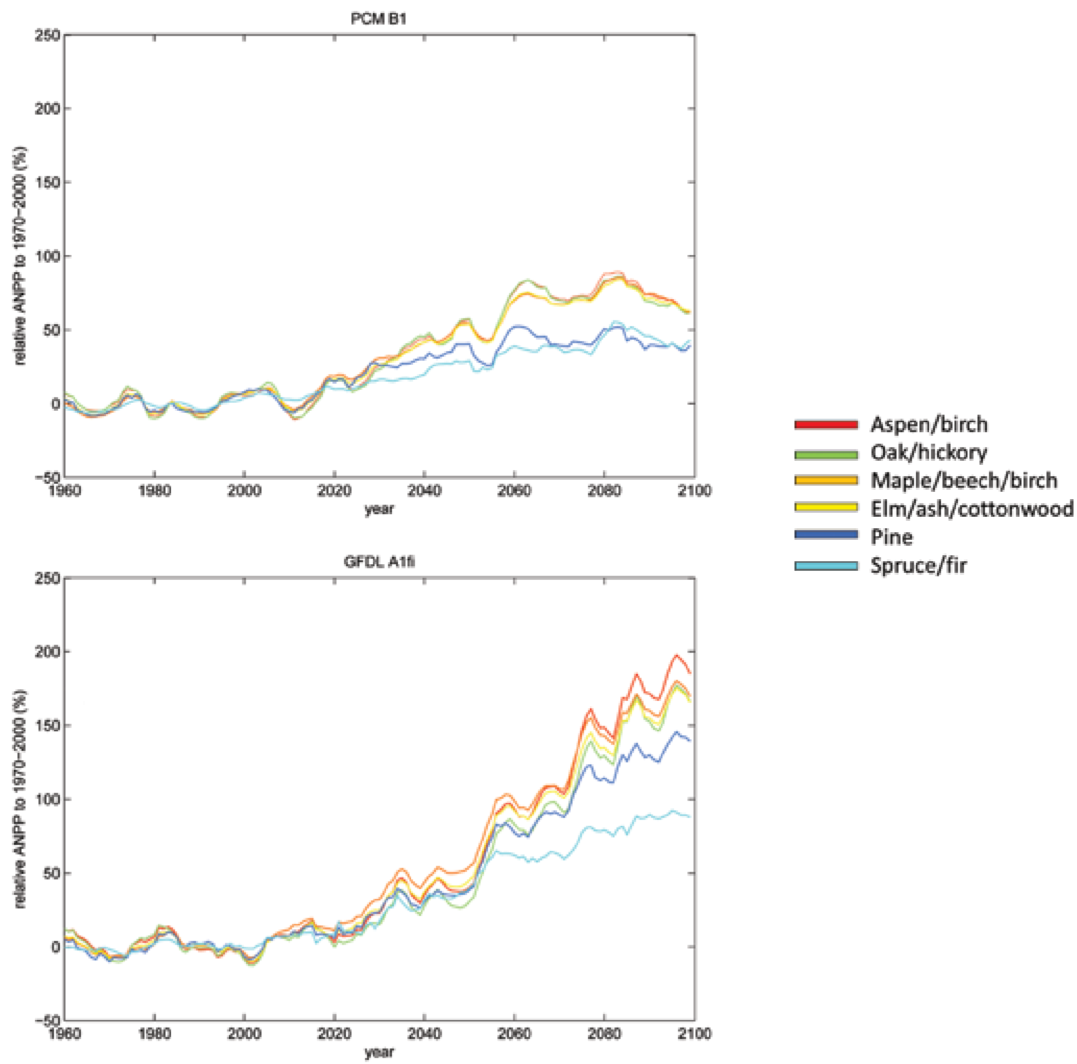


Figure 42.—Projected trends in aboveground net primary productivity (ANPP) from PnET-CN for six aggregated forest-type groups under the PCM B1 and GFDL A1FI future climate scenarios. Changes in productivity are relative to the 1971 through 2000 baseline period. Outputs have been smoothed based on a 5-year running mean.

Under GFDL A1FI, productivity is projected to increase throughout the century with no apparent plateau. The four deciduous forest-type groups exhibit increases of roughly 180 percent across the assessment area by the end of the century, with pine forests increasing in productivity by nearly 150 percent. The spruce/fir group is projected to show a smaller gain in productivity by the end of the century, not quite reaching a 100-percent increase.

For all forest-type groups across the assessment area, PCM B1 resulted in an average productivity increase of 64 percent compared to the baseline period. The absolute increase in productivity from baseline to end-of-century averages 332 grams biomass per square meter per year and ranges from 109 to 589 grams biomass per square meter per year. The productivity increases projected in GFDL A1FI are roughly two times greater than the increases projected under PCM B1. Under this scenario, the average relative increase in productivity from baseline to end-of-century is 138 percent. The absolute increase in productivity from baseline to end-of-century is on average 712 grams biomass per square meter per year and ranges from 225 to 1493 grams biomass per square meter per year across the assessment area.

The main drivers of the increased forest productivity projected by PnET-CN are CO_2 fertilization and growing season length. Elevated atmospheric CO_2 concentrations enable trees to absorb more C through stomata on their leaves. As a result, water loss is reduced and photosynthesis is increased for a given amount of water use. CO_2 fertilization effects were larger under GFDL A1FI than under PCM B1.

Warmer temperatures enhanced C uptake earlier in the spring and later in the fall, but C uptake was reduced in mid-summer due to water limitations on photosynthesis. Growing season length increased more under GFDL A1FI (1 to 2 months across the assessment area) than under PCM B1 (roughly 1 month). In general, this longer growing season allowed forests to accumulate more biomass per year in the simulation.

In separate simulations with the level of atmospheric CO_2 fixed at 350 parts per million (not shown in this assessment), climate changes alone resulted in minor to no change in productivity under PCM B1 and declines in productivity under GFDL A1FI by the end of the 21st century. Productivity was reduced in the fixed CO_2 simulations due to water limitations. These results closely mirror the LANDIS-II productivity inputs discussed above. PnET-CN tends to predict a larger CO_2 fertilization effect on productivity than do other ecosystem models, so this effect may be a generous estimate (Medlyn et al. 2011). Because field studies have not directly tested ecosystem responses to CO_2 concentrations greater than 900 ppm in mature forests, it is difficult to recalibrate the model based on current knowledge.

Although PnET-CN incorporates biogeochemical feedbacks like water and nutrient limitation, this model does not account for other factors that could reduce forest productivity. For example, the model does not reflect competition; forest management; or disturbances from deer herbivory, wind, fire, or insect pests. Additionally, the model does not account for forest-type change over time; forest composition is essentially static through the 100-year simulations. Therefore, it may be most helpful to think of these results as an indication of the potential ecosystem productivity response of existing forests to climate change.

Geographic Trends

Productivity is projected to increase from the baseline period under both future climate scenarios throughout the assessment area (Fig. 43). Productivity increases are relatively consistent throughout the assessment area under the PCM B1 scenario, with a concentration of slightly higher productivity increases around Munising in

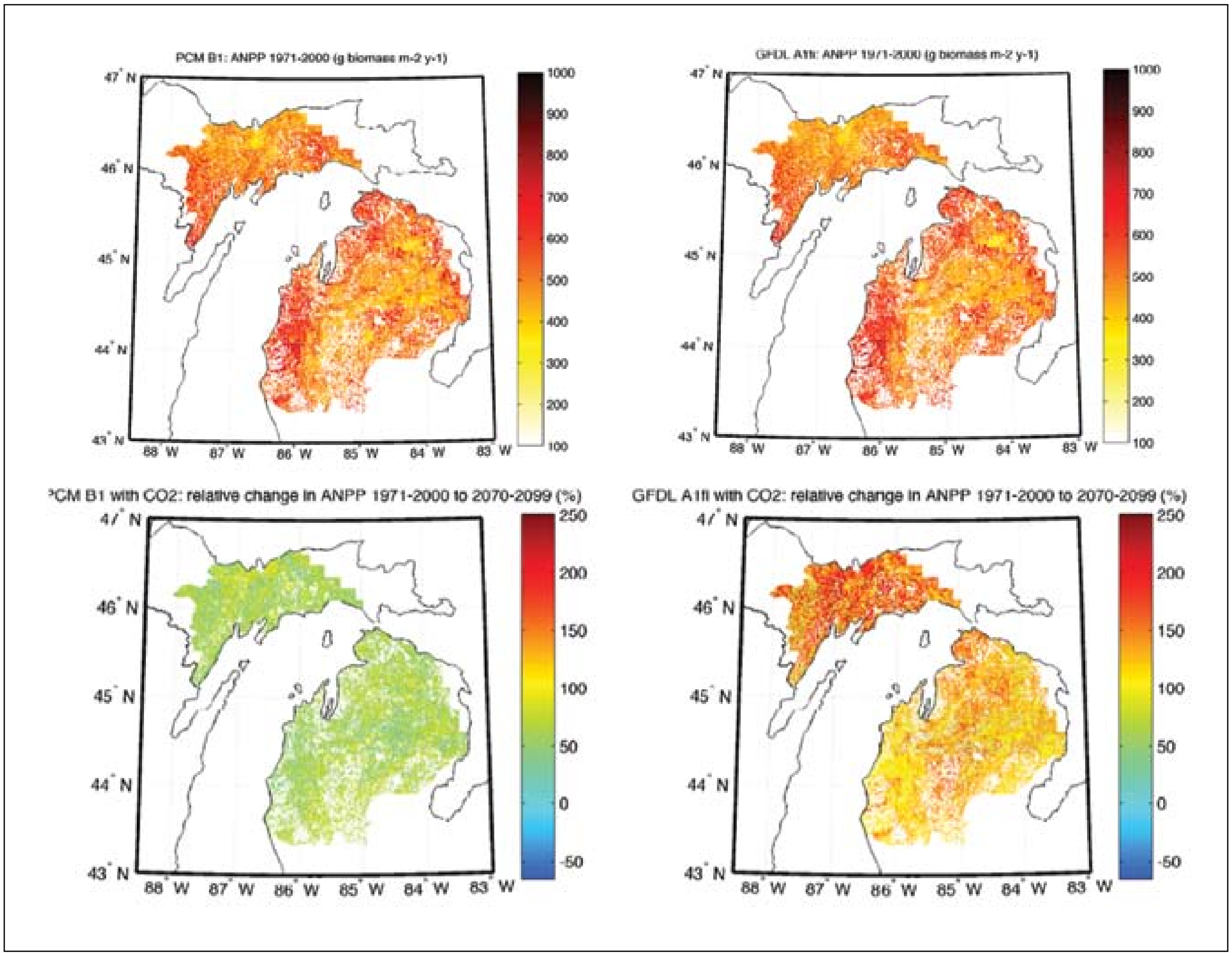


Figure 43.—Projected aboveground net primary productivity (ANPP) changes across the assessment area under the PCM B1 and GFDL A1FI future climate scenarios, from the PnET-CN model. Productivity values for the baseline period of 1971 through 2000 are absolute figures (top panels), and the future values for each scenario are relative percentages compared to the baseline period (bottom panels). Baseline values are slightly different between the two climate scenarios because of slight variations in the downscaled GCM data.

Alger County and along the southern boundary of the assessment area. Under the GFDL A1FI scenario, productivity increases are above 150 percent across most of the eastern Upper Peninsula. Productivity increases are slightly less in the Lower Peninsula, averaging approximately 100 percent.

Geographic trends in the PnET-CN outputs appear as a result of a combination of factors. The forest-type group assigned to each pixel remains constant in these simulations, and different forests have different abilities to respond to climate shifts. A variety of other parameters, such as soil type, nutrient status, and soil water-holding capacity, are also critical for determining whether a particular forest pixel will be able to successfully take advantage of climate shifts and translate favorable growing conditions into productivity increases. These factors could explain why maple/beech/birch forests in the northern Lower Peninsula show less of a productivity response under the GFDL A1FI scenario than such forests in the eastern Upper Peninsula.

The PnET-CN simulations indicate the productivity of forests in the assessment area could switch from being temperature limited to water limited by the end of the 21st century. See Chapter 4 for a discussion of area-wide changes in the ratio of evapotranspiration to precipitation, which is a related output of the PnET-CN model. Soil water-holding capacity could play a critical role in determining how forests in the assessment area respond to future climate changes. In the PnET-CN simulations, areas with lower water holding capacity were less buffered from water limitation and more prone to reductions or smaller increases in productivity (Peters et al. 2013). This conclusion is supported by previous research on the effect of climate change on southern boreal and northern temperate forests, which found that hardwood species were more able to replace declining boreal species in areas with more available soil moisture (Pastor and Post 1988, Post and Pastor 1996).

Discussion of Model Results

Agreements

The question of how ecosystems might respond to future climate changes has been a topic of study for close to 30 years (Emanuel et al. 1985, Solomon 1986). Studies relying on earlier estimates of future warming and more simplistic vegetation simulations outlined broad effects that have been reinforced by more advanced models and recent simulations. This corroboration is particularly true for forests in the northern Great Lakes region. The results of the modeling simulations performed for this assessment reinforce the concept of boreal forest decline and subsequent increase in more temperate broadleaf species and forest types, to the extent allowed by soil moisture (Emanuel et al. 1985, Pastor and Post 1988, Post and Pastor 1996, Solomon 1986).

Despite the differences between the modeling approaches, Tree Atlas, LANDIS-II, and PnET-CN show some strong similarities in forest change during the next century under a range of future climates. All three models agree that characteristic boreal species or northern species at their southern range limits will face increasing climate stress. For example, the list of declining species for both the Tree Atlas and LANDIS-II models includes many of the same species: balsam fir, balsam poplar, black spruce, jack pine, northern white-cedar, paper birch, and white spruce. The declines for these species were more substantial under GFDL A1FI than under PCM B1. Additionally, the PnET-CN results project a weaker potential productivity response for spruce/fir forests compared to other forests. As the climate warms through the 21st century, these species and forest types are projected to face increasing climate-related stress.

Moreover, both Tree Atlas and LANDIS-II tend to agree that many species may increase or remain stable under PCM B1 and decrease under GFDL A1FI. American beech, bigtooth aspen, black cherry, eastern white pine, northern red oak, and red maple all follow this general pattern. These results support the idea that GFDL A1FI represents a future climate that is beyond the tolerance of these species. These results also suggest that many temperate species present in northern Michigan could tolerate a mild degree of warming and increased precipitation, as represented by the PCM B1 scenario.

Tree Atlas and LANDIS-II also agree that American elm and white ash will increase under a range of future climates. These are temperate hardwood species, and it is not surprising that they would be tolerant of warmer year-round conditions. Outputs from PnET-CN also indicate that elm/ash/cottonwood forests have the potential for large productivity increases across the assessment area in Michigan.

Disagreements

As mentioned above, productivity projections differ between the LANDIS-II and PnET-CN simulations used for this assessment. Results from LANDIS-II are driven by projections of an overall decline in productivity under GFDL A1FI and almost no change under PCM B1. According to PnET-CN, however, large productivity increases are possible under both scenarios, with productivity gains nearly twice as large under GFDL A1FI. This discrepancy is almost certainly due to the way that these models account for the potential CO_2 fertilization effect. As mentioned above, the PnET-CN simulations appear to be driven mainly by the potential CO_2 fertilization effect, and the productivity estimates used by LANDIS-II do not account for CO_2 fertilization. It is unclear how substantial this factor will be over the long term. Experiments with CO_2 enrichment in forests suggest net primary productivity will increase under elevated CO_2, although this response can diminish over time due to water or nutrient limitation and tree age (Norby and Zak 2011, Norby et al. 2005). Additionally, productivity increases under elevated CO_2 could be partially offset by reductions in productivity from warming-induced drought stress or the effects of future disturbances (Dieleman et al. 2012).

There are a few notable disagreements between the species-level Tree Atlas and LANDIS-II model results. LANDIS-II results suggest that northern pin oak will decline under both climate scenarios, due to the low probability of seedling establishment starting around the year 2050. Neither Tree Atlas (without modifying factors) nor PnET-CN incorporates this factor. LANDIS-II also projects that black oak will decline under GFDL A1FI due to reduced productivity. Tree Atlas projects that black oak will gain suitable habitat under GFDL A1FI, however, and PnET-CN projects that oak/hickory forests will experience increasing productivity under both climate scenarios. Again, these differences are probably related to the assumptions of each model and may be influenced by the additional factors incorporated into each model—nutrient feedbacks and CO_2 fertilization in the case of PnET-CN and disturbances and management in the case of LANDIS-II.

Sugar maple is projected to increase in biomass according to the LANDIS-II projections, but Tree Atlas results indicate that this species will have less suitable habitat across the assessment area by the year 2100. Additionally, Tree Atlas projects that American basswood would gain more suitable habitat under GFDL A1FI than PCM B1, yet LANDIS-II simulations indicate that this species would decline under GFDL A1FI relative to PCM B1. The same discrepancy is true for green ash. These differences might be an effect of the different analysis area used for the LANDIS-II simulations, if suitable habitat changes in the eastern Upper Peninsula are not reflected in the LANDIS-II results. In addition, the LANDIS-II simulations include business-as-usual disturbance that may have a strong influence on long-term projections.

As mentioned above, Tree Atlas results project suitable habitat, not whether species will be physically present. Northern pin oak, black oak, sugar maple, basswood, and green ash all appear to have a short-term biomass increase before declining under GFDL A1FI, which suggests that they may face climate-related thresholds in the northern Lower Peninsula that are not reflected in Tree Atlas calculations of suitable habitat.

PnET-CN results suggest that maple/beech/birch forests will perform better than other forest types across the range of climate futures, particularly under GFDL A1FI. Tree Atlas projects a decrease in red maple suitable habitat under GFDL A1FI, which is surprising. This species has the most positive modifying factors among all the species assessed by Tree Atlas, however, so it is expected that red maple will do better than the model suggests in northern Michigan.

Limitations

All models are only simplified representations of reality. No model fully considers the entire range of ecosystem processes, stressors, interactions, and future changes to forests. Each model leaves out ecosystem processes or defining features that may be key drivers of change. Future uncertainty is not limited to climate scenarios; it is inherent in human interactions with forests. The contributing authors of this assessment summarized some of the factors not incorporated into these modeling results to facilitate further discussion. Highlights of this list are:

- Human management and policy responses to forest changes and climate trends
- Future wildfire behavior, fire suppression, and ability to apply prescribed fire
- Novel successional pathways for forest ecosystems
- Changes in regeneration ecology of species
- Indirect effects of competitor species
- Changes in competitive ability of species
- Trends in land-use change or forest fragmentation
- Dynamics in lowland or wetland forests less understood than upland forests
- New major insect pests or disease agents
- Magnitude of CO_2 fertilization effect
- Herbivory pressure in the future, particularly from white-tailed deer
- Extreme weather events not captured well in downscaled climate change or impact models
- Phenology changes and timing mismatches for key ecosystem processes
- Responses of understory vegetation, soil microorganisms, and mycorrhizal associations
- Future changes in forest industry, both in products and in markets
- Interactions among all these factors

Most of these factors could drive large changes in forests throughout the assessment area, depending on how much change occurs in the future. The potential for interactions among these factors adds additional layers of complexity and uncertainty. Despite these limitations, impact models are still the best tools available, and they are the best way to simulate a range of possible climate futures. It is most helpful to keep the above limitations in mind when weighing the different projections, and to use them to inform an overall assessment. The comparison among several different kinds of models allows for a better understanding of the range of possibilities. In the following section, we draw upon published literature to address other factors that may dictate how forest ecosystems in northern Michigan respond to climate change.

The Hughes Lake Fire in 2006. Photo by U.S. Forest Service, Huron-Manistee National Forest.

SUMMARY OF CURRENT SCIENTIFIC KNOWLEDGE

A growing body of scientific literature is gradually clarifying some of the potential ways that greenhouse gases and the climate change they cause may influence forest ecosystems. These impacts can broadly be divided into the direct effects of changing temperature, precipitation, and CO_2 levels, and the indirect effects of altered stressors or the development of additional stressors. It is also important to note that some of the impacts may in fact be positive or beneficial to native forests in the assessment area. The remainder of this chapter summarizes the state of scientific knowledge on additional direct and indirect effects of climate change on forests in the assessment area and the wider Great Lakes region.

Drought Stress

In the assessment area, the potential for more frequent droughts and moisture stress during the growing season appears to be greater under the GFDL A1FI climate scenario (Chapter 4). Even under the milder PCM B1 scenario, warmer temperatures may lead to increased transpiration and physiological stress. Even if seasonal precipitation increases slightly during the growing season, projected temperature increases may lead to net drier soil conditions due to changes in the ratio of evapotranspiration to precipitation (Chapter 4).

A recent study found that forests in both wet and dry environments around the world typically operate within a relatively narrow range of tolerance for drought conditions (Choat et al. 2012). Drought stress causes air bubbles to form in the xylem of growing trees (cavitation). Consequently, the ability to move water is diminished, which results in productivity declines or mortality, depending on the extent of the failure. Forest species from rain forests, temperate forests, and dry woodlands all showed a similarly low threshold for resisting hydraulic failure. Research indicates that drought length may be more important to tree mortality than drought severity or average dryness over a period of years (Gustafson and Sturtevant 2013). Furthermore, differences between land types can amplify or soften the effects of drought on tree mortality.

Few recent examples from published literature highlight the possibility for drought stress for northern Michigan forests. Studies in hybrid poplar plantations show that late-season moisture stress can reduce growth in the following growing season (Chhin 2010). A recent widespread aspen decline in northern Minnesota has been linked to the combined effects of a multi-year drought and insect defoliation (Worrall et al. 2013). Projections considering growing-season temperature and precipitation indicate that aspen could lose more than half its suitable habitat in the upper Great Lakes region by mid-century (Worrall et al. 2013). During the past century, drought has been linked to dieback in sugar maple, birch species, and ash species in Maine (Auclair et al. 2010). In the western United States, prolonged drought has caused widespread mortality of trembling aspen (Anderegg et al. 2012).

Conversely, modeling in northern Wisconsin suggests that drought events might benefit pioneer forest types like aspen and birch, even though individuals of these species are generally drought intolerant (Gustafson and Sturtevant 2013). Additionally, elevated atmospheric CO_2 may help adult trees of some species like bur oak withstand seasonal moisture stress (Wyckoff and Bowers 2010), and this effect may already be detectable across the eastern United States (Keenan et al. 2013). Site-level factors like stand density will also influence susceptibility to moisture stress, as high-density stands face increased competition for available moisture (D'Amato et al. 2011, Magruder et al. 2012). Additionally, drought-stressed trees are typically more vulnerable to insect pests and diseases (Dukes et al. 2009, Michigan Department of Natural Resources 2011).

Windstorms

Blowdowns from windstorms can have an important influence on the structure and species composition of forests in the assessment area, whether through small-scale events which add complexity to the landscape or through stand-replacing events (Frelich and Reich 1995a, 1995b; White and Host 2008). Species composition, stand age, soils, topography, and a host of other factors can control how a particular forest is physically affected by a given wind event (Peterson 2000; Rich et al. 2007, 2010). Some models project an overall increase in the frequency of extreme wind events across the central United States, but it is not projected that any increase in blowdowns in the assessment area will be outside the already high range of variability (Chapter 4).

Under climate change, stand-replacing events like blowdowns could potentially act as a catalyst for more rapid ecosystem change than would occur through migration and competition alone. Climatic conditions following a major wind event in the future may not favor typical successional pathways, particularly if regeneration consists of novel species mixes. Additionally, future blowdowns may lead to more wildfires if climate change results in more frequent extreme fire weather in the assessment area.

Frost and Snowfall

As discussed in Chapter 4, winter processes in the assessment area such as snowfall and soil frost may change substantially under climate change. Paradoxically, soil frost depth and the number of soil freeze-thaw events may increase in the near future as snowpack declines and soils are less insulated from cold temperatures (Hardy et al. 2001). This trend may already be affecting species with frost-intolerant root systems like sugar maple in the assessment area (Box 8). Northern hardwood species are generally shallowrooted and more vulnerable to freezing, and frost-related mortality in this forest type has been observed elsewhere in the northern United States (Auclair et al. 2010).

As winter temperatures increase over the 21st century, the average snowpack in the assessment area is projected to continue to decline. However, forest soils will be less frequently exposed to multi-day periods of extreme cold, so the net effect is projected to be a decrease in the duration of the soil frost season by 1 to 2 months across the assessment area by 2100 (Chapter 4). Shifts in the timing of the soil frost season may have cascading impacts on a variety of ecosystem processes. Unfrozen soils will be better able to absorb snowmelt and rainfall, leading to increased infiltration (Sinha and Cherkauer 2010). Increased infiltration may also lead to increased nutrient leaching from forest soils if the phenology of plant communities does not closely track the change in soil frost (Campbell et al. 2010). Studies from northern hardwood forests in New England have shown that snowmelt and soil thawing are advancing rapidly in the spring and that overstory leaf-out dates are lagging behind (Groffman et al. 2012), so these systems may lose additional soil nutrients.

Altered winter processes in the assessment area may also affect regeneration conditions for some tree species. Yellow birch is best able to disperse seeds over snow, and therefore may be impaired by less consistent snowpacks (Burns and Honkala 1990, Groffman et al. 2012).

Hydrologic Impacts

Hydrology is tightly linked to the health and function of forest ecosystems, whether through maintenance of soil moisture during the growing season, seasonal flooding, creating necessary decomposition conditions, or other processes. Many forest systems in the assessment area have particular soil moisture requirements for the seasonality and extent of saturation. Additionally, certain species

Box 8: Hardwood Decline in the Upper Great Lakes Region

Northern hardwood stands with sugar maple crown dieback have recently been reported in the upper Great Lakes region (Michigan Department of Natural Resources 2011). To investigate the cause of this dieback, researchers from Michigan Technological University have established permanent plots on industry, federal, and state land in the Upper Peninsula of Michigan, northern Wisconsin, and eastern Minnesota (Bal 2013). Plots are located in stands dominated by sugar maple with varying degrees of crown dieback. Data collection has included assessments of full crown and boles, canopy density, regeneration, earthworm impacts to the forest floor, soil compaction, topography, and nutrient status of soil and foliage. Average dieback percentage of live trees at all plots varied from 15 percent in 2009 to approximately 7 percent in 2012. A vigorous, healthy sugar maple stand should have less than 10 percent dieback.

Analysis has indicated that sugar maple dieback is related to many factors, including earthworms, climate, and site-level nutrients. Out of all plot variables measured, high densities of European earthworms removing the forest floor in northern hardwood forests were the most significant factor related to sugar maple crown dieback. The removal of the duff layer exposes roots and exacerbates further stresses on trees. Analysis of both raw tree ring data and basal area growth indicates a significant positive relationship with total winter snowfall, number of days with snowcover on the ground, and number of days below freezing temperatures across the region (Fig. 44), all of which have been decreasing in recent decades. Tree roots of sugar maple and other northern hardwoods are generally frost intolerant, and lack of adequate snowcover exposes these shallow roots to freezing conditions. Moderate drought conditions in recent years, especially in the Upper Peninsula of Michigan, have likely further contributed to maple dieback and decline. Soil and foliar nutrient analysis suggest site-specific variations in soil nutrients may have predisposed trees to decline.

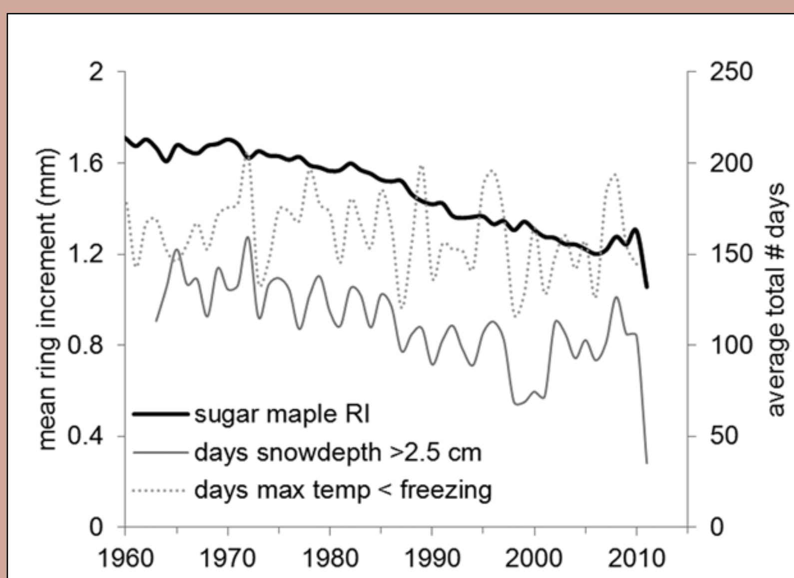


Figure 44.—Average sugar maple mean annual growth ring increment (RI) from research plots in western Upper Michigan, northern Wisconsin, and eastern Minnesota (118 plots, 313 trees), average annual total number of days with maximum temperatures below freezing, and average annual total number of days with snow depth greater than 1 inch from local weather stations (NOAA Climatic Data Center) (Bal 2013).

Forested coastline and cliffs on Grand Island in the eastern Upper Peninsula. Photo by Autumn Jauck, Hiawatha National Forest.

such as northern white-cedar and eastern cottonwood have particular seedbed requirements that are tightly linked to hydrologic conditions (Burns and Honkala 1990, Cornett et al. 2000).

Climate change is projected to alter hydrologic regimes throughout the assessment area. As discussed in Chapters 3 and 4, heavy precipitation events have been increasing across the assessment area during the past century and this trend is expected to continue. In addition to more episodic precipitation events, future climate scenarios also project a wide possible range of seasonal precipitation and soil moisture (Chapter 4). Such variability may expose forests to greater risk of hydrologic extremes: waterlogging and flooding on one hand, and moisture stress and drought on the other. Forests that are accustomed to seasonal or annual variations in water availability may be better able to tolerate this variability. In particular, riparian and lowland hardwoods and aspen-birch forests are all tolerant of varying degrees of hydrologic fluctuation. Barrens, jack pine, and red and white pine forests are adapted to periodic moisture stress and drought. Forests that depend on a more stable regime of soil moisture or water levels throughout the year or between years may be more stressed by hydrologic variation—particularly northern hardwoods and lowland conifers. Peatlands have been shown to respond in a matter of years to water table fluctuations of a few inches, and the productivity and functioning of these systems could be especially sensitive to the combination of water table variability and the direct effects of warming (Bridgham et al. 2008, Swanson and Grigal 1991).

In a review of the consequences of more extreme precipitation regimes, Knapp et al. (2008) also proposed that mesic systems may be most negatively affected because of increasing duration and severity of soil water stress. Xeric systems would generally be less affected by a more extreme precipitation regime because they already are limited by moisture stress and larger pulses of precipitation might afford them slightly longer periods of moisture. Hydric systems, on the other end of the spectrum, are already limited by anoxic conditions so longer dry periods between precipitation pulses might increase some ecosystem functions like biomass productivity. This conceptual framework does not incorporate modifiers like soil texture, root depth, and the particular regeneration requirements of tree species. The general principles make sense, as long as soil moisture changes are not dramatic enough to result in prolonged regeneration failures.

Additionally, hydric systems like lowland conifers could gradually transition to a novel community type given increased productivity and increased soil respiration. That is, these systems may be less stressed by a more extreme precipitation regime according to some measures, but they may still be vulnerable in terms of shifting to a new vegetation community. If extended drought or hydrologic alteration causes local water tables to drop and peat layers begin to decompose rapidly, a peatland forest of black spruce and tamarack could be colonized by a variety of other tree species (Gorham 1991). Conversely, if excessive flooding or hydrologic alteration causes water tables to rise, lowland conifer forests could transition to open wetland systems. These changes may be difficult to forecast given the uncertainty in future precipitation regimes and groundwater dynamics, but the effects could be important for C storage in peatland systems (Bridgham et al. 2008, Gorham 1991).

Soil Erosion

As climate change continues to intensify the hydrologic cycle, the increase in heavy rainfall events is projected to continue across the assessment area. One of the potential impacts of this trend is that soil erosion rates will increase (Nearing et al. 2004, 2005). One study from agricultural systems across the United States estimates that erosion rates could increase twice as fast as total rainfall amounts (Nearing et al. 2004). Most studies examining the effects of climate change on soil erosion have focused on agricultural settings, rather than forests. Although additional vegetative cover and root stabilization in forest systems may make forests less prone to soil erosion, not all forest soils will be equally protected. Reductions in vegetative cover due to a variety of climate-related impacts, such as earthworm invasion or prolonged drought, could increase susceptibility to erosion. Additionally, the projected decline in snowpack and the transition from snowfall to rain in winter months might make forest soils particularly vulnerable to erosion during the late fall and early spring. The northern Lower Peninsula is projected to undergo two to three more freeze-thaw cycles by the end of the century (Sinha and Cherkauer 2010), and these events can also lead to greater erosion from forest soils.

Wildfire

Wildfire is an important driver for forests across the assessment area in Michigan. Barrens and jack pine, mixed pine, and aspen-birch forests are often tied to wildfire dynamics, and these communities are often associated with particular regimes for different kinds of fire, such as surface fires or crown fires. Fire could also become an increasing source of disturbance in other forest types if climatic shifts over the 21st century result in different fire behavior. The climate of an area can directly affect the frequency, size and severity of fires; it also indirectly affects fire regimes through its influence on vegetation vigor, structure, and composition (Sommers et al. 2011).

The response of Michigan's fire regime to climate change will vary over time and space. Authors of a review paper on climate and wildfire conclude that fire-related impacts may be more important to some ecosystems than the direct effects of climate change on species fitness and migration (Sommers et al. 2011). Fire could have a greater influence because it can be a catalyst for change in vegetation, perhaps prompting more rapid change than would be expected based only on the changes in temperature and moisture availability. As with wind disturbances, the potential exists for novel successional pathways following wildfire if climatic conditions, seed sources, or management decisions favor different forest types.

Even if uncertainty exists for the near term, model simulations from around the world tend to agree that fire activity will increase by the end of the 21st century under climate change (Moritz et al. 2012). This agreement is particularly high for boreal forests, temperate coniferous forests, and temperate broadleaf and mixed forests. These global assessments correspond with more local research on climate and wildfire. Projections for boreal forests in Canada estimate that there may be a 100-percent increase in the annual area burned by the end of the century, along with a 50-percent increase in fire frequency (Flannigan et al. 2009). Research on boreal forest systems in Quebec projects that the wildfire season may shift later into the growing season, with wildfire risk doubling in August (Le Goff et al. 2009). Future fire activity may depend most on the relationship between temperature, precipitation, and evapotranspiration. If temperature and evapotranspiration increases amplify the effects of declining precipitation or overwhelm modest precipitation increases, fires are expected to increase (Drever et al. 2009).

Research suggests that human activities may have a larger influence on wildfire activity than biophysical drivers in some landscapes (Miranda et al. 2012). Land use and management decisions will be the primary factor that determines whether a change in fire risk might translate to an actual increase in wildfire activity. Key sources of uncertainty are future policies on wildfire suppression and prescribed fire. Complex spatial patterns of land use and active fire management programs also make broad-scale predictions of area burned unreliable for northern Michigan.

Invasive Species

As described in Chapter 1, nonnative invasive species are a major threat to forests in northern Michigan. It is generally expected that invasive plants will "disproportionally benefit" under climate change due to more effective exploitation of changed environments and more aggressive colonization of new areas (Dukes et al. 2009). The potential for climate change to disrupt hydrologic regimes, increase soil erosion, and intensify a variety of other stressors could increase the opportunity for invasive species to exploit altered environments. As an example of these potential interactions, studies in northern Minnesota found that a combination of invasive earthworms and warming conditions could benefit exotic understory plant species (Eisenhauer et al. 2012). Similarly, invasive species may facilitate the invasion and establishment of other nonnative species. This may be the case with European earthworms and European buckthorn, which appear to have a co-facilitating relationship (Heimpel et al. 2010). Invasive species can also limit regeneration opportunities for native tree species.

Forest Pests and Diseases

Under a high emissions scenario, researchers forecast more insect pest damage due to increased metabolic activity in active periods and increased winter survival (Dukes et al. 2009). The effect of climate on particular forest insects remains uncertain in many cases, however. Gypsy moth is limited by cold winter temperatures across the Midwest, and is anticipated to expand its range northward under future climate change scenarios (Frelich and Reich 2010, Vanhanen et al. 2007).

Hemlock wooly adelgid is limited by winter low temperatures of -10 to -15 °F (-24 to -26 °C) (Michigan Department of Natural Resources 2011). Current risk maps for this pest are based on average winter minimum temperatures (Fig. 45), but these maps do not account for the rapid rise in winter minimum temperatures that is projected across a range of climate scenarios (Chapter 4).

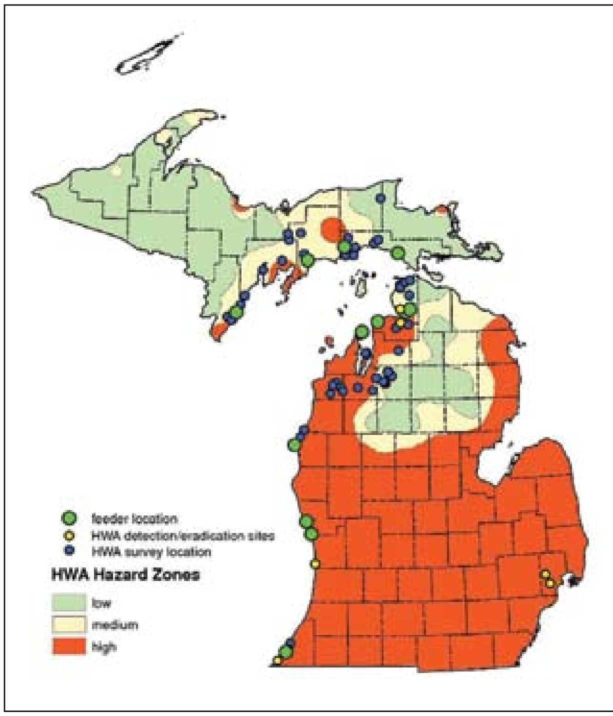
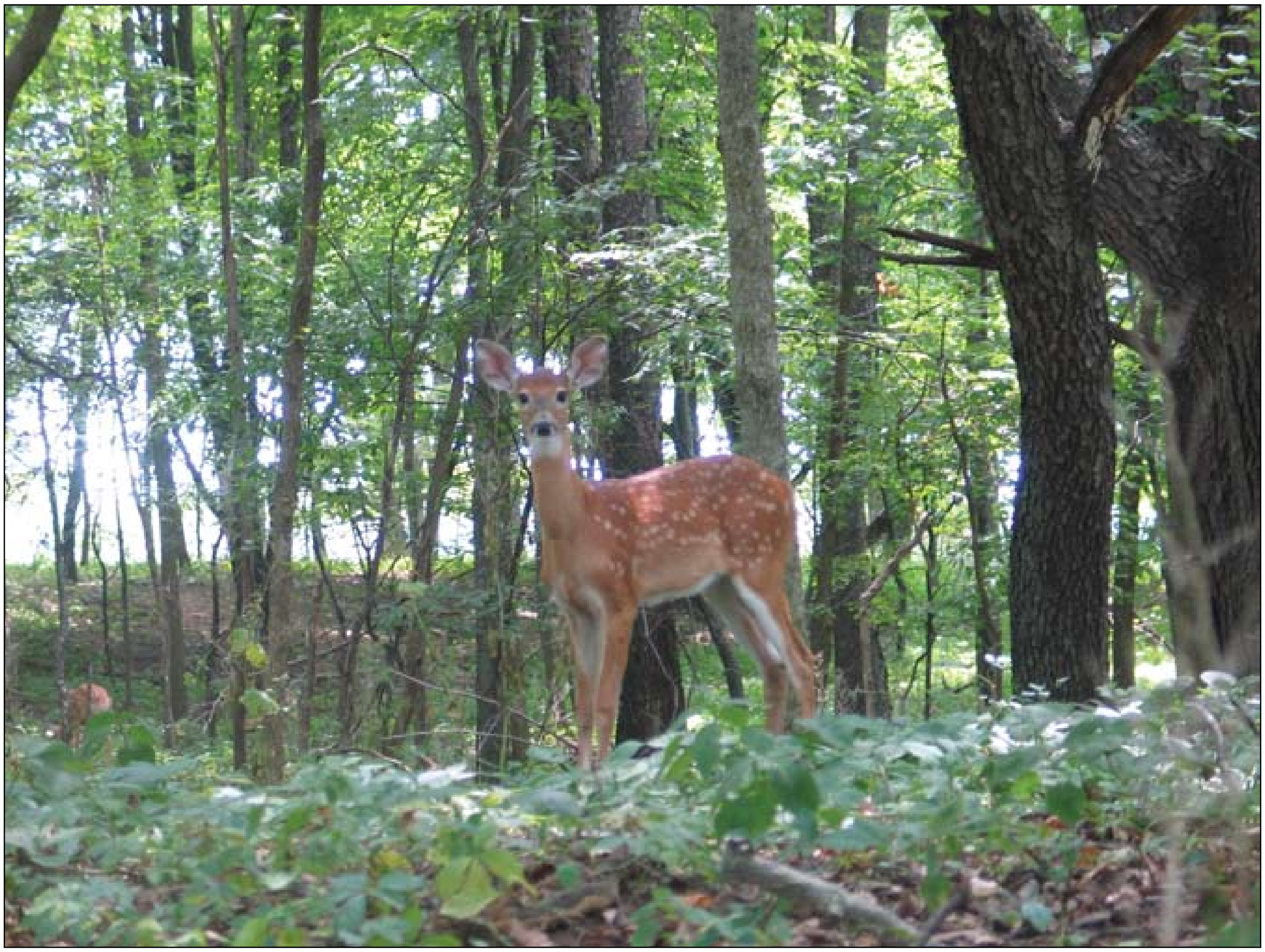


Figure 45.—Risk map for hemlock wooly adelgid (HWA) invasion in Michigan, based on observed average winter minimum temperatures, from Michigan Department of Natural Resources (2012). This map does not consider the projected increase in winter temperatures under climate change.

It is more difficult to anticipate the response of forest pathogens under a warmer future because of complex modes of infection, transmission, survival, and tree response (Dukes et al. 2009). A review of forest diseases and the potential impacts of climate change highlights the potential for interactions involving other stress agents that make trees more susceptible to diseases (Sturrock et al. 2011). Pathogens are generally expected to become more damaging in forests as the climate changes, because they will be able to adapt more quickly to new climatic conditions, migrate more quickly to suitable habitat, and reproduce at faster rates than host tree species. One example of a potential disease migrant to the assessment area is sudden oak death, a fungal pathogen currently limited to the West Coast and southeastern United States. This disease is limited by cold temperatures. Current risk maps for sudden oak death are based on the climate normal for 1971 through 2000, however, and do not account for projected climate shifts (Venette and Cohen 2006). The suitability maps for sudden oak death based on historical climate data already include all of Michigan as marginally suitable habitat. Particularly under warmer climate change scenarios, it is imaginable that this disease could survive in Michigan.

Herbivory

As mentioned above, changes in snowfall amount and duration throughout the assessment area are projected to affect the wintertime foraging behavior for herbivores such as moose, white-tailed deer, and snowshoe hare. Climate change is expected to favor white-tailed deer and reduce populations of moose throughout the assessment area (Frelich et al. 2012, Hoving et al. 2013, Rempel 2011). Warmer winter temperatures and reduced snow depth may lower the energy requirements for deer, and increase access to forage during winter months (Wisconsin Initiative on Climate Change Impacts Wildlife Working Group



A whitetailed deer fawn. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

2011). Conversely, warmer temperatures appear to cause greater physiological stress and parasite loads in moose.

If deer populations increase over the 21st century, this herbivore could have even greater impacts on forest vegetation across the assessment area than it already has. Research has found that deer browsing pressure may limit the ability of forests to respond to climate change (Fisichelli et al. 2012). Tree species anticipated to expand their ranges northward in the assessment area, such as red maple, sugar maple, and red oak, are browsed much more heavily than boreal conifers such as balsam fir and white spruce. Deer herbivory may also favor species which are not browsed heavily, such as ironwood and black cherry, or invasive species like buckthorn or Japanese barberry. Tree Atlas, LANDIS-II, and PnET-CN project that most mesic hardwood species and eastern white pine will gain in suitable habitat, biomass, and productivity in the assessment area during the 21st century, but none of these models accounts for herbivory.

Carbon Dioxide Fertilization

In addition to the effects of CO_2 on climate, the gas itself can affect plant productivity and species composition. Elevated CO_2 may enhance growth and water use efficiency of some species, potentially offsetting the effects of drier growing seasons (Ainsworth and Rogers 2007, Norby and Zak 2011, Wang et al. 2006). There is already some evidence for increased forest growth in the eastern United States (Cole et al. 2010, McMahon et al. 2010), but it remains unclear if enhanced growth can be sustained (Bonan 2008, Foster et al. 2010). The potential for water-use efficiency gains to buffer against moisture deficits could be particularly important for forests in the assessment area, given the potential for late-season moisture stress during the growing season. Research on bur oak in Minnesota indicates that this effect may have already improved the ability of adult trees to withstand seasonal moisture stress (Wyckoff and Bowers 2010).

As mentioned in the discussion of PnET-CN results, several factors might actually limit this CO_2 fertilization effect. Nutrient and water availability, ozone pollution, and tree age and size all play major roles in the ability of trees to capitalize on CO_2 fertilization (Ainsworth and Long 2005). Fire, insects, disease, and management could reduce forest productivity in discrete locations, and long-term community transitions might also influence the ability of forests to take advantage of additional atmospheric CO_2 .

Nutrient Cycling

As air temperatures warm and precipitation patterns change, changes may also occur in the way nutrients are cycled between plants, soils, and the atmosphere. Alterations in nutrient cycling have important implications for forest productivity, which can be limited by nutrients such as phosphorus, calcium, and N. Studies across the northeastern United States can give some insight into potential effects of climate change on nutrient cycling.

Decomposition of vegetation is carried out primarily by enzymes released from bacteria and fungi. These enzymes are sensitive to changes in temperature, and thus there is generally a positive effect of temperature on the rate of enzymatic activity as long as moisture is also sufficient (Brzostek and Finzi 2012, Rustad et al. 2001). In addition to increases in temperature, changes in growing season, soil frost, soil moisture, soil pH, and the interaction among these factors can affect nutrient cycling (Campbell et al. 2009). For example, more nutrients may leach from forest soils as a result of earlier spring thaws because the onset of photosynthesis in plant communities may not be advancing as rapidly and plants are not ready to take up the products of overwinter decomposition (Campbell et al. 2010).

A review of nutrient cycling and climatic factors for sugar maple concluded that extremes in light environment, temperature, and precipitation, as well as pathogen attack and herbivory, can induce or amplify nutrient imbalances (St. Claire et al. 2008). For example, excessive or inadequate soil moisture can limit nutrient acquisition by tree roots. Many studies have examined the effects of extended dry periods followed by moisture pulses on nutrient cycling (Borken and Matzner 2009). Although these moisture pulses do lead to a flush of mineral N, it is not sufficient to compensate for the lack of microbial activity during dry periods. Thus, an increase in wet-dry cycles appears to lead to a reduction in nutrient availability for trees. These results suggest that the increasingly episodic precipitation regime in the assessment area may add further stress to forests in the future.

Additionally, changes in tree species composition could alter the rate of N cycling in forest ecosystems, which would lead to further effects on productivity and vegetation changes. Conifer and oak litter contains less N compared to northern hardwood species, so hardwood species invading a spruce-fir or pine forest may create a positive feedback loop as their litter gradually increases available soil N and thereby increases their relative competitive advantage (Pastor and Post 1988).

Interactions

Clearly, none of the changes described above will occur in isolation. Climate change has the potential to alter this entire suite of ecosystem processes and stressors, in addition to others not considered here. The potential for interactions among these impacts will be critical in determining the resulting changes to forest ecosystems across the assessment area. Just as there are typically multiple interacting drivers for individual tree mortality (Dietze and Moorcroft 2011), overall community shifts will also be prompted by a variety of factors (Frelich and Reich 2010).

Recognizing the potential for these interactions will be necessary to accurately assess the risks that climate change poses to forests. Scientific research is beginning to clarify how biotic and abiotic stressors can operate in concert, but these types of studies are still rather rare (Gellesch et al. 2013). It has long been known that stressed trees are more susceptible to insect pests and diseases. For example, recent research has found that drought stress leads to more-damaging forest tent caterpillar outbreaks (Babin-Fenske and Anand 2011). Earthworm invasion tends to create warmer, drier soil surface conditions with more bare soil in forest systems, which may favor species that can germinate in these conditions (Eisenhauer et al. 2012). Earthworm invasion may also make northern hardwood forests more vulnerable to the effects of drought (Larson et al. 2010), leading to greater risk of disease and pest outbreak. The earthworm example is simply one chain of interactions, and many more links could be drawn to phenological changes, fire seasons, and other climate-mediated impacts.

SUMMARY

Climate change has the potential to affect forest ecosystems in a variety of ways. Some of these potential impacts have been investigated through a coordinated set of model projections. The model results from Tree Atlas, LANDIS-II, and PnET-CN each contribute particular kinds of information about how tree species and forest communities could potentially respond to a range of possible climate futures. Generally, these model projections agree that characteristic boreal or northern species and forest types may undergo declines in suitable habitat, landscape-level biomass, and productivity. These model projections indicate that temperate species may perform better, raising the possibility for potentially large community shifts across the assessment area in Michigan.

Furthermore, research on the direct and indirect impacts of climate change on forests highlights several potential drivers of change in the assessment area. These impacts may arise from chronic stress (e.g., extended drought), gradual changes (e.g., warming winter temperatures and declining snow levels), or discrete disturbance events (e.g., stand-replacing wildfires or insect pest outbreaks). Many of these factors may operate in concert, and synergistic or multiplying interactions may be the most difficult to understand and forecast.

Human decisions will add uncertainty to the response of ecosystems to climate change. Future land management decisions will largely dictate how these potential changes may affect forests in northern Michigan. For example, fire suppression policies and tactics may help determine the future extent and severity of wildfires across the assessment area, and public pressure and political will may determine how these decisions are made. These choices related to management and policy are beyond the scope of this assessment, but they will be critical in determining how forests in the assessment area will adapt to climate change.

CHAPTER 6: ECOSYSTEM VULNERABILITIES

This chapter describes the climate change vulnerability of nine major forest systems in the assessment area during the next century. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the susceptibility of a system to the adverse effects of climate change (IPCC 2007). It is a function of the potential impacts to a system and the adaptive capacity of that system to tolerate these impacts (Fig. 46). We consider a system to be vulnerable if it is at risk of changes leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity. This broad definition of vulnerability is warranted because forests are valued both for their particular character and mix of species and for the services they provide. The vulnerability of an ecosystem to climate change is independent of the economic or social values associated with the system, and the ultimate decision of whether to conserve vulnerable systems or allow them to shift to an alternate state will depend on the individual objectives of land management organizations.

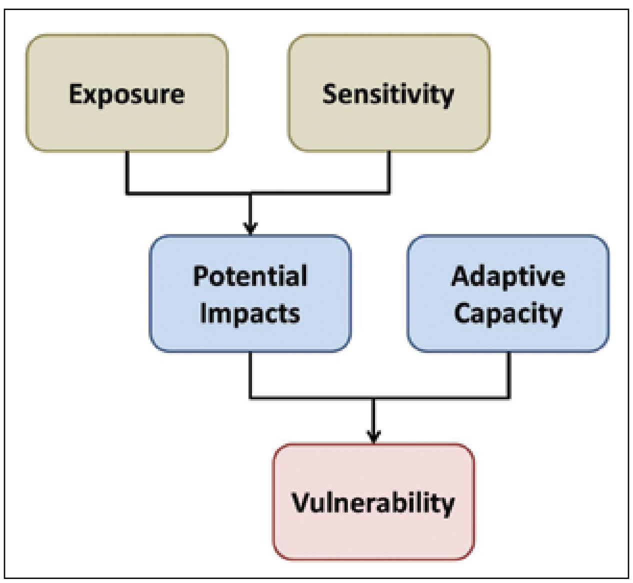


Figure 46.—Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity.

This chapter is organized into two sections. First, we present an overall synthesis of potential climate impacts on forests, organized according to drivers and stressors, ecosystem impacts, and factors that influence adaptive capacity. This synthesis is based on the current scientific consensus of published literature (Chapters 4 and 5). In the second section, we present individual vulnerability determinations for the nine forest systems considered in this assessment.

A SYNTHESIS OF CLIMATE CHANGE IMPACTS ON FOREST ECOSYSTEMS

Potential impacts are the direct and indirect effects of climate change on individual ecosystems. Impacts are a function of a system's exposure to climate change and its sensitivity to any changes. Impacts could be beneficial to a system if the changes result in improved heath or productivity, a greater area occupied by the system, or a tendency to maintain the identity of the system. Negative potential impacts would tend toward declining health and productivity, reduced territory occupied by the system, or a composition shift that leads to a substantially different identity for the system.

Throughout this chapter, statements about potential impacts and adaptive capacity factors will be qualified with a confidence statement. These confidence statements are formatted according to a confidence determination diagram from the IPCC's recent guidance for authors (Mastrandrea et al. 2010) (Fig. 47). Confidence was determined by gauging both the level of evidence and level of agreement among information sources. Evidence is robust when multiple lines of evidence are available as well as an established theoretical understanding to support the vulnerability determination. Agreement refers to the agreement among the available sources of evidence, not the level of agreement among authors of this assessment. Agreement was rated as high if theories, observations, and models tended to suggest similar outcomes.

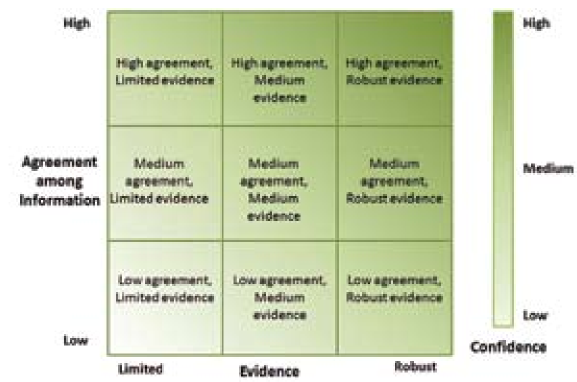


Figure 47.—Confidence determination diagram used in the assessment. Adapted from Mastrandrea et al. (2010).

Potential Impacts on Drivers and Stressors

Many physical and biological factors contribute to the state of forest ecosystems in northern Michigan. Some of these factors serve as drivers, or defining features that determine the identity of a system. Other factors can serve as stressors, reducing the health, productivity, and integrity of specific systems. Many factors, such as flooding or fire, may be drivers in one system and stressors in another. Moreover, some disturbances, such as flooding or fire, could be drivers in certain systems but could act as stressors if the timing or intensity of the disturbance changes.

Temperatures will increase (robust evidence, high agreement). *All global climate models project that temperatures will increase with continued increases in atmospheric greenhouse gas concentrations.*

A large amount of evidence from across the globe shows that temperatures have been increasing and will continue to increase due to human activities (Chapter 2). Temperatures across the assessment area have already exhibited significant increases (Chapter 3), and continued temperature increases are projected for the assessment area even under the most conservative future climate scenario (Chapter 4).

Winter processes will change (robust evidence, high agreement). *All evidence agrees that temperatures will increase more in winter than in other seasons across the assessment area, leading to changes in snowfall, soil frost, and other winter processes.*

Both climate scenarios for the assessment area project that winter temperatures will increase at a faster rate than temperatures in other seasons (Chapter 4). Even with projected increases in winter precipitation, temperature increases indicate that a greater proportion of moisture will be delivered as rainfall during this season. Combined with increased snowmelt from higher temperatures, the amount of snow on the ground is expected to decrease across the assessment area (Sinha and Cherkauer 2010). In addition, northern Michigan may have 30 to 40 fewer days of soil frost by the end of the century and more freeze-thaw events (Sinha and Cherkauer 2010). This decrease in snow cover and frozen soil is expected to affect a variety of ecosystem processes, including decomposition activity, nutrient cycling, the onset of the growing season, and other phenological factors. Warmer winters could also result in increased survival for insect pests.

Growing seasons will get longer (robust evidence, high agreement). *There is high agreement among information sources that projected temperature increases will lead to longer growing seasons in the assessment area.*

Evidence at both global and local scales indicates that growing seasons have been getting longer, and this trend is projected to become even more pronounced over the next century (Chapters 3 and 4). Longer growing seasons have the potential to affect the timing and duration of ecosystem and physiological processes across the region (Dragoni and Rahman 2012). As seasons shift so that spring arrives earlier and fall extends later into the year, phenology may shift for plant species that rely on temperature as a cue for the timing of leaf-out, reproductive maturation, and other developmental processes (Schwartz et al. 2006a, Walther et al. 2002). Longer growing seasons could also result in greater growth and productivity of trees and other vegetation, but only if balanced by available water and nutrients (Chapter 5). Moreover, an extended growing season might not benefit all tree species equally (Chapter 4).

The amount and timing of precipitation will change (medium evidence, high agreement). *All global climate models agree that there will be changes in precipitation patterns across the assessment area.*

For the climate projections used in this assessment (Chapter 4) and other publications, large variation exists for projected changes in precipitation for the assessment area (Kling et al. 2003, Winkler et al. 2012). Although individual model projections for the assessment area may differ, there is general agreement that annual precipitation is expected to remain consistent or increase slightly during the 21st century. Models also tend to agree that precipitation patterns between seasons may shift substantially (Kunkel et al. 2013). Precipitation increases are generally expected to be larger in winter and spring, which is in agreement with both climate scenarios presented in this assessment (Chapter 4). Summer precipitation is projected to increase slightly or decrease sharply (Chapter 4).

Intense precipitation events will continue to become more frequent (medium evidence, medium agreement). *There is some agreement that the number of heavy precipitation events will continue to increase in the assessment area. If they do increase, impacts from flooding and soil erosion may also become more damaging.*

Heavy precipitation events have been increasing in number and severity in the upper Midwest in general and for Michigan in particular (Groisman et al. 2012, Kunkel et al. 2008, Saunders et al. 2012), and many models agree that this trend will continue during the next century (IPCC 2007, Kling et al. 2003, Kunkel et al. 2013). Most heavy precipitation events occur during summer in Michigan. The magnitude or frequency of flooding could also potentially increase in the winter and spring due to increases in total runoff and peak stream flow during those times (Cherkauer and Sinha 2010). Flood risks will ultimately depend on local geology as well as future decisions regarding infrastructure and land use, which remain unknown. Increases in runoff following heavy precipitation events could also lead to an increase in soil erosion (Nearing et al. 2004).

Droughts will increase in duration and area (limited evidence, low agreement). *A study using multiple climate models indicates that drought may increase in length and extent, and an episodic precipitation regime could mean longer dry periods between events.*

With an increasingly episodic precipitation regime, it has been suggested that there may be longer intervals between heavy rainfall events in the future (Knapp et al. 2008). Studies examining a range of climate model projections disagree with this conclusion, projecting that northern Michigan may experience fewer consecutive days without precipitation in the future (Kunkel et al. 2013).

Overall, there is relatively low confidence in the projected future frequency of droughts across the central United States. Climate projections described in this assessment also highlight the possibility of reduced precipitation and increased moisture stress during summer months, particularly for the GFDL A1F1 scenario (Chapter 4).

Soil moisture patterns will change (medium evidence, high agreement), with drier soil conditions later in the growing season (medium evidence, medium agreement). *Studies show that climate change will affect soil moisture, but there is disagreement among climate and impact models on how soil moisture will change during the growing season.*

As discussed above, seasonal changes in precipitation are expected across the assessment area. Due to projected decreases in summer precipitation and increases in winter and spring precipitation, it is reasonable to expect that soil moisture regimes will also shift. Longer growing seasons and warmer temperatures may also result in greater evapotranspiration losses and lower soil-water availability later in the growing season (Chapter 4). Outputs from the PnET-CN model indicate that forests in the assessment area may become increasingly moisture-limited under climate change (Chapter 5). This condition may be particularly true in locations where soils and landforms do not allow retention of precipitation from intense events. The northern Lower Peninsula generally has coarse, sandy soils, which may offer limited water storage capacity. There is a lot of variation among model projections, however, and it is also possible that the assessment area will experience an increase in precipitation sufficient to offset increases in evapotranspiration (Winkler et al. 2012).

Climate conditions will increase fire risks by the end of the century (medium evidence, medium agreement). *Some national and global studies suggest that wildfire risk will increase in the region, but few studies have specifically looked at wildfire potential in the assessment area.*

At a global scale, the scientific consensus is that fire risk will increase by 10 to 30 percent due to higher summer temperatures (IPCC 2007). For the early part of the 21st century, there is low agreement in this trend across climate models (Moritz et al. 2012). By the end of the 21st century, however, most models project an increase in wildfire probability, particularly for boreal forests, temperate coniferous forests, and temperate broadleaf forests. Studies from southern Canada also project more active wildfire regimes in the future (Drever et al. 2009, Flannigan et al. 2009, Le Goff et al. 2009). In addition to the direct effects of temperature and precipitation, increases in fuel loads from pest-induced mortality or blowdown events could increase fire risk, but the relationship between these factors can be complex (Hicke et al. 2012). Forest fragmentation and unknown future wildfire management decisions also make fire projections more uncertain for the assessment area. Additionally, we do not have clear projections of how the nature of the fire regimes in Michigan may change—the proportion of surface fires to crown fires, for example.

Many invasive species, insect pests, and pathogens will increase or become more damaging (limited evidence, high agreement). *Evidence indicates that an increase in temperature and greater moisture stress may lead to increases in these threats, but research to date has examined few species.*

Invasive species are already a persistent and growing stressor across much of the United States. Changes may exacerbate this problem, as warmer temperatures may allow some invasive plant species, insect pests, and pathogens to expand their ranges farther north (Dukes et al. 2009). Northern Michigan may lose some of the protection offered by a traditionally cold climate and short growing season. Combinations of factors may also favor invasive species, such as exotic earthworms, and facilitation among several nonnative species (Chapter 5). Pests and pathogens are generally more damaging in stressed forests, so there is high potential for these agents to interact with other climate-mediated stressors. Unfortunately, we lack basic information on the climatic thresholds that apply to many forest pests, and our ability to predict the mechanisms of infection, dispersal, and transmission for disease agents remains low. Furthermore, it is not possible to predict all future invasive species, pests, or pathogens that may enter the assessment area during the 21st century.

Potential Impacts on Forests

Shifts in drivers and stressors mentioned above will naturally lead to changes in forests throughout the assessment area over the next century. Indirect impacts of climate change may become manifest through shifts in suitable habitat, species composition, or function of forest ecosystems.

Boreal species will face increasing stress from climate change (medium evidence, high agreement). *Impact models agree that boreal or northern species will experience reduced suitable habitat and biomass across the assessment area, and that they may be less able to take advantage of longer growing seasons and warmer temperatures than temperate forest communities.*

Across northern latitudes, it is generally expected that warmer temperatures will be more favorable to species that are located at the northern extent of their range and less favorable to those at the southern extent (Parmesan and Yohe 2003). Results from climate impact models project a decline in suitable habitat and landscape-level biomass for northern species such as balsam fir, black spruce, white spruce, tamarack, jack pine, northern white-cedar, and paper birch (Chapter 5). PnET-CN results also suggest that spruce-fir forests may be less able to experience productivity gains than other forest types across the range of anticipated climate futures. These northern species may persist in the assessment area throughout the 21st century, but with declining vigor. Boreal species may remain in areas with favorable soils, management, or landscape features. Additionally, boreal species may be able to persist in the assessment area if competitor species are unable to colonize these areas (Iverson et al. 2008).

Southern species will be favored by climate change (medium evidence, high agreement). *Impact models agree that suitable habitat and biomass will increase for many temperate species across the assessment area, and that longer growing seasons and warmer temperatures will lead to productivity increases for temperate forest types.*

Model results project that species near their northern range limits in the assessment area may become more abundant and more widespread under a range of climate futures (Chapter 5). Species projected to increase in suitable habitat in the assessment area include American basswood, black cherry, green ash, white ash, white oak, and a variety of minor southern species (Chapter 5). PnET-CN outputs also indicate that deciduous forest types have the potential for large productivity increases across northern Michigan. In addition, Tree Atlas results project that suitable habitat may become available for species not currently found in the assessment area (e.g., mockernut hickory, honeylocust, and post oak) by the end of the century. Conversely, LANDIS-II projects that many temperate and southern species may experience biomass declines under the GFDL A1FI scenario. This projection indicates that many potential increasers may in fact be limited under hotter, drier conditions. Habitat fragmentation and dispersal limitations could hinder the northward movement of southerly species, despite the increase in habitat suitability. Most species can be expected to migrate more slowly than their habitats will shift (Iverson et al. 2004a, 2004b; McLachlan et al. 2005; Scheller and Mladenoff 2008). Pests and diseases such as emerald ash borer and Dutch elm disease are also expected to limit some species projected to increase.

Forest communities will change across the landscape (limited evidence, high agreement). *Although few models have specifically examined how communities may change, model results from individual species and ecological principles suggest that recognized forest communities may change in composition as well as occupied range.*

Species will respond individually to climate change, which may lead to the dissolution of traditional community relationships (Davis et al. 2005, Root et al. 2003). The model results presented in Chapter 5 raise the possibility of potentially large changes in forest communities across northern Michigan. Generally, the models indicate that climate trends may favor hardwoods across the landscape after 2050, though ecological lag times and management decisions may slow forest-type conversions.

Douglas Lake at the University of Michigan Biological Station. Photo by Stephen Handler, U.S. Forest Service.

Conceptual models based on ecological principles lend support to this possibility, particularly along ecological transition zones (Frelich and Reich 2010). Modeling studies also project that forest communities may move across the assessment area (Iverson et al. 2008, Lenihan et al. 2008). Thus, the forest systems described in the assessment area may shift and rearrange into novel communities. Observed trends have suggested that forest species may be more prone to range contraction at southern limits and less able to expand ranges northward to track climate change (Murphy et al. 2010, Woodall et al. 2013, Zhu et al. 2012). Therefore, possibility also exists for nonnative species to take advantage of shifting forest communities and unoccupied niches if native forest species are limited (Hellmann et al. 2008).

Forest productivity will increase across the assessment area (medium evidence, medium agreement). *Some model projections and other evidence support modest productivity increases for forests across the assessment area, although there is uncertainty about the effects of CO_2 fertilization. It is expected that productivity will be reduced in localized areas.*

Results from PnET-CN and other studies on CO_2 fertilization show support for general increases in productivity across the assessment area (Chapter 5). Warmer temperatures are expected to speed nutrient cycling and increase photosynthetic rates for most tree species in the assessment area. Longer growing seasons could also result in greater growth and productivity of trees and other vegetation, but only if sufficient water and nutrients are available (Chapter 5). Conversely, LANDIS-II modeling results for this assessment project gradual productivity declines under the GFDL A1FI scenario. Simulations in LANDIS-II do not include the possible effects of CO_2 fertilization, which could increase productivity. Episodic disturbances such as fires, wind events, droughts, and pest outbreaks may reduce productivity in certain areas over different time scales. In addition, lags in migration of species to newly suitable habitat may also reduce productivity until a new equilibrium is reached (Pastor and Post 1988, Post and Pastor 1996, Solomon 1986).

Adaptive Capacity Factors

Adaptive capacity is the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption (Glick et al. 2011). Below, we summarize factors that could enhance or reduce the adaptive capacity of forest systems within the assessment area. Greater adaptive capacity tends to reduce climate change vulnerability, and lower adaptive capacity tends to increase vulnerability.

Low-diversity systems are at greater risk (medium evidence, high agreement). *Studies have consistently shown that more-diverse systems are more resilient to disturbance, and low-diversity systems have fewer options to respond to change.*

Climate change is expected to alter the nature and timing of many kinds of disturbance events across the assessment area (Chapters 4 and 5). In general, species-rich communities have exhibited greater resilience to extreme environmental conditions and greater potential to recover from disturbance than less diverse communities (Ogden and Innes 2007; Tilman 1996, 1999). Consequently, less diverse communities are inherently more susceptible to future changes and stressors (Swanston et al. 2011). Elmqvist et al. (2003) emphasize that “response diversity,” or the diversity of potential responses of a system to environmental change, is a critical component of ecosystem resilience. Response diversity is generally reduced in less diverse ecological systems. Northern hardwood forests generally support a large number of tree species and therefore have many possible future trajectories, but aspen-birch forests have fewer potential paths. Genetic diversity within species is also critical for the ability of populations to adapt to climate change, because species with high genetic variation have better odds of producing individuals that can withstand extreme events and adapt to changes over time (Reusch et al. 2005).

Species in fragmented landscapes will have less opportunity to migrate in response to climate change (limited evidence, high agreement). *The dispersal ability of individual species is reduced in fragmented landscapes, but the future degree of landscape fragmentation and the potential for human-assisted migration are two areas of uncertainty.*

Habitat fragmentation can hinder the ability of tree species to migrate to more suitable habitat on the landscape, especially if the surrounding area is not forested (Ibáñez et al. 2006, Iverson et al. 2004a). Modeling results indicate that mean centers of suitable habitat for tree species will migrate between 60 and 350 miles by the year 2100 under a high emissions scenario and between 30 and 250 miles under milder climate change scenarios (Iverson et al. 2004a). Based on gathered data of seedling distributions, it has been estimated that many northern tree species could possibly migrate northward at a rate of 60 miles per century (Woodall et al. 2009), and other evidence indicates that natural migration rates could be far slower for some species (McLachlan et al. 2005, Murphy et al. 2010). Fragmentation makes this disparity even more challenging because the landscape is essentially less permeable to migrating species (Jump and Peñuelas 2005, Scheller and Mladenoff 2008).

Systems that are limited to particular environments will have less opportunity to migrate in response to climate change (limited evidence, high agreement). *Despite a lack of published research demonstrating this concept in the assessment area, our current ecological understanding indicates that migration to new areas will be particularly difficult for species and systems with narrow habitat requirements.*

Several species and forest types in northern Michigan are confined to particular habitats on the landscape, whether through particular requirements for hydrologic regimes or soil types, or other reasons. Similar to species occurring in fragmented landscapes, isolated species and systems face additional barriers to migration (Jump and Peñuelas 2005). More-widespread species may also have particular habitat requirements. For example, sugar maple is often limited to soils that are rich in nutrients like calcium, so this species may actually have less newly suitable habitat in the assessment area than might be projected solely from temperature and precipitation patterns. Riparian forests are not expected to migrate to upland areas because many species depend on seasonal flood dynamics for regeneration and a competitive advantage. Similarly, lowland conifer systems often contain a unique mix of species that are adapted to low pH values, peat soils, and particular water table regimes. These systems face additional challenges in migration compared to more-widespread species with broad ecological tolerances.

Systems that are more tolerant of disturbance have less risk of declining on the landscape (medium evidence, high agreement). *Basic ecological theory and other evidence support the idea that systems adapted to more frequent disturbance will be at lower risk.*

Disturbances such as wildfire, flooding, and pest outbreaks are expected to increase in the assessment area (Chapters 4 and 5). Northern hardwoods in particular are adapted to gap-phase disturbances, with stand-replacing events occurring over hundreds or thousands of years. If climate changes the nature of disturbance events in these systems so that stand-replacing events become more frequent, northern hardwoods may suffer. Mesic systems can create conditions that could buffer against fire and drought to some extent, but these systems may not do well if soil moisture declines significantly (Nowacki and

Abrams 2008). Forest systems in the assessment area that are more tolerant of drought, flooding, or fire are expected to be better able to withstand climate-driven disturbances. This principle holds true only to a given point, because it is also possible for disturbance-adapted systems to undergo too much disruption. For example, jack pine systems might cover a greater extent under drier conditions with more frequent fire, but these systems might also convert to barrens or open grasslands if drought becomes too severe or fire becomes too frequent. Similarly, more-frequent surface fires could benefit red pine and white pine forests, but a shift to a crown-fire regime could reduce these species.

VULNERABILITY DETERMINATIONS FOR INDIVIDUAL FOREST SYSTEMS

Climate-induced shifts in drivers, stressors, and dominant tree species will result in different impacts to forested systems within the assessment area. Some communities may have a greater capacity to adapt to these changes than others, whereas some may be susceptible to relatively minor impacts. Therefore, it is helpful to consider these factors for individual forest systems, in addition to describing general principles related to vulnerability and adaptive capacity. Table 18 presents a summary of major drivers and stressors for each forest community covered in this assessment.

The following vulnerability determinations draw on the information presented in previous chapters, as well as an expert panel assembled from a variety of organizations and disciplines across the assessment area. The 27 panelists evaluated anticipated climate trends for the assessment area and model projections (Chapter 5), in combination with their own expertise. For each forest system, panelists considered the potential impacts and adaptive capacity to assign a vulnerability determination and a level of confidence in that determination using the same confidence scale described above. For a complete description of the methods used to determine vulnerability, see Appendix 5.

Overall vulnerability determinations ranged from moderate-low (oak associations and barrens) to high (upland spruce-fir) (Table 19). Impacts were rated as being most negative for upland spruce-fir and lowland conifers, and most positive for barrens. Adaptive capacity was rated lowest for upland spruce-fir, and highest for northern hardwoods, oak associations, and barrens. Panelists tended to rate the amount of evidence as medium (between limited and robust) for most forest systems. Incomplete knowledge of future wildfire regimes, interactions among stressors, and precipitation regimes limited this component of overall confidence. The ratings of agreement among information also tended to be in the medium range. Contrasting information about precipitation regimes under the high and low climate change scenarios was one factor that limited the level of agreement among information. The way that forest communities were organized and described for this assessment also limited the agreement in some instances. In general, ratings were slightly higher for agreement than for evidence. Evidence appears not to be as robust as the experts would prefer, but the information that is available leads them to reach a similar conclusion.

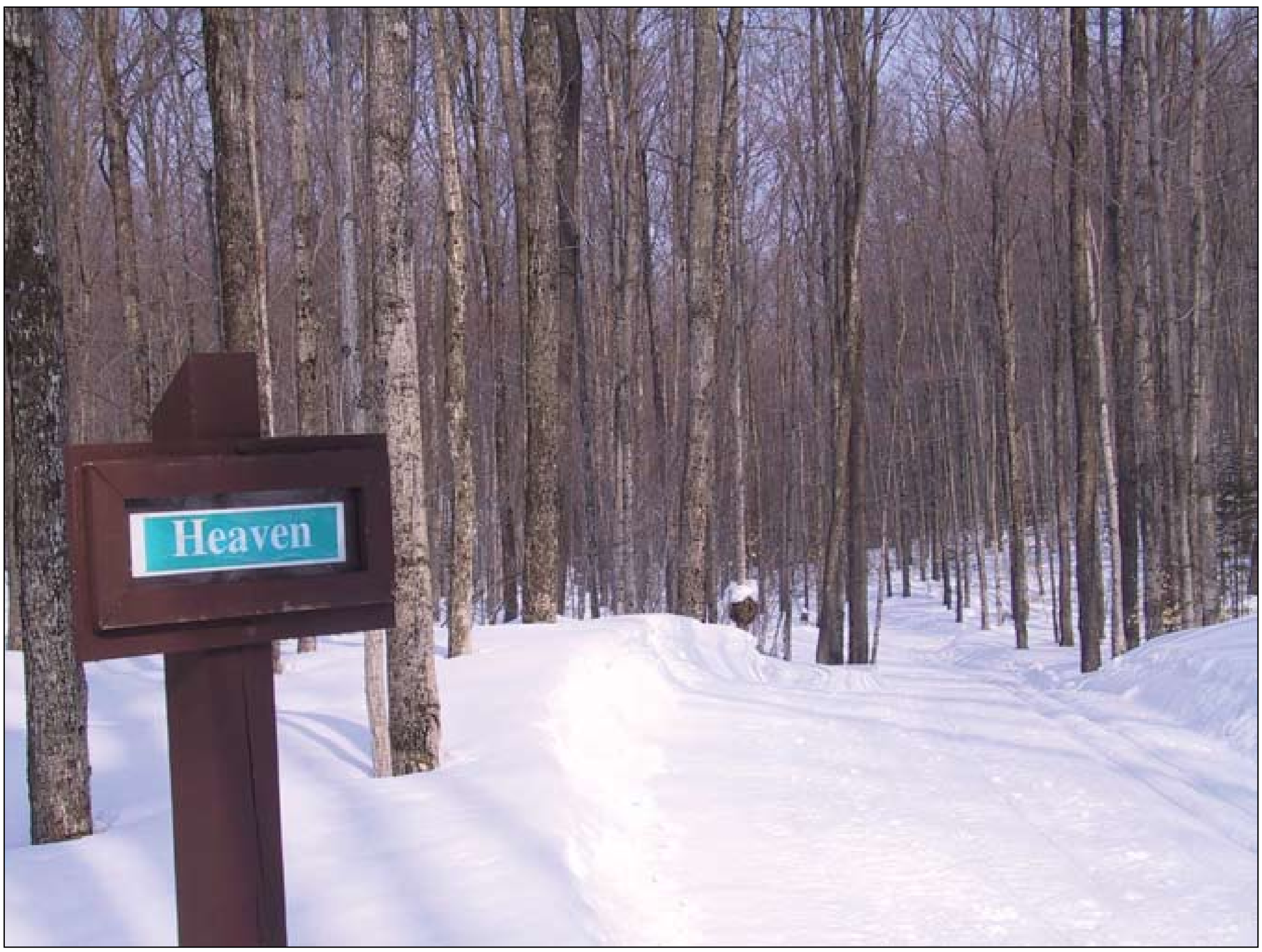
In the sections that follow, we summarize the climate-related impacts on drivers, stressors, and dominant tree species that were major contributors to the vulnerability determination for each forest system. In addition, we summarize the main factors contributing to the adaptive capacity of each system.

Table 18.—Forest systems considered in this assessment, with a summary of major drivers and stressors for each system (Cohen 2000a, 2000b, 2001, 2002a, 2002b, 2006, 2007; Comer 1996; Kost 2002; Kost et al. 2007; Slaughter et al. 2007; Tepley et al. 2004; Weber et al. 2006, 2007)

Forest system	Major drivers	Major stressors
Upland spruce-fir	favored in thin nutrient-poor soils or glacial lake plains, high snowfall areas with short growing seasons, favored by moderated climate in lake-effect areas, catastrophic disturbances from fire, wind, and pests	spruce budworm and other pests, drought, deer and moose herbivory
Jack pine (including pine-oak)	coarse-textured soils, upland areas, drought-tolerant, fire-return intervals 50 to 250 years, requires scarification or fire for regeneration, favored by cold temperatures	fire suppression or exclusion, insect pests and diseases, difficulty of applying prescribed fire
Red pine-white pine	sandy to dry-mesic soils, limited by high summer temperatures, dependent on disturbance for regeneration, red pine regeneration primarily through planting, favored by drought, fire-return intervals 50 to 250 years	fire suppression or exclusion, difficulty of applying prescribed fire, hardwood encroachment, insect pests and diseases, deer herbivory
Lowland conifers	peat or mineral soils, low landscape positions, groundwater seepage, saturated throughout growing season, windthrow events, stand-replacing fire on long cycles, limited by drought	changes to water table, roads and beaver dams, insect pests and diseases, deer herbivory, loss of coarse woody debris, drought and stand-replacing fire
Aspen-birch	gradient of soil types and landforms, frequent disturbance or management, limited by warm temperatures and moisture stress	fire suppression, forest tent caterpillar and gypsy moth, drought, deer herbivory, hypoxylon canker
Northern hardwoods	mesic soils or deep impermeable layers, consistent moisture and nutrients, gap-phase disturbances with stand-replacing events every 400 to 2,000 years	exotic earthworms, invasive plants, insect pests, diseases, freeze-thaw cycles, drought, deer herbivory, management that removes coarse woody debris or reduces diversity
Lowland-riparian hardwoods	alluvial soils or impermeable clay lens, nutrient-rich soils, seasonally or annually inundated or saturated, connectivity to river or water table, tip-up mounds and periodic dry conditions important for regeneration	changes to soil moisture regime, ongoing ash decline, invasive species, insect pests and disease, drought, deer herbivory
Oak associations	sandy to dry-mesic soils, limited by cold temperatures, dependent on disturbance for regeneration, drought tolerant, fire-return intervals 50 to 250 years or longer	fire suppression or exclusion, difficulty of applying prescribed fire, insect pests and diseases, deer and rabbit herbivory, exotic species, severe drought, root frost
Barrens	coarse-textured and excessively drained soils, overlapping or short-interval fires, canopy cover only 5 to 25 percent, favored by cold temperatures and frost pockets	fire suppression or exclusion, insect pests and diseases, difficulty of applying prescribed fire, competition from herbaceous species and woody encroachment, invasive species

Table 19.—Vulnerability determination summaries for the forest systems considered in this assessment

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Upland spruce-fir	Negative	Low	High	Medium-High	Medium-High
Jack pine (including pine-oak)	Moderate	Moderate-Low	High-Moderate	Medium	Medium-High
Red pine-white pine	Moderate	Moderate-Low	High-Moderate	Limited-Medium	Medium
Lowland conifers	Negative	Moderate-Low	High-Moderate	Medium	Medium
Aspen-birch	Moderate-Negative	Moderate	Moderate	Medium	Medium
Northern hardwoods	Moderate	Moderate-High	Moderate	Medium	Medium
Lowland-riparian hardwoods	Moderate-Negative	Moderate	Moderate	Medium	Low-Medium
Oak associations	Moderate	Moderate-High	Low-Moderate	Medium	Medium
Barrens	Moderate-Positive	Moderate-High	Low-Moderate	Limited-Medium	Medium



Cross-country ski trails in the eastern Upper Peninsula. Photo by U.S. Forest Service, Hiawatha National Forest.

Upland Spruce-Fir

High Vulnerability (medium-high evidence, medium-high agreement)

The boreal species within upland spruce-fir forests are not projected to tolerate warmer temperatures, increased competition from other forest types, and more-active forest pests. These forests are generally restricted to lake-effect areas on the landscape and are not well-equipped to adapt to climate change.

Negative Potential Impacts

Drivers: Within the assessment area, upland spruce-fir forests are typically confined to areas with shorter growing seasons and lake-effect snow and fog. Water temperatures of the Great Lakes are increasing faster than air temperatures, so lake-effect fog may become less common during the growing season. Uncertainty exists for snowfall levels in the assessment area, particularly for lake-effect snow, but it is projected that snowfall will decline by the end of the century. Additionally, several species in this system are limited by high growing-season temperatures, so projected warming in the assessment area may exceed the physiological limits of this forest type.

Dominant Species: Considering the range of possible climate futures, most dominant species that constitute upland spruce-fir forests are projected to decline in suitable habitat and biomass across the assessment area (balsam fir, northern white-cedar, white spruce, and paper birch). These are boreal species near their southern range limits. The same modeling studies offer mixed results for red maple, quaking aspen, and white pine, but these species are all generally projected to fare worse under the hotter, drier GFDL AFF1 scenario. Spruce-fir forests may be less able to take advantage of warmer conditions and longer growing seasons for productivity increases.

Stressors: Insect pests like spruce budworm may become more active and damaging under a warmer climate. Prolonged droughts and warmer temperatures expected under climate change will also be particularly stressful for this forest type. White-tailed deer populations are also anticipated to increase with warmer winters, so herbivory on preferred species may continue to hinder regeneration for certain species like northern white-cedar. Conversely, non-palatable boreal conifers may benefit from reduced competition if deer herbivory prevents hardwood expansion into these sites.

Low Adaptive Capacity

Upland spruce-fir forests can persist on sandy, nutrient-poor soils, so they may be able to tolerate short-term moisture stress. Several of these species produce seed and regenerate well after disturbance such as fire. These forests have relatively low diversity, however, which leads to fewer possible future trajectories (lower response diversity). Boreal forests are also spatially confined in the assessment area based on lake-effect conditions, and they are not expected to colonize new areas under anticipated future conditions. Hardwood forests may be able to invade sites occupied by boreal forests as growing seasons lengthen, but poor soils and comparably colder temperatures may limit the ability of some hardwoods to outcompete boreal conifers.

A mature upland spruce-fir forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

A spruce plantation with an aspen component. Photo by Maria Janowiak, U.S. Forest Service.

A previously burned upland spruce-fir forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Jack Pine (including Pine-Oak)

High-Moderate Vulnerability (medium evidence, medium-high agreement)

Impact models project declines in suitable habitat and biomass for jack pine, and the potential exists for increased hardwood competition and greater pest and disease activity. A high tolerance for disturbance and the current management emphasis increase the adaptive capacity of this system.

Moderate Potential Impacts

Drivers: Jack pine forests are generally found on sites with coarse-textured soils, and may be able to tolerate the projected soil moisture decreases during the summer months. Studies project that wildfires may burn larger areas in northern Michigan under climate change. Severe wind events or pest outbreaks could also provide more fuel buildup for large fire events. Greater wildfire activity could be positive for these forest types, but too much change to the fire regime might hamper regeneration and cause these forests to shift to barrens. Jack pine forests are also found in frost pocket areas, and future warmer temperatures may allow frost-intolerant species like oaks to invade these sites.

Dominant Species: Considering the range of possible future climates, jack pine is expected to decline in suitable habitat and biomass across the assessment area over the next 100 years. This species is at the southern extent of its range in Michigan. Red pine is also projected to decline in biomass and suitable habitat, particularly under the hotter, drier GFDL A1FI scenario. Projections are mixed for eastern white pine, northern red oak, northern pin oak, and red maple, but these species are generally expected to decline under GFDL A1FI. Pine forests may be able to take advantage of warmer conditions and longer growing seasons, if CO_2 fertilization does in fact boost long-term water-use efficiency and productivity.

Stressors: Insect pests like jack pine budworm and diseases like scleroderris canker may become more damaging under a warmer climate, and the possibility exists for new pests such as western bark beetles to arrive in the assessment area. The window of opportunity for applying prescribed fire to jack pine forests may shift under future climate change, but it is unclear if it would expand the potential to use fire as a management tool. The potential also exists for warmer temperatures to accelerate litter layer decomposition in these forests, leading to lower water-holding capacity and greater moisture stress. These conditions could prompt a shift to barrens systems in some locations.

Low-Moderate Adaptive Capacity

Jack pine forests are tolerant of drought and disturbances and thus have greater adaptive capacity to climate change. These forests can persist on poor soils and, under future drier conditions, may gain territory that is currently more mesic. Contemporary forest management practices, including Kirtland's warbler management, favors jack pine forests in certain areas on the landscape, including heavily managed plantations. Overall, low species diversity gives this forest type few alternatives if conditions shift beyond tolerable limits.

Jack pine forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Bigtooth aspen in a young jack pine stand. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

Fire scars in a jack pine stand. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

Red Pine-White Pine

High-Moderate Vulnerability (limited-medium evidence, medium agreement)

A major threat to red pine and white pine forests is the potential for greater pest and disease activity, along with the potential for interactions among stressors. Tolerance for drought and disturbance increases the adaptive capacity of these forests, and the future fire regime is a primary uncertainty.

Moderate Potential Impacts

Drivers: More frequent moisture stress or more extensive droughts could benefit red pine and white pine (RP-WP) forests on mesic soils, but could impair stands on the driest sites. Moisture stress could favor jack pine or northern pin oak on already marginal RP-WP sites. Increased surface fires could be a positive influence for these forest types, but a shift to more frequent crown fires could hamper regeneration and favor jack pine. Management has maintained red pine across much of the assessment area, and regeneration of this species usually relies on planted seedlings. Seasonal shifts in precipitation patterns, particularly the trend toward wetter springs and drier summers, may impair the survival of planted seedlings.

Dominant Species: Considering the range of possible climate futures, models project declines in suitable habitat and biomass for red pine across the assessment area. Projections are mixed for white pine, but models indicate that this species will fare worse under the hotter, drier GFDL A1FI scenario. Pine forests may be able to increase productivity with warmer conditions and longer growing seasons, but this depends on the potential effects of CO_2 fertilization. Minor components of RP-WP forests like northern red oak, black oak, and red maple also have mixed projections, although jack pine is anticipated to decline.

Stressors: Insect pests and diseases such as white pine tip weevil and red pine shoot blight may become more virulent and damaging under a warmer climate. The continued shift toward mesic species in these forests may continue if fire suppression activities remain constant and broadleaf species like red maple and black cherry increase under climate change. With the anticipated increase in white-tailed deer populations resulting from warmer winters, herbivory on preferred species may continue to hinder regeneration. Red pine in particular may be limited by warm temperatures, so projected warming in the assessment area may exceed the physiological limits of this species.

Moderate-Low Adaptive Capacity

Red pine and white pine forests are generally tolerant of drought and disturbances, which lends these forests greater adaptive capacity to climate change. This forest type could also expand to new favorable locations on the landscape if overall conditions result in increased drying. Thus, RP-WP forests could gain territory in mesic aspen-birch, oak, or northern hardwood sites. Low species diversity is a drawback for this forest type in general. White pine can tolerate a wider range of soil and moisture conditions than can red pine, and red pine has relatively low genetic diversity. Natural regeneration of red pine is often limited following harvest, particularly in the southern portion of the assessment area.

Red pine stand at the University of Michigan Biological Station. Photo by Stephen Handler, U.S. Forest Service.

Prescribed fire in a white pine stand. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

Mature stand of red pine. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Lowland Conifers

High-Moderate Vulnerability (medium evidence, medium agreement)

Lowland conifer forests have limited tolerance to changes in water tables. Additionally, the dominant species in these forests are expected to decline under a range of climate futures. Low agreement on future precipitation and groundwater levels are the primary uncertainties for this forest type.

Negative Potential Impacts

Drivers: Climate change has the potential to alter the precipitation patterns and soil moisture regimes in low-lying areas across the assessment area. Lowland conifer forests function in a relatively narrow window of water table conditions, although larger lowlands may be able to withstand a wider range of conditions than small, isolated depressions. Sphagnum moss, the primary source of peat in these systems, may be susceptible to warmer conditions. Lowlands may occupy potential refugia sites if they remain cooler longer than upland areas across the landscape, but this benefit may be temporary.

Dominant Species: Most lowland conifer species are near southern range limits in Michigan, and may not tolerate warmer conditions. Balsam fir, black spruce, eastern hemlock, northern white-cedar, paper birch, tamarack, and quaking aspen are projected to experience significant declines in suitable habitat and biomass across the landscape. The same modeling studies offer mixed results for eastern white pine, but nearly all conifers are projected to fare worse under GFDL A1FI. Spruce-fir forests may be less able to increase productivity under future conditions than other forest types. These forests may not maintain their identity if dominant species decline and water tables change. Impact models presented in this assessment are not well-suited specifically to address lowland forests, so results should be interpreted with a degree of caution.

Stressors: Roads and other watershed modifications are already harming lowland conifer forests in some parts of the assessment area. Water table impacts may be intensified as the hydrologic cycle becomes more episodic. Warmer growing seasons may increase evapotranspiration rates and reduce the rate of peat accumulation in these forests, and peat layers may begin to erode as decomposition rates increase. Warmer winters may also increase the occurrence of winter-burn in lowland conifer forests, and allow for more frequent outbreaks of pests like tamarack sawfly and spruce budworm. Deer herbivory limits regeneration of northern white-cedar in particular.

Low-Moderate Adaptive Capacity

Lowland conifer forests that are connected to groundwater may be less vulnerable to seasonal or short-term moisture deficits. Low-lying areas on the landscape might also be protected from summer droughts if increased winter and spring precipitation is retained. Prolonged droughts, however, would be harmful to this forest type. Lowland conifer forests are not expected to expand to new territory within the assessment area or outcompete other forest types, but acid or alkaline soil conditions may make them less suitable for invasive species or competing forest types. Additionally, black spruce is capable of reproducing asexually in lowland systems.

Northern white-cedar in riparian area. Photo by Matthew Duveneck, Portland State University, used with permission.

Lowland conifer forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Complex structure in a lowland conifer forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Aspen-Birch

Moderate Vulnerability (medium evidence, medium agreement)

Impact models project substantial declines for aspen and birch in northern Michigan, and the potential exists for multiple stressors to interact under climate change—particularly drought and forest pests. But these forests are a management priority, are adapted to disturbance, and exist on a wide range of sites.

Moderate-Negative Potential Impacts

Drivers: If climate change results in increased moisture stress during the growing season, drier sites will be exposed to greater drought stress and mortality. Warmer growing-season temperatures might encourage more suckering after disturbance, but projected temperatures in the assessment area may be beyond the physiological limits of aspen and birch species. Disturbance from wildfire, blowdown events, or continued management could benefit this forest type, but it is unknown whether aspen-birch forests would continue to persist if stand-replacing disturbances become much more frequent.

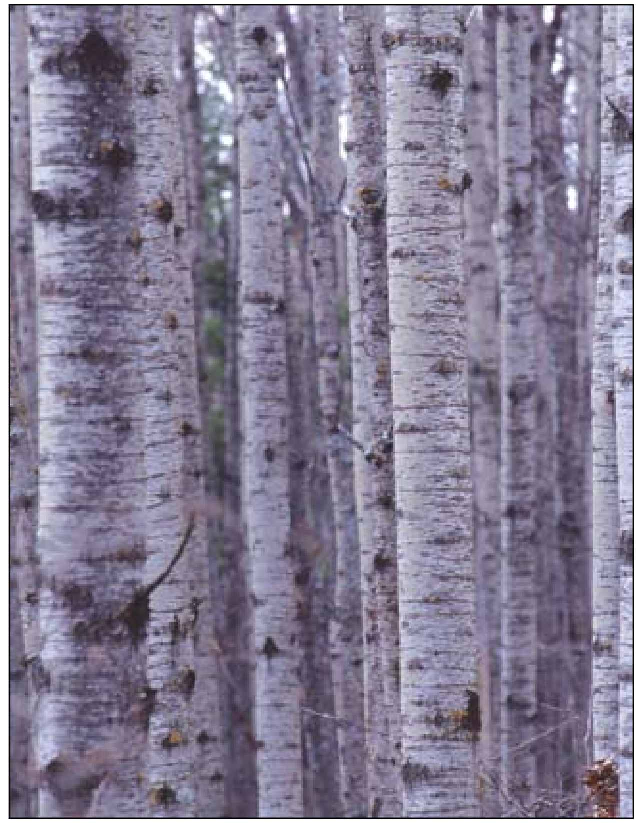
Dominant Species: Under a range of possible climate futures, balsam poplar, bigtooth aspen, and paper birch are expected to decline in suitable habitat and biomass across the assessment area. Balsam poplar and paper birch are near their southern range limits in Michigan. Models show mixed results for quaking aspen under the PCM B1 scenario, but they project that quaking aspen will decline substantially under GFDL A1FI. If future climate change is less extreme than the GFDL A1FI scenario, the possibility exists for this species to fare better across the assessment area.

Stressors: Climate change is expected to intensify several key stressors for aspen-birch forests. Insect pests such as forest tent caterpillar and gypsy moth may become more damaging under a warmer climate, along with diseases like hypoxylon canker. White-tailed deer herbivory may also increase with warmer winters. The possibility exists for interactions among multiple stressors to lead to more-severe climate change impacts. For example, overlapping drought, earthworm activity, and insect pest outbreaks could have negative synergistic effects. Multiple harvests of aspen may also lead to a decline of nutrient status or productivity on these sites, so interactions may occur between management actions and climate-driven stressors.

Moderate Adaptive Capacity

Aspen and birch are adapted to disturbance and capable of persisting at low densities until openings appear. These species also exist on a wide range of soils and landforms. The ability to reproduce clonally is also an advantage in some instances, particularly for clones with higher tolerance for warmer conditions or droughts. This forest type is a management priority for many landowners. The aspen-birch forest type may be vulnerable to declines across the landscape, even if aspen and birch species still occur sporadically in the future. This forest type also has low species diversity, which may reduce adaptability to future changing conditions.

A young aspen stand. Photo by Maria Janowiak, U.S. Forest Service.



Aspen in the northern Lower Peninsula. Photo by Catherine Salm, Huron-Manistee National Forest.

A stand of paper birch in autumn. Photo by Autumn Jauck, U.S. Forest Service, Hiawatha National Forest.

Northern Hardwoods

Moderate Vulnerability (medium evidence, medium agreement)

Climate change may intensify several major stressors for northern hardwoods, such as drought, invasive species, and forest pests. High species diversity may increase resilience to future change. Uncertainty regarding future moisture regimes and potential interactions between stressors limits the confidence in this determination.

Moderate Potential Impacts

Drivers: Climate change poses a threat to these forests for multiple reasons, including increased moisture stress, freeze-thaw events, and susceptibility to other stress agents. Hardwoods on moist, rich soils may be buffered from short-term droughts or seasonal moisture stress. Climate change may also alter the gap-phase dynamics that enable the regeneration of many shade-tolerant species if blowdowns, pest outbreaks, or wildfires become more frequent or widespread.

Dominant Species: Models projections are mixed for many common species that make up northern hardwood forests. American basswood, green ash, and sugar maple are generally projected to increase under PCM B1, but models disagree on whether these species will increase or decrease under GFDL A1FI. American beech, black cherry, eastern white pine, northern red oak, and red maple are projected to increase under PCM B1 and decrease under GFDL A1FI. Eastern hemlock, yellow birch, and northern white-cedar are projected to decline in biomass and suitable habitat across a range of climate scenarios. Deciduous forest systems may be more able to increase productivity across a range of climate scenarios than coniferous forest systems, however. Emerald ash borer and Dutch elm disease are expected to continue to limit ash and elm species.

Stressors: Climate change may amplify several major stressors to northern hardwoods, particularly for stands on marginal soils. The potential for more freeze-thaw events could exacerbate ongoing hardwood dieback in the assessment area. Beech bark disease, white pine blister rust, and other diseases could become more active and virulent under a warmer climate. Forest tent caterpillar, gypsy moth, and other pests may cause more frequent and severe damage in climate-stressed forests, and new pests such as Asian longhorn beetle present unknown risks. White-tailed deer herbivory may also increase if deer populations grow with warmer winters. Unanticipated interactions may also occur between stressors, such as earthworms, drought, and invasive species.

Moderate-High Adaptive Capacity

Northern hardwoods usually contain many species and exist on a range of soil types and landforms, which leads to a high response diversity (many potential future trajectories). Hardwood forests could also gain territory lost by other forest types under wetter or drier future conditions. This system contains several species at their northern range limits, which may benefit from gene flow from southern populations. Increased CO_2 concentrations may also increase the water-use efficiency of some species, reducing the risk of moisture stress. Sites dominated by a single species like sugar maple are more susceptible to future stressors, however, as are stands with reduced structural diversity.

A snag in a mixed pine-hardwood forest. Photo by Stephen Handler, U.S. Forest Service.

Canopy gap in a northern hardwood forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

A mature northern hardwood forest in the Upper Peninsula. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

A mixed hardwood forest in the northern Lower Peninsula. Photo by Stephen Handler, U.S. Forest Service.

Lowland and Riparian Hardwoods

Moderate Vulnerability (medium evidence, low-medium agreement)

Climate change is projected to alter the water regimes in riparian and lowland systems, and may amplify the effects of insect pests and invasive species. High diversity and the presence of southern species raise the adaptability of these forests. The future precipitation regime is the primary uncertainty.

Moderate-Negative Potential Impacts

Drivers: Climate change has the potential to alter the hydrologic regimes in riparian systems and lowlands across the assessment area. These hardwood forests are particularly adapted to annual and seasonal fluxes in water tables, and the regeneration requirements of several species within this forest type are linked to these cycles. Shifts in the timing or amount of precipitation could disrupt the function of these forests.

Dominant Species: Under a range of climate futures, many lowland and riparian hardwood species (American elm, black willow, Eastern cottonwood, green ash, silver maple, swamp white oak, and white ash) are expected to gain suitable habitat across the assessment area. Sycamore and hackberry are two southern species expected to gain new suitable habitat in the assessment area. Elm/ash/cottonwood forests could have large potential productivity gains under a range of climate scenarios. Species expected to decline include northern white-cedar, black ash, balsam fir, yellow birch, and paper birch. Pests and diseases such as emerald ash borer and Dutch elm disease are expected to limit some species that models project to increase.

Stressors: Invasive species such as reed canarygrass, Japanese barberry, and buckthorn species are existing threats to these forests, and invasive species have the potential to increase in abundance in the assessment area under climate change. Emerald ash borer is expected to reduce or eliminate ash species in lowland hardwood forests in the future. Gypsy moth and other forest pests may also be more damaging in climate-stressed forests. White-tailed deer populations are expected to increase with warmer winters, which may hinder regeneration of certain species in these forests. The trend toward more intense and variable precipitation events may present risks to this system through excessive waterlogging or prolonged droughts.

Moderate Adaptive Capacity

There is a lack of management history in these forests compared to other forest types in the assessment area, so management experience is limited. Many species in riparian and lowland forests can tolerate intermittent wet and dry conditions, and they can tolerate periodic floods and moisture stress. Extended droughts would cause significant damage to shallow-rooted species, but increased winter and spring precipitation could buffer summer droughts in low-lying areas on the landscape. These forests are rather diverse, so they have many possible future trajectories under changing conditions. Riparian forests tend to contain more southern species than lowland forests, so they may be less vulnerable to future conditions in the assessment area.

A lowland hardwood forest. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

A floodplain hardwood forest on a tributary of the Muskegon River. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

Lowland hardwoods on the Huron-Manistee National Forest. Photo by U.S. Forest Service, Huron-Manistee National Forest.

Oak Associations

Low-Moderate Vulnerability (medium evidence, medium agreement)

Oaks are relatively tolerant of drought and warmer temperatures. The presence of white oak and black oak increases the adaptive capacity of this system in the northern Lower Peninsula, but the rarity of this forest type makes it more vulnerable in the eastern Upper Peninsula.

Moderate Potential Impacts

Drivers: Oak associations occur on sandy to loamy soils. Oaks are relatively drought tolerant and may endure more variable precipitation under climate change. This community is limited by cold temperatures in the assessment area, so warming may allow oaks to expand into previously unsuitable areas. Past management and wildfire suppression allowed oak associations to expand into barrens and pine forests, but continued fire suppression is allowing mesic species like red maple to invade these stands. Therefore, climate change influences on the wildfire regime and ability to apply prescribed fire will have great consequence for oak associations. More frequent crown fires may encourage a shift to pine forests and barrens, but a continued lack of surface fires may promote hardwood forests.

Dominant Species: Models project that white oak may gain suitable habitat and biomass in the assessment area, though results are mixed for northern red oak, northern pin oak, and black oak. Most oaks are near northern range limits in the assessment area, so they may gain territory under projected warming. Several new oak species, including bur oak, pin oak, scarlet oak, and post oak, may gain suitable habitat across the assessment area. Natural migration and expansion of these oak species to the eastern Upper Peninsula may be limited by barriers like the Great Lakes and fragmentation in the southern portion of the assessment area.

Stressors: Climate change could amplify several stressors to oak associations. Forest tent caterpillar and gypsy moth may cause more frequent and severe damage under climate change, and new pests such as Asian longhorn beetle present unknown risks. Stressed forests may also be more susceptible to oak wilt and oak decline. White-tailed deer populations may also increase with warmer winters, which may hinder regeneration as well as the expansion of this forest type. Invasive species like buckthorn, honeysuckle, and garlic mustard can also impair regeneration, and are poised to increase under climate change.

Moderate-High Adaptive Capacity

Oak associations are generally expected to fare well under climate change, and the diversity of these forests (species as well as genetic diversity) leads to a high response diversity, or many possible future trajectories. These forests could gain territory lost by other forest types under drier future conditions, particularly in the northern Lower Peninsula. Species at their northern range limits may also benefit from gene flow between southern populations. The oak-dominated cover type may suffer from increased competition with more mesic hardwoods if fire suppression continues.

An oak-dominated forest. Photo by U.S. Forest Service, Huron-Manistee National Forest.

Northern red oak seedlings in sandy soil. Photo by Matthew Duveneck, Portland State University, used with permission.

Using a drip torch to apply a prescribed burn in an oak forest. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

Barrens

Low-Moderate Vulnerability (limited-medium evidence, medium agreement)

Barrens may be well-adapted to tolerate warmer temperatures and more episodic precipitation in the assessment area. Increased wildfire activity might also benefit this system, but excessive wildfire could shift barrens to open grassland systems.

Moderate-Positive Potential Impacts

Drivers: Barrens typically occur on excessively drained, nutrient-poor sands. Infrequently, barrens occur on thin soils over bedrock. Climate change-induced moisture stress or extended droughts may favor this system. In the assessment area, barrens are typically maintained by management activities, prescribed fire, or wildfire. Therefore, barrens could benefit if climate change increases the frequency or severity of wildfire in xeric areas across the assessment area. Too much fire, however, could result in conversion to open grassland systems. Conversely, warmer temperatures might allow species like oaks to invade barrens maintained by frost pockets.

Dominant Species: Models do not explicitly consider the habitat suitability and performance of tree species in open systems, so these results should be interpreted with caution. Considering the range of possible climate futures, jack pine and red pine are expected to decline in suitable habitat and biomass across the assessment area. White oak is projected to fare well under a range of climate futures. The same modeling studies offer mixed results for other minor species (northern pin oak, black oak, and eastern white pine) occurring in barrens systems.

Stressors: Fire suppression has contributed to woody encroachment and an increased presence of invasive species in many barrens systems, and climate change could pose an additional threat if the window to apply prescribed fires is reduced. Invasive species such as leafy spurge, spotted knapweed, and St. John's wort are existing threats to these systems, and invasive species have the potential to increase in abundance in the assessment area under climate change. White-tailed deer herbivory is less of a threat to barrens, and may actually help promote open canopy conditions. Similarly, insect pest outbreaks from jack pine budworm or western pine beetles might favor barrens systems across the landscape.

Moderate-High Adaptive Capacity

The strong management presence in barrens systems is expected to continue, so there is a better chance that managed barrens will persist across the assessment area. Other dry forest types may convert to barrens if extended droughts cause prolonged regeneration failures or if stand-replacing wildfires increase in frequency, so this system may gain territory under climate change. Barrens are also expected to tolerate episodic precipitation and warmer temperatures. These systems require only minor tree cover, and many of the species that can occur in these systems are expected to remain stable across the landscape.

Lupine in a savanna in the northern Lower Peninsula. Photo by Heather Keough, U.S. Forest Service, Huron-Manistee National Forest.

An oak-pine savanna. Photo by Christopher Hoving, Michigan Department of Natural Resources, used with permission.

A pine barren in the northern Lower Peninsula. Photo by Joshua Cohen, Michigan Natural Features Inventory, used with permission.

CONCLUSIONS

Forest ecosystems in northern Michigan will be affected by climate change, although systems and species will respond to these changes individually. The synthesis statements in the first half of this chapter can be applied as general rules of thumb when specific information about expected climate change impacts is lacking. Overall, we expect forest systems that are adapted to a narrow range of conditions or that contain few species to be more vulnerable to changing conditions. Communities with higher diversity that are adapted to tolerate a wide range of conditions and disturbances have a greater chance to persist under a range of plausible climates.

The vulnerability determinations for individual forest systems are best interpreted as broad trends and expectations across the assessment area. This assessment makes use of the most up-to-date information from the scientific literature, a coordinated set of modeling results and climate projections, and the input of a large team of local experts. Even so, there are limitations and unknowns that make these determinations imperfect. As new information continues to be generated on the potential impacts of climate change on Michigan forests, this assessment should be supplemented with additional resources.

It is essential to consider local characteristics such as past management history, soils, topographic features, species composition, forest health issues, and recent disturbances when applying these general vulnerabilities to local scales. Some site-level factors may amplify these expected vulnerabilities, yet others may buffer the effects of climate change. Developing a clear understanding of climate-related vulnerabilities across relevant scales will then enable forest managers, landowners, planners, or other resource specialists to consider appropriate adaptation responses. This is true whether the task is to manage a single stand over a few years, or to design a long-term management plan for a large tract of land.

In the following chapter, we extend the discussion to consider the implications of climate trends and forest vulnerabilities for other ecosystem services and resource areas that are often important for forest managers.

CHAPTER 7: MANAGEMENT IMPLICATIONS

The previous chapters of this assessment have described observed and anticipated climate trends, potential impacts to forest ecosystems, and the climate-related vulnerability of major forest systems in the assessment area. This chapter takes one further step, by summarizing the implications of these climate change impacts and vulnerabilities for a variety of topics important to forest managers. Changes in climate, impacts on forests, and ecosystem vulnerability will combine to create both challenges and opportunities in forest management.

Topics were selected to encompass major resource areas that are priorities for public and private land managers. These topics, and the descriptions of climate change implications, are not comprehensive. Some topics have received less scientific attention or contain greater uncertainty. For some topics we relied on input from subject-area experts to discuss climate change implications (Appendix 6). Our goal is to provide a springboard for thinking about management implications of climate change and to connect managers to other relevant resources. When available, the "more information" sections provide links to key resources for managers to find more information about the impacts of climate change on that particular topic.

This chapter does not make recommendations as to how management should be adjusted to respond to climate impacts. We recognize that the implications of climate change will vary by forest type, ownership, and management objective. Therefore, we provide broad summaries rather than focusing on particular management issues. A separate document, *Forest Adaptation Resources*, has been developed to assist land managers in a decisionmaking process to adapt their land management to projected impacts (Swanston and Janowiak 2012).

WILDLIFE

Climate change effects on fish and wildlife species and their management are areas of active research, and the subject is summarized only briefly here. A more thorough assessment can be found in *Changing Climate, Changing Wildlife: A Vulnerability Assessment of 400 Species of Greatest Conservation Need and Game Species in Michigan* (Hoving et al. 2013). Michigan's wildlife community is the result of many interacting factors, including weather and climate. Weather and climate affect wildlife species directly through heat stress, snowfall, or annual saturation of ephemeral wetlands. Climate and weather also affect wildlife indirectly through climate-related habitat shifts, pests and diseases, disturbance events, and other factors. For example, spruce grouse occur in the assessment area because past climate has favored spruce regeneration and competition with deciduous trees. Many species in northern Michigan, such as the gray jay and the American marten, are not common farther south. If conifers decrease in the assessment area, these wildlife species may decrease as their habitats change. Conversely, species like white-tailed deer and wild turkey populations are hindered by severe winters. A decline in the frequency of severe winters will favor those species. Because Michigan forests are habitat for many wildlife species at the north or south edge of their range, even small climate-induced changes may have noticeable impacts.

Wildlife species throughout the Midwest are responding to climate change, and several assessments and vulnerability analyses suggest that wildlife will continue to change (Hall 2012). Several tools have been developed to help managers evaluate the climate change vulnerabilities of wildlife species. For example, the Climate Change Bird Atlas examines the potential for climate change to alter the distribution of 147 bird species across the eastern United States (Matthews et al. 2011a).

More Information

- The Michigan State Wildlife Action Plan identifies wildlife species, and their habitats, that are in greatest conservation need. Many species of greatest conservation need may be particularly affected by climate change: http://www.michigan.gov/dnr/0,4570,7-153-10370_30909---,00.html
- *Changing Climate, Changing Wildlife*, a new report from the Michigan Department of Natural Resources – Wildlife Division, assesses how climate change may affect 400 wildlife species in the state: www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

A ruffed grouse in the eastern Upper Peninsula. Photo by U.S. Forest Service, Hiawatha National Forest.

- Many states are working to incorporate climate change information into their state wildlife action plans. Voluntary guidance has been provided by the Association of Fish and Wildlife Agencies: www.fishwildlife.org/files/AFWA-Voluntary-Guidance-Incorporating-Climate-Change_SWAP.pdf
- The Climate Change Bird Atlas is a companion to the Climate Change Tree Atlas and uses information about direct climate effects as well as changes in habitat to project changes in bird species distributions: www.nrs.fs.fed.us/atlas/bird/
- Season's End, a collaboration of many hunting and conservation organizations, includes many resources on how climate change may affect wildlife: http://www.cakex.org/virtual-library/784
- The Forest Service's Climate Change Resource Center provides a summary of how climate change may affect wildlife species: www.fs.fed.us/ccrc/topics/wildlife/

THREATENED AND ENDANGERED SPECIES

As discussed in Chapter 6, it is expected that plant or animal species that are already rare, threatened, or endangered may be especially vulnerable to shifts in temperature and precipitation. Rare plants and rare plant communities often rely on very particular combinations of environmental and habitat conditions, in many cases as relict populations from previous climate conditions (Devall 2009). Threatened and endangered species often face population declines due to a variety of other factors, including habitat loss, competition from invasive species, and disease. As temperatures become warmer and the precipitation regime changes, already rare or declining species may therefore be among the first to experience climate-related stress. The limited range of rare species makes it difficult to model the effects of climate and climate change on distribution and abundance (Schwartz et al. 2006b). In the absence of human intervention, rare or threatened species may face greater extinction risks. Alternatively, rare species that live in habitats that are buffered from climate shifts (e.g., caves or other climatic refugia) may be able to persist.

Michigan's Special Animals and *Michigan's Special Plants* include information on the state's 665 endangered, threatened, and special concern species (Michigan Natural Features Inventory 2013a, 2013b). Many of these species occur in the assessment area: 189 species in the eastern Upper Peninsula and 233 species in the northern Lower Peninsula. There has not been a comprehensive review of the potential for climate change to affect all of these species, and the particular climate tolerances of many of them are unknown. The new report from the Michigan Department of Natural Resources, *Changing Climate, Changing Wildlife*, addresses implications for many of these species (Hoving et al. 2013).

More Information

- Michigan's Rare Species Explorer is produced and updated by the Michigan Natural Features Inventory: mnfi.anr.msu.edu/explorer/search.cfm
- *Changing Climate, Changing Wildlife*, a new report from the Michigan Department of Natural Resources – Wildlife Division, assesses how climate change may affect 400 wildlife species in the state: www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

FIRE AND FUELS

Climate change is expected to have implications for fire and fuels management in the assessment area. As discussed above, this summary does not address the ways that land managers should adapt to the potential changes. A wide range of possible choices in policy, funding, and public attitude will ultimately define the response that makes the most sense, and these responses may be different for different organizations and land owners.

As described in Chapter 5, weather and climate are major drivers of fire behavior. Across northern Michigan and the Great Lakes region, the fire season is controlled by a combination of day length, weather, and fuel conditions. Typically, day length, cool temperatures, and wet fuels delay the onset of fire season until April or May. Although the summer months have the longest days and warmest temperatures, living vegetation requires extended dry periods of 2 weeks or more to increase the potential for fire ignition and spread. Live trees drop leaves and go dormant in the fall, but most forests become receptive to fire around the same time that short days and cool temperatures return. The type and condition of available fuels may lead to surface fires, which consume ground fuels, or crown fires, which burn across the forest canopy.

Drought periods can exacerbate wildfire risk during any of these periods, and drought is a critical precursor of large summer fire events. Droughts may increase fire potential quickly, and indicators of fire potential suggest that hot and dry periods of weeks rather than months may be sufficient to stress live fuels and make them more susceptible to ignition and spread. The projected trend toward more-intense precipitation could raise the potential for longer dry intervals between rain events (Chapter 4). Combined with warmer temperatures and a range of other climate-driven stressors, the potential exists for more forests to be prone to wildfire throughout the growing season. The two climate scenarios examined in this assessment reveal a wide range of possible precipitation values (Chapter 4), so it is uncertain to what degree drought stress may harm forests in the assessment area.

Logging area burned in the Duck Lake Fire in May 2012. Photo by Stephen Handler, U.S. Forest Service.

As with other parts of the country, critical fire weather conditions have been responsible for many of the major fire events across the Great Lakes region. Large, intensely burning fires generally require a combination of strong gradient winds, significant atmospheric instability, and dry air. The fires that occur in fire-prone landscapes during these weather events tend to produce the most severe fire effects. Fire-weather events are poorly captured by modeling tools. Because large wildfires are driven primarily by these fire weather events, it is difficult to forecast exactly how the projected climate trends may translate into changes in fire activity. Additionally, complex interactions between climate change, vegetation communities, seasonal precipitation, and discrete fire weather events will dictate whether fires are manifested as surface fires or crown fires. This distinction has important consequences for forest communities and fire management, and the limits of our understanding are a major uncertainty.

Projected changes in climate could also affect the ability to apply prescribed fire in Michigan. Wetter springs could make it difficult to conduct prescribed burns in spring, shifting opportunities for dormant-season burning to the fall. If summer or fall becomes drier, burning under those conditions could involve greater risk and managers may be less inclined to implement this practice.

More Information

- The Lake States Fire Science Consortium provides fire science information to resource managers, landowners, and the public about the use, application, and effects of fire: lakestatesfiresci.net/index.html
- The Forest Service's Climate Change Resource Center provides a summary of how climate change may affect wildland fire in forest ecosystems: www.fs.fed.us/ccrc/topics/wildfire/

WATER RESOURCES

There are many potential interactions and relationships between climate change, forest ecosystems, and water resources in Michigan. Below, we outline a few examples of these potential implications. In addition to reflecting land-use decisions, water resources in the assessment area are influenced by a diverse array of management decisions and policies, including infrastructure planning and maintenance, water quality discharge permitting, water extraction/diversion permitting, and biological resource management. These layers of policy and management decisions complicate the picture, but reinforce the notion that management decisions will be intertwined with ecological changes in the future.

Infrastructure

Many landowners and agencies are responsible for managing water infrastructure such as dams, drainage ditches, and culverts. Specifications for water infrastructure are based on past climate patterns, and the trend of intensifying precipitation has placed additional strains on old and fragile infrastructure. As a recent regional example, the flood event in June 2012 in Duluth and across northern Minnesota caused more than $100 million in damage, primarily to roads, bridges, and private property (Passi 2012). In addition, associated landslides and stream bank erosion extensively damaged area streams; restoration costs are estimated at $1 million per stream.

Water Quality

Water resource managers in the assessment area have long been concerned with the impacts of multiple stressors, including the effects of commercial or residential development and climate patterns on in-stream temperature and increased turbidity (water cloudiness). The cold and cold-transitional rivers and streams within the assessment area (Chapter 1) may be increasingly at risk due to warming temperatures and altered hydrologic regimes. Impairments due to turbidity are also common for rivers and lakes in northern Michigan. Processes leading to increased turbidity are particularly sensitive to climate-related phenomena, such as increased storm intensity and frequency, rain-on-snow events, and other trends that promote stream bank erosion. These events can also diminish water quality by introducing excessive nutrients and contaminants.

Thermal habitat in cold-water lakes and streams may also continue to be impaired as temperatures continue to warm. If conifers are replaced by deciduous trees or tree cover is reduced in the assessment area, aquatic resources will also receive less shade throughout the year (Blann et al. 2002). As ice cover is reduced on lakes in the assessment area, water temperatures and oxygen profiles may be more affected in shallow and moderate-depth lakes (Fang et al. 2004a, 2004b, 2004c; Stefan et al. 2001). Ongoing work within Lake Superior Basin to investigate climate change impacts on water temperature and base flow finds that streams may be affected by higher stream temperatures and low flow in the future (Lucinda Johnson and Meijun Cai, Natural Resources Research Institute; William Herb, University of Minnesota, personal comm., February 2013).

Fish

Fish and other aquatic organisms are projected to be affected by water quality changes, more-intense precipitation events, and other changes to the hydrology of the assessment area. These impacts may not occur evenly across species or even across life stages for a given organism. For example, fish eggs and fry associated with gravel habitats and fine sediments, as opposed to other habitats, appear to have been most affected by the June 2012 floods in northern Minnesota (personal comm., D. Hendrickson, Minnesota Department of Natural

Resources, December 2012). Water temperature is generally considered to be the primary parameter for physical habitat suitability for trout, and upper temperature limits seem to depend specifically on the duration of high temperatures (Wehrly et al. 2007). The new report from the Michigan Department of Natural Resources – Wildlife Division, *Changing Climate, Changing Wildlife*, assesses how climate change may affect fish species in the state (Hoving et al. 2013). Compared to other taxa, fish are among the most vulnerable animals in Michigan. More than 80 percent of the fish species were assessed as vulnerable to climate change.

More Information

- The Great Lakes Environmental Assessment and Mapping (GLEAM) project compiles spatial information regarding many threats to Great Lakes ecosystems, including climate change: www.greatlakesmapping.org/
- *Changing Climate, Changing Wildlife*, a new report from the Michigan Dept. of Natural Resources – Wildlife Division, assesses how climate change may affect fish species in the state: www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

FOREST PRODUCTS

In Michigan, the forest industry accounts for roughly $8 billion in economic activity (Price 2010). Information presented in Chapters 5 and 6 indicates that species composition in the assessment area is projected to change during the 21st century, which could have important implications for the forest products industry. Major harvested species like quaking aspen are projected to decline significantly under a range of possible climate futures. Conversely, hardwood species like American basswood and northern red oak may increase throughout the assessment area. Large potential shifts in commercial species availability may pose risks for the forest products sector if the shifts are rapid and the industry is unprepared. The forest products industry may benefit from awareness of anticipated climate trends and shifts in forest species. In many cases, forest managers can take actions to reduce potential risks associated with climate change or proactively encourage species and forest types anticipated to fare better under future conditions (Swanston and Janowiak 2012). There may be regional differences in forest responses, as well as potential opportunities for new merchantable species to gain suitable habitat in the assessment area. If the industry can adapt effectively, it is possible that the net effect of climate change on the forest products industry across the Midwest will be positive (Handler et al. 2012).

Overall, how climate change will affect the forest products industry depends not only on ecological responses to the changing climate, but also on socioeconomic factors that will undoubtedly continue to change over the coming century. Major socioeconomic factors include national and regional economic policies, demand for wood products, and

Harvest operations in a white pine stand. Photo by U.S. Forest Service, Huron-Manistee National Forest.

competing values for forests (Irland et al. 2001). Great uncertainty is associated with each of these factors. The forest products industry has adjusted to substantial changes during the past 100 years, and continued responsiveness can help the sector remain viable.

More Information

- The 2010 Resources Planning Act Assessment presents projections for forest products and other resources through the year 2060 and examines social, economic, land use, and climate change influences: www.fs.fed.us/research/rpa/

NONTIMBER FOREST PRODUCTS

Changes in climate will have implications for nontimber forest products in the assessment area and throughout the Great Lakes region. Hundreds of these products are used for food, medicine, craft materials, and other purposes. Many of these will be affected by changes in temperature, hydrology, and species assemblages. As illustrations, effects of climate change on two Northwoods nontimber forest products with broad cultural and economic importance are discussed briefly here.

Natural wild rice is a Northwoods cultural keystone species (Minnesota Department of Natural Resources 2008). It is central to the migration story of the Anishinaabe (also known as Ojibwe, Chippewa, or Odawa), for whom wild rice is a sacred food and medicine. Wild rice growth and productivity are sensitive to hydrologic conditions such as water depth and temperature. Although wild rice is adapted to some seasonal variation, it thrives in water depths of 0.5 to 3 feet. Germination requires a 3- to 4-month dormant period in water at 35 °F or less. Wild rice seed does not survive prolonged drying. With regional and global models predicting increased heavy precipitation events, higher average temperatures, later winter onset, and earlier spring onset, the future of natural wild rice in the Northwoods may be at risk. Specific threats include:

- prolonged droughts leading to lowered water depths or seed desiccation, or both
- flooding, particularly in the early summer “floating leaf” life stage
- shortened periods of cold water temperatures
- predation and/or displacement by species favored by warmer water temperatures (e.g., carp and reed canarygrass).

Another example of a valuable nontimber forest product of the Northwoods is morel mushrooms, which people throughout northern Michigan passionately hunt (Fine 2003). Annual morel festivals and sales to restaurants provide supplemental income for many people, communities, and small businesses. Under climate change, increased fire frequency and severity may result in increased morel fruiting. In a process similar to the spike in morel fruiting with the massive die-off of American elms from Dutch elm disease, climate-related deaths of associated tree species also may result in immediate increases in morel fruiting. However, evidence from the mid-Atlantic suggests such a spike would be followed by a decline in fruiting frequency (Emery and Barron 2010). In addition, because morel fruiting is highly responsive to temperature and humidity, changes in these regimes also can be expected to alter the timing and intensity of morel fruiting.

FOREST MANAGEMENT OPERATIONS

Climate variability and change present many challenges for forest managers who seek to maintain the diverse goods and services that forests provide. In particular, changes in winter conditions in the assessment area and throughout the northern Great Lakes region may shorten the available timeframe for conventional forest management operations.

Most management in lowland areas is accomplished during the winter. As summarized in Chapter 4, climate change in northern Michigan is projected to result in shorter seasons of frozen ground, more midwinter thaws, less snowpack, and more rain during winter months. Frozen ground facilitates timber harvest and transport, and snowpack provides protection for soils during harvest operations. Although special equipment is available to increase flotation on shallow snowpack or in the absence of snowpack, this equipment is costly. Additionally, a lack of frozen ground might increase the need to build roads to facilitate winter harvest, which would drive up costs compared to conventional practices.

Projected changes in precipitation during the growing season could also have important implications for forest management operations. Intense precipitation events could delay harvest operations in areas of poor drainage, but these events may be less disruptive in areas of coarse, sandy soils. Alternatively, summer droughts could possibly extend operating windows in low-lying areas or clay soils. Extended or severe droughts could present problems in sandy areas, if it becomes necessary to install gravel over logging roads.

Changes in severe weather patterns could increase the number of salvage harvests that are undertaken. Harvesting green timber allows resource managers to strategically achieve desired objectives and outcomes. Salvage harvesting following a tornado or derecho, by contrast, generally arises from a more immediate need to remove hazardous fuels or clear affected forest areas. A salvage sale also does not garner the same amount of financial return as does a green timber sale opportunity.

Analysis of timber harvest records in northern Wisconsin has identified some consequences of the changes in frozen ground condition (C. Rittenhouse and A. Rissman, unpublished data). In years with warm winters, there has been a shift toward greater harvest of jack pine and less harvest of black spruce, hemlock, and red maple. Interviews with loggers revealed that growing-season restrictions on harvest designed to limit oak wilt and other diseases reduced the annual harvest window. Additionally, such ongoing stressors as overcapitalization, loan and insurance payments, and high fuel prices increased pressure on loggers to harvest year-round. Interviews with transportation officials revealed concerns that operating trucks on marginally frozen roads (or “over-weighting”) contributed to conflicts over roads between industry and local governments. Thus, climate change impacts on forestry operations have complex implications for management and governance of timber production, logger livelihoods, water quality, and transportation systems.

More Information

- The Michigan Society of American Foresters has produced forest management guidelines for the state. These voluntary guidelines do not specifically consider climate change or climate variability, but they can be a useful starting point for assessing the various ways climate change could influence forest management operations: michigansaf.org/Business/MSAFguide-2010/1-MainPage.html

INFRASTRUCTURE ON FOREST LAND

Changes in climate and extreme weather events are expected to have impacts on infrastructure on forest lands throughout the region, such as roads, bridges, and culverts. Rising temperatures alone could have important impacts. A recent report suggests that heat stress may have substantial effects on surface transportation infrastructure in the assessment area (Posey 2012). Heavy precipitation events, which are already increasing and projected to increase further in the future, may overload existing infrastructure that has not been built to that capacity. For example, improper location or outdated building standards can make older road systems particularly susceptible

Woods road through a northern hardwood forest. Photo by U.S. Forest Service, Hiawatha National Forest.

to increased rainfall events. Engineers are already adapting to these changes: as infrastructure is replaced, it is being constructed with heavier precipitation events in mind. This extra preparedness often comes at an increased cost to upgrade to higher standards and capacity. Extreme events may also require more frequent maintenance of roads and other infrastructure, even if designed to appropriate specifications. Additionally, forest managers may find it necessary to take additional precautions to prevent erosion when designing road networks or other infrastructure.

As described in Chapter 4, changes in precipitation are projected to result in seasonal changes in streamflow, such as higher peak flows, which could affect infrastructure around streams and rivers. An increase in the frequency or intensity of windstorms, which may occur over the next century, could also increase operating and repair expenses related to infrastructure.

More Information

- A technical report summarizing climate change impacts on the transportation sector (including infrastructure) was recently released as input for the Midwest region for the National Climate Assessment: glisa.msu.edu/docs/NCA/MTIT_Transportation.pdf

FOREST CARBON

The accumulated carbon (C) pool within forest soils, belowground biomass, dead wood, and aboveground live biomass is enormous (Birdsey et al. 2006). Climate change and associated impacts to forest ecosystems may change the ability of forests in northern Michigan to store C. A longer growing season and carbon dioxide (CO_2) fertilization may lead to increased productivity and C storage in forests in the assessment area (Chapter 5). This increase could be offset by climate-related physical and biological disturbances (Gough et al. 2008, Hicke et al. 2011), leading to increases in C storage in some areas and decreases in others. As long as forests recover following a disturbance, total C losses may be negligible over the long term. If forests convert to nonforested conditions or if C stored in peat soils is lost to the atmosphere, then C storage is reduced over much longer time scales.

Different forest-type groups in the assessment area store different amounts of C (Chapter 1). On average, spruce/fir forests are the most C dense, but most of this C occurs in organic soils. Maple/beech/birch forests generally contain the most aboveground C, so an increase in these species and a decline in spruce/fir forests may affect C storage in some areas. Modeling studies in northern Wisconsin examining the effects of species composition changes on landscape-scale C stocks suggest that some forests may increase in biomass and overall productivity, despite declines in boreal or northern species (Chiang et al. 2008, Scheller and Mladenoff 2005). The LANDIS-II model results presented in Chapter 5 raise the possibility that existing species in northern Michigan may decline in landscape-level biomass across the assessment area under the GFDL A1FI climate scenario, but these projections do not account for increases in other species or the potential effects of CO_2 fertilization. As long as forests are maintained as forests in the assessment area, a large-scale decline in C stocks across northern Michigan is not expected.

More Information

- The Forest Service's Climate Change Resource Center provides a summary of how climate change may affect forests' ability to store C: www.fs.fed.us/ccrc/topics/forests-carbon/
- A recent article, *A Synthesis of the Science on Forests and Carbon for U.S. Forests*, summarizes the key issues related to forest management and C: www.fs.fed.us/rm/pubs_other/rmrs_2010_ryan_m002.pdf

WILDERNESS

There are a handful of federal wilderness areas in the assessment area, including the Seney Wilderness, Beaver Basin Wilderness, and the Delirium Wilderness. Climate change was not anticipated when the Wilderness Act was created, and now the potential for extensive ecosystem change raises difficult questions about the future management of these and other wilderness areas.

Climate change is poised to influence the forest ecosystems in the assessment area in a variety of ways. Fire seasons are expected to shift, and more area is projected to burn each year under climate change (Chapter 5). Additionally, many of the characteristic boreal species in the assessment area are projected to decline, and invasive species may increase in abundance and vigor (Chapter 5). Depending on the amount and timing of future precipitation, lake levels and aquatic ecosystems in the assessment area could be affected as well. Weather and climate could also influence recreational use, if spring and fall seasons become more attractive for visits or the threat of wildfires reduces visits in certain months. Furthermore, managers accept the fact that natural hazards and obstacles are inherently a part of the wilderness experience, but they try to remove trees that are posing immediate threats to visitors. Tree mortality from storm events, drought, or insect and disease attack could increase the need for this activity. Weather conditions also affect the need for maintenance of the trail tread, particularly when heavy rain events cause excessive erosion, or when wind events uproot trees and leave craters in parts of the trail.

It is difficult to anticipate how climate-related impacts will influence management in wilderness areas, because of the legal requirement for federally designated wilderness areas to be natural and untrammeled. Some arguments favor more-proactive management for wilderness areas to help create a "graceful transition" under climate change based on maintaining native tree species and natural processes like fire (Frelich and Reich 2009). Any changes to the management of federally designated wilderness areas would require complex choices and a thorough planning process to consider potential pros and cons.

More Information

- The Wilderness.net Climate Change Toolbox offers information about climate change and wilderness, including management guidelines and strategies: www.wilderness.net/climate.
- The Forest Service's Climate Change Resource Center provides a summary of how climate change may affect wilderness area management: www.fs.fed.us/ccrc/topics/wilderness/

CULTURAL RESOURCES

Certain species can hold unique cultural importance, often based on established uses. Changes in forest composition and extent may alter the presence or availability of culturally important species throughout the region. For example, Dickmann and Leefers (2003) compiled a list of more than 50 tree species in Michigan that are used by several Native American tribes in the region. Among these, northern white-cedar and paper birch stand out as having particular importance for defining a culture and way of life. Under climate change, however, these two species are expected to decline in suitable habitat and biomass over the next century (Chapter 5).

Climate change may also present challenges for managers of cultural resources on public lands. Extreme wind events such as tornadoes and derechos can directly damage buildings and other structures. Storm-damaged cultural resources may subsequently be further damaged by salvage harvest operations, because unsafe walking conditions and low ground surface visibility often make it impossible to conduct a cultural resources inventory before the salvage sale.

A change in the frequency, severity, or duration of heavy precipitation and flooding could affect cultural resources as well. Historical and prehistoric habitation sites are often located near lakes or waterways. Flood events or storm surges can result in increased erosion or obliteration of significant archaeological sites. Similarly, torrential rains can trigger or exacerbate erosion of cultural resources. Erosion from storm surges in the Great Lakes has already begun to wash away cultural sites within the Grand Portage National Monument and Apostle Islands National Lakeshore (Saunders et al. 2011).

More Information

- *Climate Change and World Heritage: Report on Predicting and Managing the Impacts of Climate Change on World Heritage* includes a list of climate change threats to cultural heritage sites: whc.unesco.org/documents/publi_wh_papers_22_en.pdf

RECREATION

Forests are the centerpiece of outdoor recreation in the Great Lakes region (Handler et al. 2012). People throughout this region enjoy hunting; fishing; camping; wildlife watching; and exploring trails on foot, bicycles, skis, snowshoes, horseback, and off-highway vehicles, among many other recreational pursuits. The vulnerabilities associated with climate change in forests may result in shifted timing or participation opportunities for forest-based recreation (Saunders et al. 2011). Forest-based recreation and tourism are strongly seasonal, and most visits to public lands are planned during times when the weather is most conducive to particular activities.

Projections indicate that seasonal shifts will continue toward shorter, milder winters and longer, hotter summers in the future (Chapter 4). Climate change generally stands to reduce opportunities for winter recreation in the Great Lakes region, although warm-weather forms of nature-based recreation may benefit (Dawson and Scott 2010, Jones and Scott 2006, Mcboyle et al. 2007). For example, opportunities for winter-based recreation activities such as cross-country skiing, snowmobiling, and ice fishing may be reduced due to shorter winter snowfall seasons (Notaro et al. 2011) and decreasing periods of lake-ice (Kling et al. 2003, Magnuson et al. 2000, Mishra et al. 2011). However, it is possible that areas prone to lake-effect snow may have more snowfall in the short term.

Warm-weather recreation activities such as mountain biking, off-highway vehicle riding, and fishing may benefit from extended seasons in the Midwest (Nicholls 2012). High spring precipitation could increase risks for flash flooding or lead to unpleasant conditions for recreation, however. Severe storms and flash flooding might also threaten infrastructure such as visitor centers, campsites, and trails. Fall will potentially be drier, which could lead to reduced water levels, and hence diminished water recreation opportunities. Warmer, drier conditions in the summer and fall may raise the risk of wildfire, increasing visitor safety risk and restrictions on open flames. Lengthening of spring and fall recreation seasons will also have implications for staffing, especially for recreation-related businesses that rely on student labor—which will be unavailable during the school year (Nicholls 2012).

Climate can also have important influences on hunting and fishing. The timing of certain hunts or fishing seasons correspond to seasonal events, which are in part driven by climate. Waterfowl hunting seasons, for example, are designed to correspond to the times when birds are migrating south in the fall, an event that is expected to shift later in the year as temperatures warm. As mentioned above, climate change may also result in substantial changes in habitat availability and quality for wildlife and fish species. In a recent assessment of climate change vulnerability for wildlife species in Michigan, game species were generally rated as less vulnerable than Species of Greatest Conservation Need (Hoving et al. 2013), but nearly 20 percent of game species were rated as moderately, highly, or extremely vulnerable to climate change.

More Information

- A recent report submitted for the National Climate Assessment summarizes the impacts of climate change on outdoor recreational tourism across the Midwest, including the assessment area: glisa.msu.edu/docs/NCA/MTIT_RecTourism.pdf
- Season's End, a collaboration of many hunting and conservation organizations, includes many resources on how climate change may affect wildlife: http://www.cakex.org/virtual-library/784
- *Changing Climate, Changing Wildlife*, a new report from the Michigan Department of Natural Resources – Wildlife Division, assesses how climate change may affect 400 wildlife species in the state, including many fish and game species: www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

HUMAN HEALTH CONCERNS

Vector-borne diseases, such as Lyme disease and West Nile virus, pose an important risk to forest managers and visitors alike. This issue may become increasingly important in northern Michigan during the 21st century. As an illustration of how climate change can influence these kinds of diseases, we present a synopsis of vector-borne diseases. Vector-borne diseases are transmitted by arthropod vectors (e.g., ticks or mosquitoes) and cycle back and forth between arthropod vectors and animal reservoirs, usually mammal or bird hosts. Humans are typically infected incidentally when they are bitten instead of animal hosts.

Climate is one of many important interacting variables that affect people's risk for vector-borne diseases in Michigan. Climate directly affects physical conditions (e.g., temperature, rainfall) and indirectly affects biologic conditions (plants, animals). These physical and biologic conditions can, in turn, influence vector-borne disease risk by altering the abundance and distribution of ticks or mosquitoes, the percentage of infected vectors, the abundance and distribution of animal reservoirs, the presence of suitable habitat for these vectors, and human behaviors that bring them into contact with infected vectors.

Most arthropod vectors of disease are sensitive to physical conditions, such as levels of humidity, daily high and low temperatures, rainfall patterns, and winter snowpack. For instance, blacklegged ticks (a.k.a. "deer ticks"), which are the vector for Lyme disease and several other diseases, are most active on warm, humid days. They are most abundant in wooded or brushy habitats (especially mesic hardwoods and managed aspen) with abundant small mammals and deer. Projected expansion of mesic hardwoods with changing climate conditions may increase the incidence of Lyme disease and other tick-borne diseases if those habitats are frequently visited by humans (i.e., residential, occupational, or recreational exposures).

More Information

- The Michigan Emerging Disease Issues Web site has more information on Lyme disease: www.michigan.gov/emergingdiseases
- The Minnesota Vector-borne Diseases Web site has more information on vector-borne diseases: www.health.state.mn.us/divs/idepc/dtopics/vectorborne/index.html
- The Michigan Department of Community Health has a Web site on the climate change implications for human health: www.michigan.gov/mdch
- The Centers for Disease Control and Prevention Climate and Health Program includes information on a variety of subjects: www.cdc.gov/climateandhealth/

URBAN FORESTS

Climate change is expected to affect urban forests in the assessment area as well. Urban environments can pose additional stresses to trees, such as pollution from vehicle exhaust, confined root environments, and road salts. Urban environments also cause a "heat island effect," and thus warming in cities may be even greater than in natural communities. Impervious surfaces can make urban environments more susceptible to floods, placing flood-intolerant species at risk. All of these abiotic stressors can make urban forests more susceptible to exotic species invasion, and insect and pathogen attack, especially because a limited range of species and genotypes is often planted in urban areas. Urban settings are often where exotic insect pests are first introduced.

Projected changes in climate can pose both challenges and opportunities for the management of urban forests. Shifts in temperature and changes in extreme events may have effects on selection of species for planting. Native species projected to decline under climate change may not tolerate the even more-extreme conditions presented by urban settings. Conversely, urban environments may favor heat-tolerant or drought-tolerant native species or new migrants (Chapter 5). Determining appropriate species for planting may be a challenge, but community foresters are already familiar with the practice of planting species novel to an area. Because of urban effects on climate, many community forests already contain species that are from planting zones south of the area or cultivars that tolerate a wide range of climate conditions.

Large disturbance events may also become more frequent or intense in the future, necessitating informed decisions in response. For example, wind events or pest outbreaks may be more damaging to already-stressed trees. If leaf-out dates advance earlier in the spring due to climate change, community forests may be increasingly susceptible to early-season frosts or snow storms. More people and larger budgets may be required to handle an increase in the frequency or intensity of these events, which may become more difficult in the face of reduced municipal budgets and staffing.

More Information

- The Forest Service's Climate Change Resource Center provides a summary of how climate change may affect urban forests: www.fs.fed.us/ccrc/topics/urban-forests/
- British Columbia has developed an urban forestry climate adaptation guide that includes some general considerations for adapting urban forests to climate change: www.toolkit.bc.ca/Resource/Urban-Forests-Climate-Adaptation-Guide
- The Clean Air Partnership has developed a climate change impact assessment and adaptation plan for Toronto's urban forest: www.cleanairpartnership.org/pdf/climate_change_adaptation.pdf

FOREST-ASSOCIATED TOWNS AND CITIES

A human community's ability to respond to changes in its environment is directed by its adaptive capacity—resources that can be leveraged by the community to monitor, anticipate, and proactively manage stressors and disturbances. Although impact models can predict ecological community responses to climate change, considerably less is known about the social and cultural impacts of climate or forest change and how human communities might best respond. Many towns and cities in the assessment area are intimately tied to the health and functioning of surrounding forests, whether for economic, cultural, or recreational reasons.

Every forest-associated community has particular conditions, capacities, and constraints that might make it more vulnerable or resilient to climate change. Moreover, the effects of climate change and forest impacts are not evenly distributed geographically or socially. Different communities (e.g., indigenous communities with forest-dependent cultural practices, tourism-dependent communities) and social groups within communities (e.g., individuals working in forest products industries) may be more vulnerable to these impacts and less able to adapt.

If resource professionals, community leaders, and local organizations are to help communities adapt, they must be able to assess community vulnerabilities and capacities to organize and engage resources. In the Great Lakes region, most human community vulnerability assessment work to date has focused on coastal communities (Minnesota Sea Grant 2012). Local examples of community-based climate change assessment and adaptation are underway in Michigan (see below).

When planning for climate change, decisionmakers can consider how ecological events or changes (e.g., floods, droughts, wildfire, windstorms, introduced species, insect or pathogen outbreaks) will affect their communities and community members by asking:

- Is access to healthy ecosystems at risk?
- Is there a potential for resource scarcity?
- Are cultural practices or recreational opportunities at risk?
- Is there potential for loss of social connectedness or increased social or cultural conflict?
- Is there potential for disproportionate impacts to certain populations?

- Is there potential for human health problems including stress, anxiety, despair, or sense of powerlessness?

More Information

- The Resilience Alliance has created a workbook for practitioners to assess resilience of social-ecological systems: www.resalliance.org/index.php/resilience_assessment
- Michigan Sea Grant produced a community self-assessment to address climate change readiness, and its Web site includes several resources useful for communities: www.miseagrant.umich.edu/
- The Superior Watershed Partnership and Lake Trust has prepared a Lake Superior Climate Adaptation, Mitigation, and Implementation Plan focused on communities within Michigan's Upper Peninsula: www.superiorwatersheds.org/images/climate-jan.pdf
- Alger and Delta Counties, in Michigan's Upper Peninsula, have prepared community-based climate change adaptation plans through participation in the Model Forest Policy Program's Climate Solutions University: www.mfpp.org/csu/

LAND ACQUISITION

Climate change has many important implications for land conservation planning in northern Michigan. Put most simply, climate change science can be used to help prioritize land conservation investments and help guide project design.

In terms of prioritizing specific parcels of land, it may be important to identify parcels that have large C mitigation potential. This is particularly important in the upper Great Lakes region, where private forestlands have some of the highest stored C levels in the entire country. Climate change trends and ecosystems models can also be used to identify lands that have long-term potential to provide habitat refugia and protection for shifting water supplies.

In the design of land conservation projects, there are important decisions to be made about long-term ownership and management prescriptions attached to the conservation agreement. In some cases, the best strategy may be to leave lands in private ownership, and to develop conservation easement terms that support adaptive management by the landowner to address climate shifts. In other cases, perhaps where complex restoration or species-specific management is needed, it might be appropriate to seek a public agency owner that can provide the necessary financial and technical resources.

Private nonprofits, government agencies, landowners, and potential funders will need research-based results on anticipated climate trends and impacts, including spatially explicit information on how these shifts will play out over the land. This science can enable effective use of funding, staff time, and other resources that are essential to advancing "climate-informed" conservation of forests in Michigan, and shaping conservation efforts to deliver a more resilient landscape.

PLANNING

Until recently, climate change has not played a large role in natural resource planning. Many federal and state-level land management agencies are now beginning to address the issue. For example, the Forest Service's 2012 Planning Rule directly addresses the impacts and ramifications of climate change. In fact, climate change was among the stated purposes for revising the Rule (FR Vol. 77, No. 68, 21163 & 21164). As the Hiawatha and Huron-Manistee National Forests revise their management plans in the coming years, they will be required to address climate change under the new Planning Rule. Similarly, Michigan's State Forest Management Plans have not historically addressed the issue. The *2010 State Forest Resource Assessment and Strategy* document points to climate change as a potential influence on the long-term sustainability of Michigan's forests (Price 2010).

Incorporating climate change considerations into natural resources planning will always be a complex endeavor. The uncertainties associated with planning over long time horizons are only compounded with climate change. Management plans for national forests or state agencies are typically written to guide management for a 10- to 15-year period, and it may be difficult to envision projected shifts in climate within this short planning horizon. Additionally, major storms or disturbance events are inherently unpredictable, and often force managers to deviate from planned analysis or treatment cycles. If climate change results in more frequent disturbances or unanticipated interactions among major stressors, managers may be hard-pressed to adhere to the stated goals, objectives, and priorities in current plans. Future land management plans may have to incorporate adaptive management principles and include built-in flexibility to address shifting conditions and priorities.

More Information

- More information on the Forest Service's 2012 Planning Rule can be found here: www.fs.usda.gov/planningrule
- Michigan's *Forest Resource Assessment and Strategies* documents include discussions of climate change: www.forestactionplans.org/states/michigan
- Michigan's State Forest Planning program, along with the Regional State Forest Management Planning program, is explained on the Michigan Department of Natural Resources Web site. The recently released Regional State Forest Management Plans consider climate change explicitly:
  www.michigan.gov/dnr/0,1607,7-153-30301_30505---,00.html
  www.michigan.gov/dnr/0,4570,7-153-30301_30505_62551---,00.html

CONCLUSIONS

The breadth of the topics above highlights the wide range of effects climate change may have on forest management in northern Michigan. It is not the role of this assessment to identify adaptation actions that should be taken to address these climate-related risks and vulnerabilities, nor would it be feasible to prescribe suitable responses for all future circumstances. Decisions to address climate-related risks for forest ecosystems in northern Michigan will be affected by economic, political, ecological, and societal factors. These factors will be specific to each land owner and agency, and are highly unpredictable.

Confronting the challenge of climate change presents opportunities for managers and other decisionmakers to plan ahead, manage for resilient landscapes, and ensure that the benefits that forests provide are sustained into the future. Resources are available to help forest managers and planners incorporate climate change considerations into existing decisionmaking processes (Swanston and Janowiak 2012) (www.forestadaptation.org). This assessment will be a useful foundation for land managers in that process, to be further enriched by local knowledge and site-specific information.

GLOSSARY

aerosol
a suspension of fine solid particles or liquid droplets in a gas, such as smoke, oceanic haze, air pollution, and smog. Aerosols may influence climate by scattering and absorbing radiation, acting as condensation nuclei for cloud formation, or modifying the properties and lifetime of clouds.

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

agreement
the extent to which evidence is consistent in support of a vulnerability statement or rating (see also **confidence**, **evidence**).

alluvial
referring to a deposit of clay, silt, sand, and gravel left by flowing streams in a river valley or delta, typically producing fertile soil.

asynchronous quantile regression
a type of regression used in statistical downscaling. Quantile regression models the relation between a set of predictor variables and specific percentiles (or quantiles) of the response variable.

biomass
the mass of living organic matter (plant and animal) in an ecosystem; also organic matter (living and dead) available on a renewable basis for use as a fuel; biomass includes trees and plants (both terrestrial and aquatic), agricultural crops and wastes, wood and wood wastes, forest and mill residues, animal wastes, livestock operation residues, and some municipal and industrial wastes.

carbon dioxide (CO_2) fertilization
increased plant uptake of CO_2 through photosynthesis in response to higher concentrations of atmospheric CO_2 .

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

climate model
see **general circulation model**.

climate normal
the arithmetic mean of a climatological element computed over three consecutive decades.

community
an assemblage of plants and animals living together and occupying a given area.

confidence
a qualitative assessment of uncertainty as determined through evaluation of evidence and agreement (see also **evidence**, **agreement**).

convective storm
convection is a process whereby heat is transported vertically within the atmosphere. Convective storms result from a combination of convection, moisture, and instability. Convective storms can produce thunderstorms, tornadoes, hail, heavy rains, and straight-line winds.

derecho
widespread and long-lived convective windstorm that is associated with a band of rapidly moving showers or thunderstorms characterized by wind gusts that are greater than 57 miles per hour and that may exceed 100 miles per hour.

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

downscaling
methods for obtaining high-resolution climate or climate change information from coarse-resolution general circulation models.

driver
any natural or human-induced factor that directly or indirectly causes a change in an ecosystem.

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

ecoregion
a region characterized by a repetitive pattern of ecosystems associated with commonalities in climate and landform.

ecological province
climatic subzones, controlled primarily by continental weather patterns such as length of dry season and duration of cold temperatures. Provinces are also characterized by similar soil orders and are evident as extensive areas of similar potential natural vegetation.

ecosystem
a volumetric unit of the earth's surface that includes air (climate), land (landform, soil, water), and biota. Ecosystems are defined by land area, and contain all the interactions between living organisms and their physical environment.

emissions scenario
a plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on demographic, technological, or environmental developments.

evapotranspiration
the sum of evaporation from the soil and transpiration from plants.

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

fire-return interval
the number of years between two successive fire events at a specific location.

forest land
land that is at least 10 percent stocked by forest trees of any size, or land formerly having such tree cover, and not currently developed for a nonforest use.

forest type
a classification of forest vegetation based on the dominant species present, as well as associate species commonly occurring with the dominant species.

forest-type group
based on FIA definitions, a combination of forest types that share closely associated species or site requirements and are generally combined for brevity of reporting.

fragmentation
a disruption of ecosystem or habitat connectivity, caused by human or natural disturbance, creating a mosaic of successional and developmental stages within or between forested tracts of varying patch size, isolation (distance between patches), and edge length.

fundamental niche
the total habitat available to a species based on climate, soils, and land cover type in the absence of competitors, diseases, or predators.

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

greenhouse effect
the rise in temperature that the Earth experiences because certain gases in the atmosphere (water vapor, carbon dioxide, nitrous oxide, and methane, for example) absorb and emit energy from the sun.

growing season
the period in each year when the temperature is favorable for plant growth.

hardwood
a dicotyledonous tree, usually broad-leaved and deciduous. Hardwoods can be split into soft hardwoods (red maple, paper birch, quaking aspen and American elm) and hard hardwoods (sugar maple, yellow birch, black walnut, and oaks).

hydric
referring to sites or habitats with abundant moisture throughout the year, frequently including saturation, ponding, or flooding.

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

impact model
a model simulating impacts on trees, animals, and ecosystems. It uses general circulation model projections as inputs, and includes additional inputs such as tree species, soil types, and life history traits of individual species.

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

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

Kyoto Protocol
adopted at the 1997 Third Session of the Conference of Parties to the U.N. Framework Convention on Climate Change in Kyoto, Japan; it contains legally binding commitments to reduce anthropogenic greenhouse gas emissions by at least 5 percent below 1990 levels in the period 2008-2012.

mesic
referring to sites or habitats where soil moisture is available to plants throughout the growing season.

model reliability score
in the Climate Change Tree Atlas model, a “tri-model” approach to assess reliability of model predictions for each species, classified as high, medium, or low.

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

parcelization
the subdivision of a single forest ownership into two or more ownerships. Parcelization may result in fragmentation if habitat is altered under new ownership.

peak flow
the maximum instantaneous discharge of a stream or river at a given location.

phenology
the timing of natural events such as the date that migrating birds return, the first flower dates for plants, and the date on which a lake freezes in the autumn or opens in the spring. Also refers to the study of this subject.

prairie
a natural community dominated by perennial grasses and forbs with scattered shrubs and very few trees (less than 10 percent canopy cover).

process model
a model that relies on computer simulations based on mathematical representations of physical and biological processes that interact over space and time.

productivity
the rate at which biomass is produced per unit area by any class of organisms, or the rate of energy utilization by organisms.

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

proxy
a figure or data source that is used as a substitute for another value in a calculation. Ice and sediment cores, tree rings, and pollen fossils are all examples of things that can be analyzed to infer past climate. The size of rings and the isotopic ratios of elements (e.g., oxygen, hydrogen, and carbon) in rings and other substrates allow scientists to infer climate and timing.

pulpwood
roundwood, whole-tree chips, or wood residues used for the production of wood pulp for making paper and paperboard products.

realized niche
the portion of potential habitat a species occupies; usually it is less than what is available because of predation, disease, and competition with other species.

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

runoff
that part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions or storage.

savanna
fire-maintained grasslands with open-grown, scattered, orchard-like trees or groupings of trees and shrubs.

saw log
a log meeting minimum standards of diameter, length, and defect, including logs at least 8 feet long, sound and straight, and with a minimum diameter inside bark of 6 inches for softwoods and 8 inches for hardwoods, or meeting other combinations of size and defect specified by regional standards.

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

severity
the proportion of aboveground vegetation killed and the degree of forest floor and soil disruption.

significant trend
in this report, least-squares regression *p*-values of observed climate trends are significant when $p<0.10$. For trends where $p>0.10$, observed trends have a higher probability of being due to chance alone.

softwood
a coniferous tree, usually evergreen, having needles or scale-like leaves.

snow water equivalent
the amount of water contained in snowpack. It is a way of measuring the amount of snow while accounting for differences in density.

snowpack
layers of accumulated snow that usually melts during warmer months.

species distribution model
a model that uses statistical relationships to project future change.

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

stratosphere
the layer of the Earth's atmosphere which lies between 6 and 30 miles above the Earth.

streamflow
discharge that occurs in a natural surface stream course whether or not it is diverted or regulated.

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

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

swamp
freshwater, woody communities with surface water throughout most of the year.

timberland
forest land that is producing or capable of producing in excess of 20 cubic feet per acre per year of wood.

transpiration
liquid water phase change occurring inside plants with the vapor diffusing to the atmosphere.

troposphere
the lowest part of the atmosphere from the surface to about 6 miles in altitude in mid-latitudes (ranging on average from 5 miles in high latitudes to 9 miles in the tropics) where clouds and weather phenomena occur.

topkill
death of aboveground tree stem and branches.

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

veneer
a roundwood product from which veneer is sliced or sawn and that usually meets certain standards of minimum diameter, length, and maximum defect.

vulnerability
the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. For this assessment, a system may be considered to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity.

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

windthrow
trees uprooted or broken by wind.

woodland
highly variable natural communities with a canopy of trees ranging from 30- to 100-percent openness, a sparse understory, and a dense ground flora rich in grasses, sedges, and forbs.

xeric
pertaining to sites or habitats characterized by decidedly dry conditions.

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APPENDIX 1: SPECIES LISTS

Table 20.—Common and scientific names of plant species mentioned in this assessment

Common Name	Scientific Name
balsam fir	*Abies balsamea*
boxelder	*Acer negundo*
striped maple	*Acer pensylvanicum*
red maple	*Acer rubrum*
silver maple	*Acer saccharinum*
sugar maple	*Acer saccharum*
mountain maple	*Acer spicatum*
Ohio buckeye	*Aesculus glabra*
garlic mustard	*Alliaria petiolata*
tag alder	*Alnus rugosa*
pawpaw	*Asimina triloba*
Japanese barberry	*Berberis thunbergii*
yellow birch	*Betula alleghaniensis*
sweet birch	*Betula lenta*
river birch	*Betula nigra*
paper birch	*Betula papyrifera*
Pennsylvania sedge	*Carex pensylvanica*
American hornbeam	*Carpinus caroliniana*
bitternut hickory	*Carya cordiformis*
pignut hickory	*Carya glabra*
shellbark hickory	*Carya laciniosa*
shagbark hickory	*Carya ovata*
black hickory	*Carya texana*
mockernut hickory	*Carya tomentosa*
sugarberry	*Celtis laevigata*
hackberry	*Celtis occidentalis*
spotted knapweed	*Centaurea maculosa*
eastern redbud	*Cercis canadensis*
flowering dogwood	*Cornus florida*
common persimmon	*Diospyros virginiana*
autumn olive	*Elaeagnus umbellata*
leafy spurge	*Euphorbia esula*
American beech	*Fagus grandifolia*
white ash	*Fraxinus americana*

Common Name	Scientific Name
black ash	*Fraxinus nigra*
green ash	*Fraxinus pennsylvanica*
honeylocust	*Gleditsia triacanthos*
St. John's wort	*Hypericum perforatum*
butternut	*Juglans cinerea*
black walnut	*Juglans nigra*
eastern redcedar	*Juniperus virginiana*
tamarack	*Larix laricina*
yellow-poplar	*Liriodendron tulipifera*
Osage-orange	*Maclura pomifera*
red mulberry	*Morus rubra*
blackgum	*Nyssa sylvatica*
eastern hophornbeam (ironwood)	*Ostrya virginiana*
reed canarygrass	*Phalaris arundinacea*
white spruce	*Picea glauca*
black spruce	*Picea mariana*
jack pine	*Pinus banksiana*
red pine	*Pinus resinosa*
eastern white pine	*Pinus strobus*
sycamore	*Platanus occidentalis*
balsam poplar	*Populus balsamifera*
eastern cottonwood	*Populus deltoides*
bigtooth aspen	*Populus grandidentata*
quaking aspen	*Populus tremuloides*
wild plum	*Prunus americana*
pin cherry	*Prunus pensylvanica*
black cherry	*Prunus serotina*
chokecherry	*Prunus virginiana*
white oak	*Quercus alba*
swamp white oak	*Quercus bicolor*
scarlet oak	*Quercus coccinea*
northern pin oak	*Quercus ellipsoidalis*
shingle oak	*Quercus imbricaria*

(Appendix 1 continued on next page)

Table 20 (continued).

Common Name	Scientific Name
bur oak	*Quercus macrocarpa*
blackjack oak	*Quercus marilandica*
chinquapin oak	*Quercus muehlenbergii*
pin oak	*Quercus palustris*
chestnut oak	*Quercus prinus*
northern red oak	*Quercus rubra*
post oak	*Quercus stellata*
black oak	*Quercus velutina*
European buckthorn	*Rhamnus cathartica*
black locust	*Robinia pseudoacacia*
multiflora rose	*Rosa multiflora*
peachleaf willow	*Salix amygdaloides*
black willow	*Salix nigra*
sassafras	*Sassafras albidum*
sphagnum moss	*Sphagnum* spp.
northern white-cedar	*Thuja occidentalis*
American basswood	*Tilia americana*
eastern hemlock	*Tsuga canadensis*
American elm	*Ulmus americana*
slippery elm	*Ulmus rubra*
rock elm	*Ulmus thomasii*
wild rice	*Zizania palustris*

Table 21.—Common and scientific names of fauna species mentioned in this assessment

Common Name	Scientific Name
northern goshawk	*Accipiter gentilis*
hemlock wooly adelgid	*Adelges tsugae*
bronze birch borer	*Agrilus anxius*
emerald ash borer	*Agrilus planipennis*
moose	*Alces alces*
Asian long-horned beetle	*Anoplophora glabripennis*
ruffed grouse	*Bonasa umbellus*
red-shouldered hawk	*Buteo lineatus*
beaver	*Castor canadensis*
spruce budworm	*Choristoneura fumiferana*
jack pine budworm	*Choristoneura pinus pinus*
larch casebearer	*Coleophora laricella*
earthworms (nonnative)	*Dendrobaena octaedra, Lumbricus rubellus,* and *L. terrestris*
eastern larch beetle	*Dendroctonus simplex*
spruce grouse	*Falcipennis canadensis*
birch leaf miner	*Fenusa pusilla*
common opossum	*Glaucomys sabrinus*
northern flying squirrel	*Glaucomys sabrinus*
southern flying squirrel	*Glaucomys volans*
bark beetles	*Ips* spp. and *Dendroctonus* spp.
blacklegged tick	*Ixodes scapularis*
snowshoe hare	*Lepus americanus*
gypsy moth	*Lymantria dispar dispar*
Canada lynx	*Lynx canadensis*
forest tent caterpillar	*Malacosoma disstria*
American marten	*Martes americana*
red-headed woodpecker	*Melanerpes erythrocephalus*
wild turkey	*Meleagris gallopavo*
southern red-backed vole	*Myodes gapperi*
Indiana bat	*Myotis sodalis*
woodland jumping mouse	*Napaeozapus insignis*
red-headed pine sawfly	*Neodiprion lecontei*
white-tailed deer	*Odocoileus virginianus*
gray jay	*Perisoreus canadensis*
white-footed mouse	*Peromyscus leucopus*
woodland deer mouse	*Peromyscus maniculatus gracilis*
black-backed woodpecker	*Picoides arcticus*
white pine tip weevil	*Pissodes strobi*
balsam fir bark beetle	*Pityokteines sparsus*
Karner blue butterfly	*Plebejus melissa samuelis*
tamarack sawfly	*Pristiphora erichsonii*
brook trout	*Salvelinus fontinalis*
lake trout	*Salvelinus namaycush*
American woodcock	*Scolopax minor*
Kirtland's warbler	*Setophaga kirtlandii*
eastern massasauga	*Sistrurus catenatus*
least chipmunk	*Tamias minimus*
eastern chipmunk	*Tamias striatus*
sharp-tailed grouse	*Tympanuchus phasianellus*
golden-winged warbler	*Vermivora chrysoptera*

Table 22.—Common and scientific names of other species mentioned in this assessment

Common Name	Scientific Name
Armillaria	*Armillaria mellea*
dwarf mistletoe	*Arceuthobium pusillum*
Lyme disease	*Borrelia burgdorferi*
oak wilt	*Ceratocystis fagacearum*
white pine blister rust	*Cronartium ribicola*
Diplodia	*Diplodia pinea* and *D. scrobiculata*
West Nile virus	*Flavivirus* spp.
scleroderris canker	*Gremmeniella abietina*
annosum root disease	*Heterobasidion irregulare*
hypoxylon canker	*Hypoxylon mammatum*
morel mushroom	*Morchella* spp.
Dutch elm disease	*Ophiostoma ulmi*
sudden oak death	*Phytophthora ramorum*
sirococcus shoot blight	*Sirococcus conigenus*
sphaeropsis shoot blight	*Sphaeropsis sapinea*

APPENDIX 2: TREND ANALYSIS AND HISTORICAL CLIMATE DATA

To examine historical trends in precipitation and temperature for the analysis area, we used the ClimateWizard Custom Analysis Tool (ClimateWizard 2012, Gibson et al. 2002, Girvetz et al. 2009). Data for ClimateWizard are derived from PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Gibson et al. 2002). The PRISM model interpolates historical data from the National Weather Service cooperative stations, the Midwest Climate Data Center, and the Historical Climate Network, among others. Data undergo strict quality control procedures to check for errors in station measurements. PRISM finds linear relationships between these station measurements and local elevation by using a digital elevation model (digital gridded version of a topographic map). Temperature and precipitation are then derived for each pixel on a continuous 2.5-mile grid across the conterminous United States. The closer a station is to a grid cell of interest in distance and elevation, and the more similar it is in its proximity to coasts or topographic features, the higher the weight the station will have on the final, predicted value for that cell. More information on PRISM can be found at: www.prism.oregonstate.edu/

This gridded historical data set is different from that used in the National Climate Assessment, which uses a new gridded historical data set (CDDv2) from the National Climatic Data Center (Kunkel et al. 2013). The new gridded data set was not publicly available at the time this assessment was completed, and therefore we cannot fully compare this new version with the one available through PRISM. However, both are based on cooperative weather station data, cover the period from 1895 through 2011, and have similar resolutions (3.1- vs. 2.5-mile grid). In addition, the overall trends reported as input into the National Climate Assessment are generally consistent with those reported in this assessment (Kunkel et al. 2013).

Linear trend analysis for 1901 through 2011 was performed by using restricted maximum likelihood (REML) estimation (Girvetz et al. 2009). Restricted maximum likelihood methods were used for trend analysis of past climate for the Intergovernmental Panel on Climate Change Working Group 1 Report and are considered an effective way to determine trends in climate data over time (Trenberth et al. 2007). A first-order autoregression was assumed for the residuals, meaning that values one time step away from each other are assumed to be correlated. This method was used to examine trends for every 2.5-mile grid cell. The slope and *p*-values for the linear trend over time were calculated annually, seasonally, and monthly for each climate variable, and then mapped. An overall trend for an area is based on the trend analysis of the average value for all grid cells within the area over time (Table 23).

Developers of the ClimateWizard Tool advise users to interpret the linear trend maps in relation to the respective map of statistical confidence (Figs. 48 and 49). In this case, statistical confidence is described by using *p*-values from a t-test applied to the linear regression. A *p*-value can be interpreted as the probability of the slope being different from zero by chance alone. For this assessment, *p*-values of less than 0.1 were considered to have sufficient statistical confidence. Areas with low statistical confidence in the rate of change (gray areas on the map) should be interpreted with caution.

Table 23.—Average annual, seasonal, and monthly values and linear trend analysis for selected climate variables from 1901 through 2011 for the assessment area

Month or season	Mean precip. (inches)	Precip. change (inches)	Precip. *p*-value*	Mean TMean (°F)	TMean change (°F)	TMean *p*-value*	Mean TMax (°F)	TMax change (°F)	TMax *p*-value*	Mean TMin (°F)	TMin change (°F)	TMin *p*-value*
January	1.81	0.35	0.15	18.19	0.94	0.51	26.44	0.41	0.76	9.94	1.46	0.34
February	1.45	-0.17	0.33	18.56	5.14	**<0.01**	28.19	4.68	**<0.01**	8.93	5.6	**0.01**
March	1.87	0.09	0.74	27.76	2.66	**0.03**	37.72	3.33	**0.01**	17.79	1.99	0.11
April	2.43	0.82	**0.01**	40.71	2.8	**<0.01**	51.54	3.31	**<0.01**	29.89	2.28	**0.01**
May	2.92	-0.02	0.95	52.18	2.32	**0.01**	64.35	2.57	**0.02**	40.01	2.06	**0.02**
June	3.06	0.59	0.13	61.98	1.11	0.25	74.21	0.94	0.4	49.77	1.27	0.16
July	2.87	0.21	0.53	67.06	0.46	0.47	79.28	-0.11	0.88	54.84	1.03	**0.08**
August	3.07	0.88	**0.02**	65.33	1.99	**0.01**	77.07	1.39	**0.09**	53.59	2.58	**<0.01**
September	3.43	0.56	0.15	57.97	0.16	0.86	68.94	0.4	0.67	47.01	-0.08	0.92
October	2.83	0.83	**0.04**	47.2	-0.21	0.83	57.03	-0.23	0.85	37.38	-0.19	0.83
November	2.59	0.27	0.36	35.09	1.35	0.14	42.53	1.44	0.19	27.66	1.26	0.13
December	1.96	0.48	**0.05**	23.62	1.98	**0.08**	30.79	1.46	0.16	16.44	2.5	**0.05**
Annual	30.3	4.89	**<0.01**	42.97	1.72	**<0.01**	53.18	1.64	**<0.01**	32.77	1.81	**<0.01**
Winter	5.22	0.65	0.15	20.13	2.7	**0.01**	28.48	2.2	**0.02**	11.77	3.2	**0.01**
Spring	7.21	0.85	**0.08**	40.21	2.58	**<0.01**	51.2	3.06	**<0.01**	29.24	2.11	**<0.01**
Summer	9.01	1.69	**<0.01**	64.78	1.2	**0.03**	76.85	0.76	0.2	52.73	1.63	**<0.01**
Fall	8.85	1.68	**0.02**	46.75	0.44	0.48	56.16	0.55	0.45	37.34	0.34	0.57

**P*-values represent the probability of observing that trend by chance alone. *P*-values in boldface indicate a 10-percent probability (or less) that the trend was due to chance alone. TMean = mean temperature, TMin = minimum temperature, TMax = maximum temperature.

In addition, because maps are developed from weather station observations that have been spatially interpolated, developers of the ClimateWizard tool and PRISM data set recommend that inferences about trends should not be made for single grid cells or even small clusters of grid cells. The number of weather stations has also changed over time, and station data are particularly limited before 1948, meaning grid cells from earlier in the century are based on an interpolation of fewer points than later in the century (Gibson et al. 2002). Therefore, interpretations should be based on many grid cells showing regional patterns of climate change with high statistical confidence. For those interested in understanding trends in climate at a particular location, it is best to refer to weather station data for the closest station in the Global Historical Climatology Network from the National Climatic Data Center (http://www.ncdc.noaa.gov/).

We selected the time period 1901 through 2011 because it was sufficiently long to capture inter- and intra-decadal variation in climate for the region. We acknowledge that different trends can be inferred by selecting different beginning and end points in the analysis. Therefore, trends should be interpreted based on their relative magnitude and direction, and the slope of any single trend should be interpreted with caution.

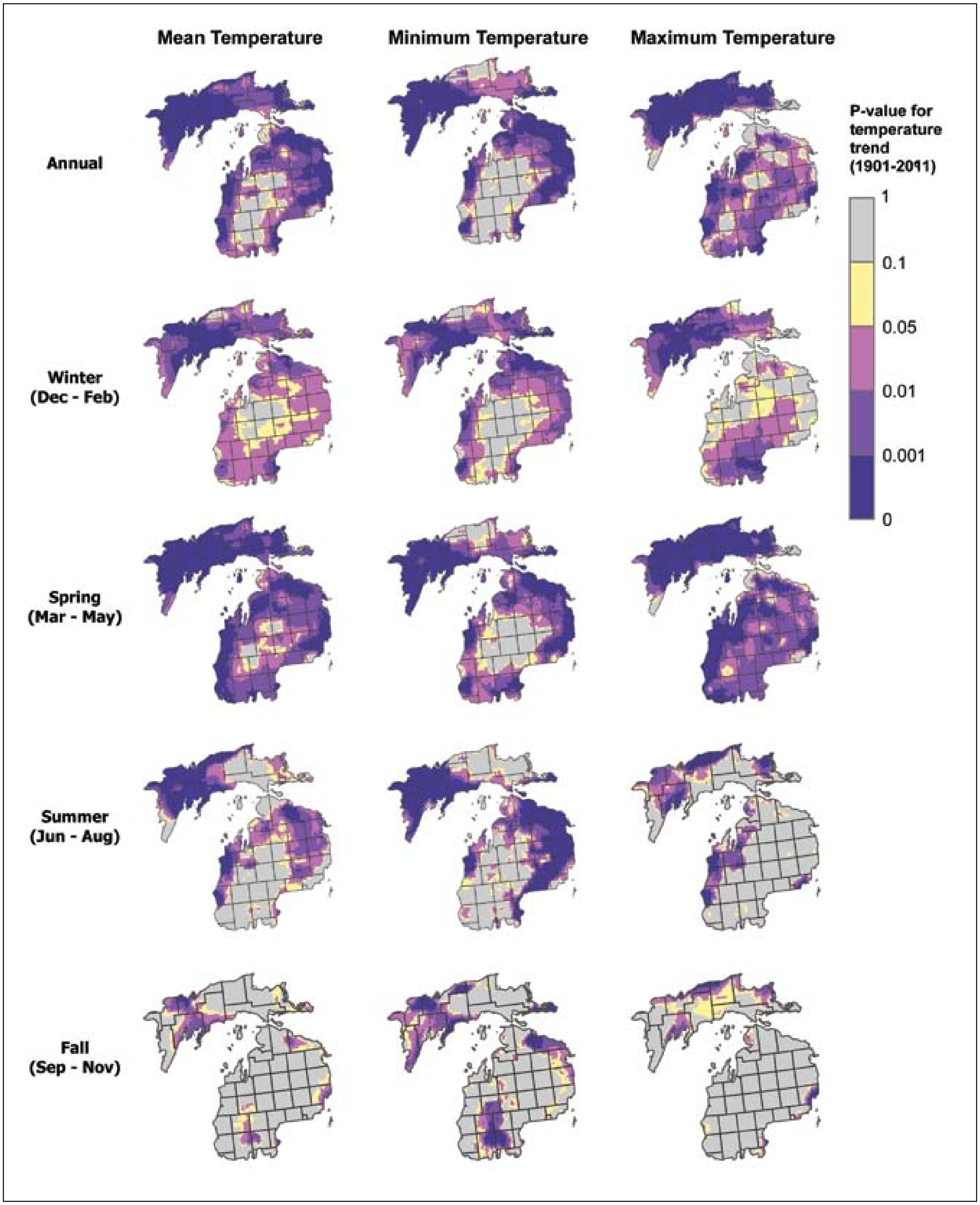

Figure 48.—Map of statistical confidence (*p*-values for the linear regression) for trends in temperature from 1901 through 2011. Gray values represent areas of low statistical confidence.

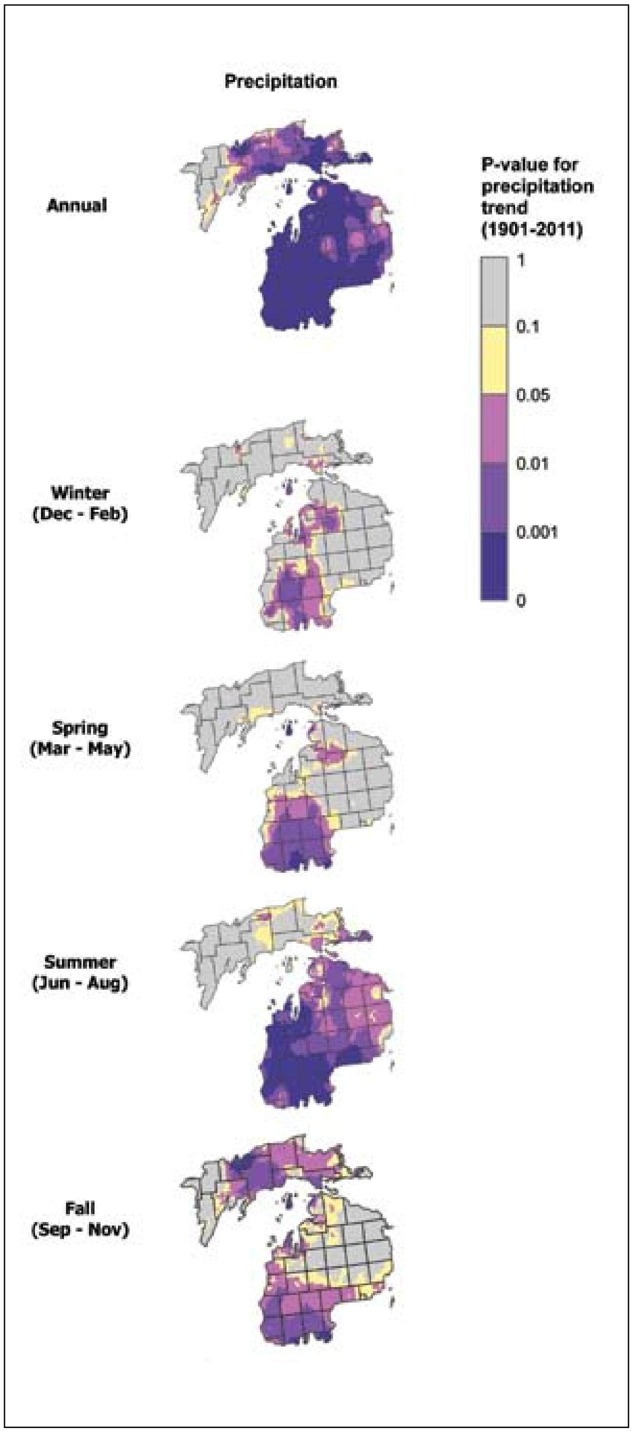

Figure 49.—Map of statistical confidence (*p*-values for the linear regression) for trends in precipitation from 1901 through 2011. Gray values represent areas of low statistical confidence.

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APPENDIX 3: ADDITIONAL FUTURE CLIMATE INFORMATION

This appendix presents supplementary information to Chapter 4: tables of projected change in temperature and precipitation for the assessment for the end of the 21st century (Tables 24 and 25) and maps of projected change for early- and mid-century (Figs. 50 through 57).

Table 24.—Projected changes in mean average, maximum, and minimum temperatures under two future climate scenarios for the assessment area over the next century

	Baseline temperature (°F) (1971-2000)	Temperature departure from baseline (°F)			
		Scenario	2010-2039	2040-2069	2070-2099
Mean					
Annual	43.2	PCM B1	1.0	1.7	2.2
		GFDL A1FI	2.2	6.0	8.1
Winter (Dec.-Feb.)	20.5	PCM B1	1.1	2.2	2.5
		GFDL A1FI	2.2	6.1	7.3
Spring (Mar.-May)	41.1	PCM B1	-0.2	0.9	1.7
		GFDL A1FI	0.7	4.1	6.0
Summer (June-Aug.)	64.9	PCM B1	1.3	1.8	2.2
		GFDL A1FI	3.6	8.6	11.2
Fall (Sept.-Nov.)	46.2	PCM B1	2.3	2.1	2.7
		GFDL A1FI	2.6	5.7	8.2
Mean maximum					
Annual	53.6	PCM B1	0.8	1.4	1.9
		GFDL A1FI	1.9	5.6	7.3
Winter (Dec.-Feb.)	28.9	PCM B1	0.8	1.5	1.6
		GFDL A1FI	1.7	4.8	5.7
Spring (Mar.-May)	52.4	PCM B1	-0.9	0.4	1.2
		GFDL A1FI	-0.3	2.8	4.3
Summer (June-Aug.)	77	PCM B1	1.7	2.0	2.6
		GFDL A1FI	3.8	9.0	11.4
Fall (Sept.-Nov.)	55.8	PCM B1	2.1	2.0	2.6
		GFDL A1FI	2.6	6.1	8.2
Mean minimum					
Annual	32.9	PCM B1	1.3	1.9	2.5
		GFDL A1FI	2.5	6.5	8.9
Winter (Dec.-Feb.)	12	PCM B1	1.4	2.9	3.5
		GFDL A1FI	2.7	7.4	9.0
Spring (Mar.-May)	29.8	PCM B1	0.4	1.4	2.1
		GFDL A1FI	1.6	5.4	7.7
Summer (June-Aug.)	52.8	PCM B1	1.0	1.6	1.8
		GFDL A1FI	3.4	8.1	11.0
Fall (Sept.-Nov.)	36.7	PCM B1	2.5	2.1	2.8
		GFDL A1FI	2.5	5.3	8.1

Table 25.—Projected changes in precipitation under two future climate scenarios for the assessment area over the next century

	Baseline precipitation (inches) (1971-2000)	Departure from baseline (inches)			
		Scenario	2010-2039	2040-2069	2070-2099
Annual	31.7	PCM B1	1.1	3.1	2.6
		GFDL A1FI	1.8	-1.5	1.0
Winter (Dec.-Feb.)	5.5	PCM B1	0.5	0.8	1.1
		GFDL A1FI	0.6	0.4	0.8
Spring (Mar.-May)	7.3	PCM B1	0.1	1.0	0.8
		GFDL A1FI	1.0	1.6	2.6
Summer (June-Aug.)	9.8	PCM B1	0.5	1.5	1.0
		GFDL A1FI	-0.1	-3.0	-3.8
Fall (Sept.-Nov.)	9.2	PCM B1	0.1	-0.3	-0.3
		GFDL A1FI	0.2	-0.6	1.4

Lupine in the northern Lower Peninsula. Photo by U.S. Forest Service, Huron-Manistee National Forest.

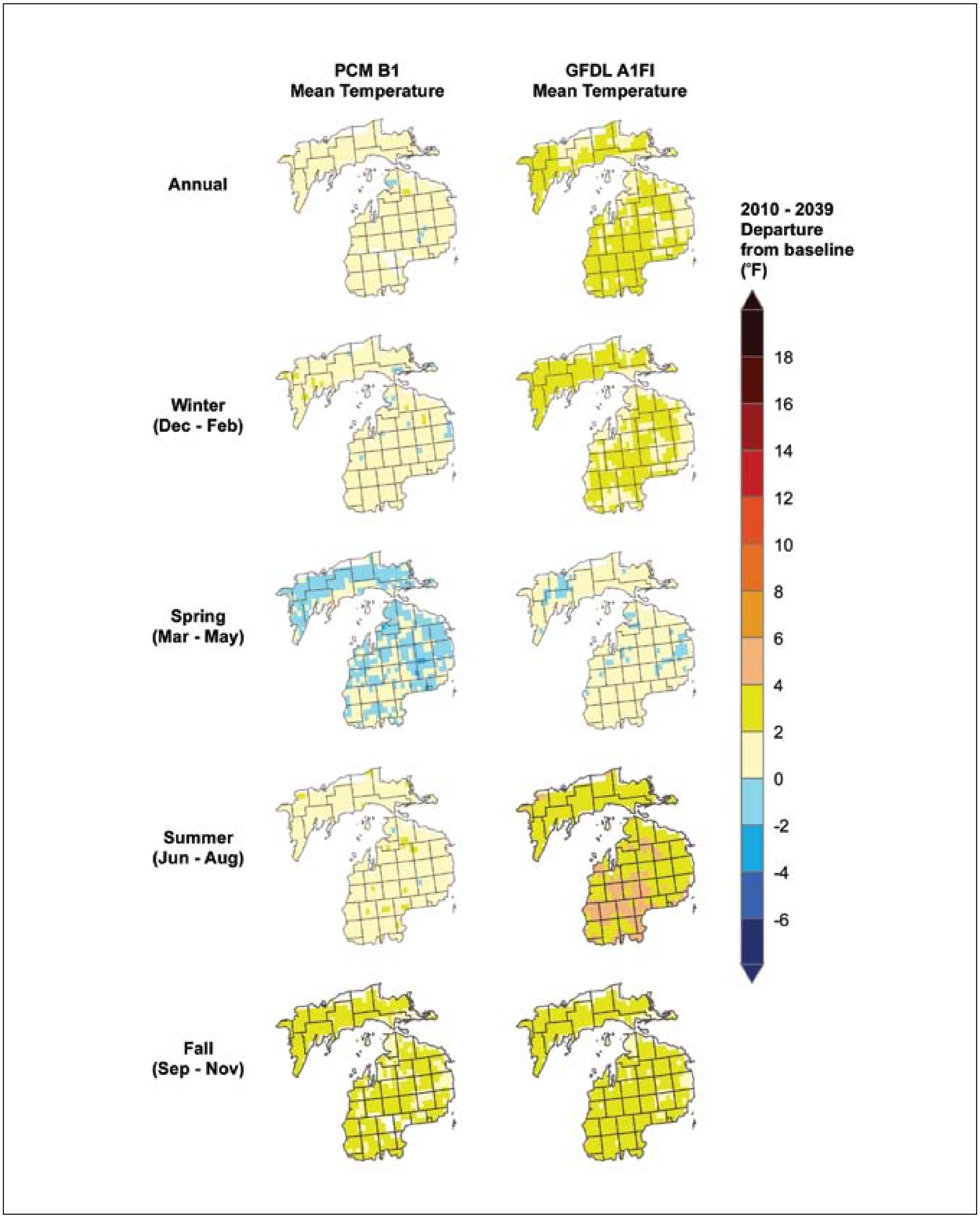

Figure 50.—Projected difference in mean daily temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000), under two climate scenarios.

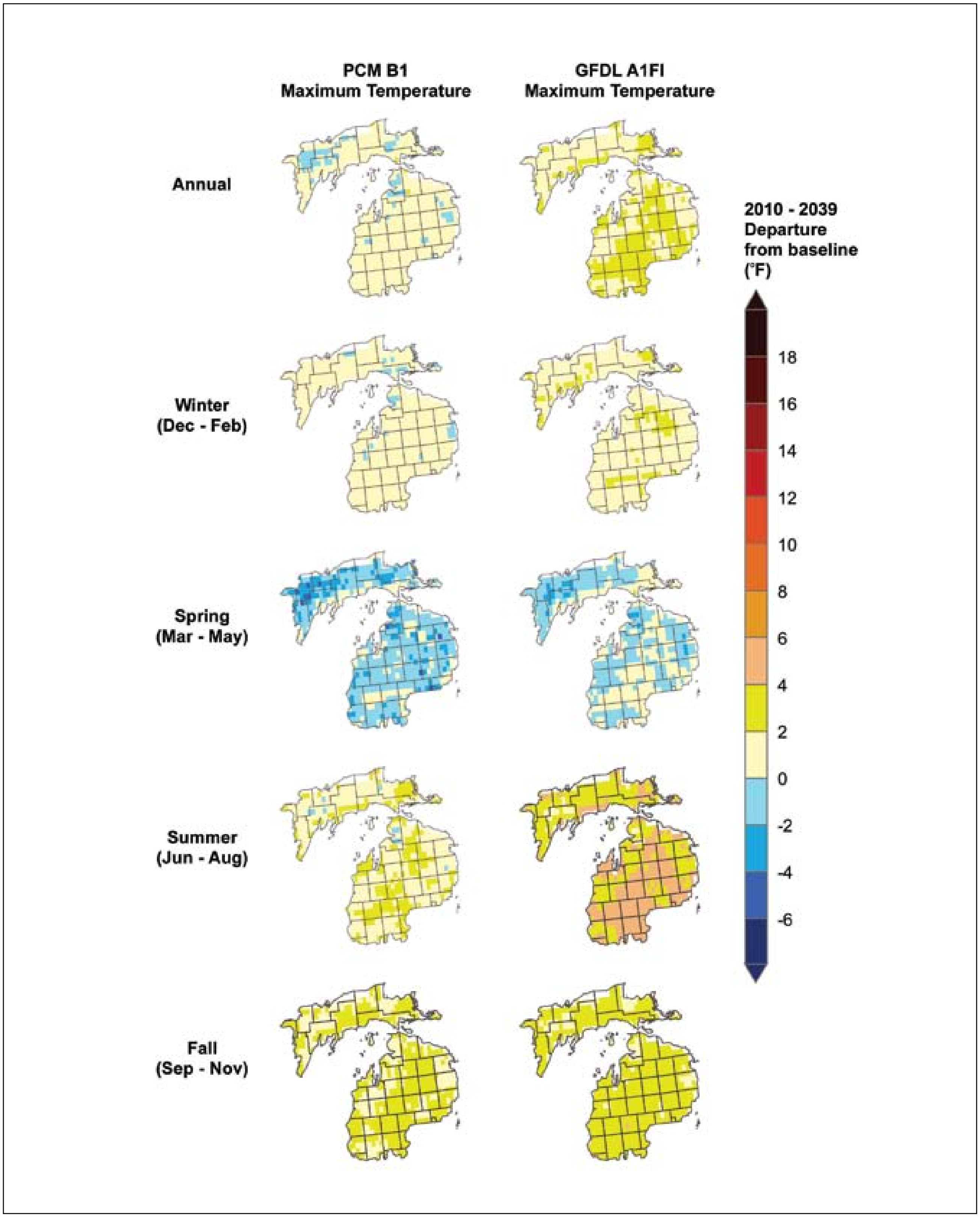

Figure 51.—Projected difference in mean maximum temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000), under two climate scenarios.

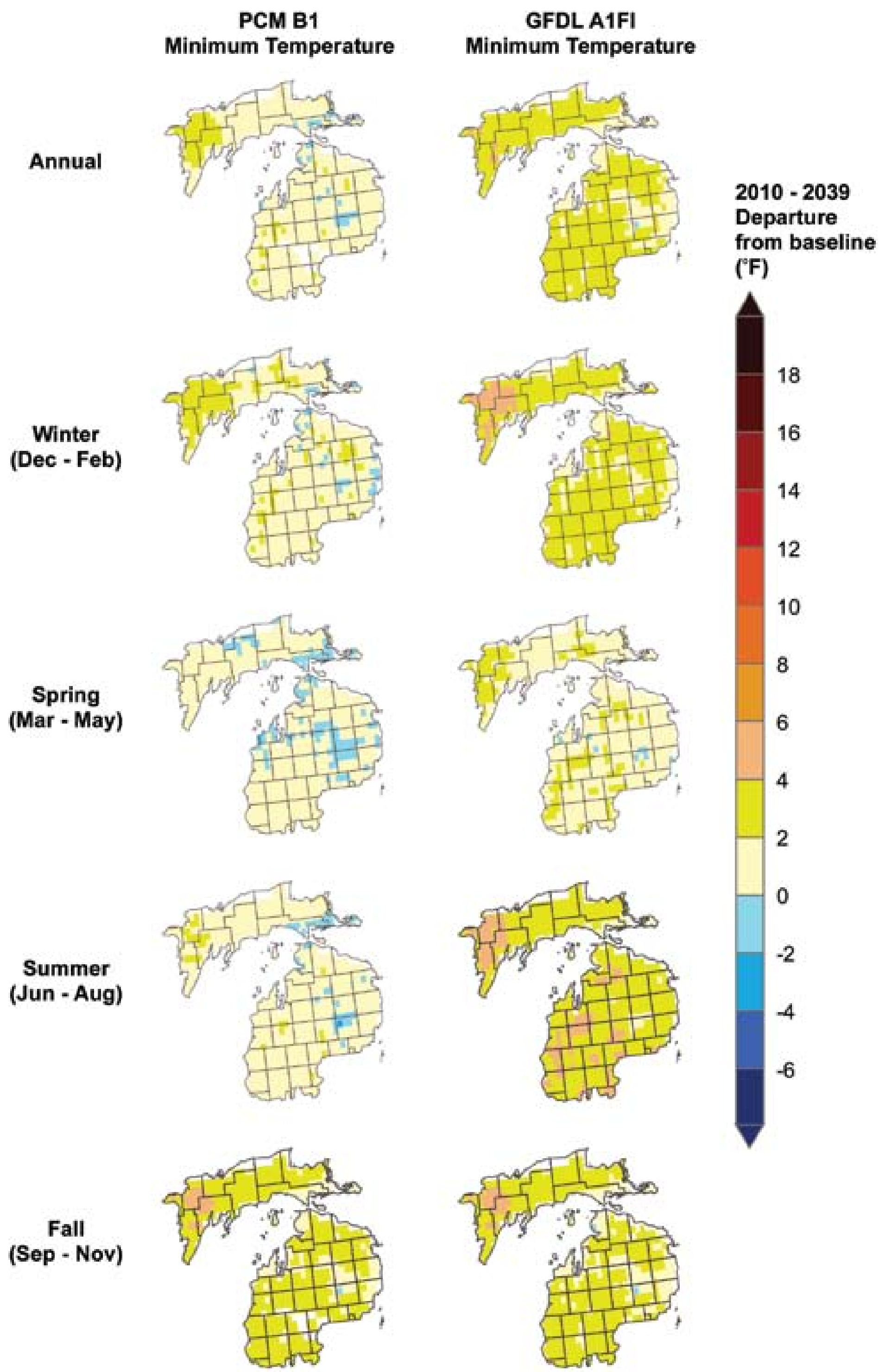

Figure 52.—Projected difference in mean minimum temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000), under two climate scenarios.

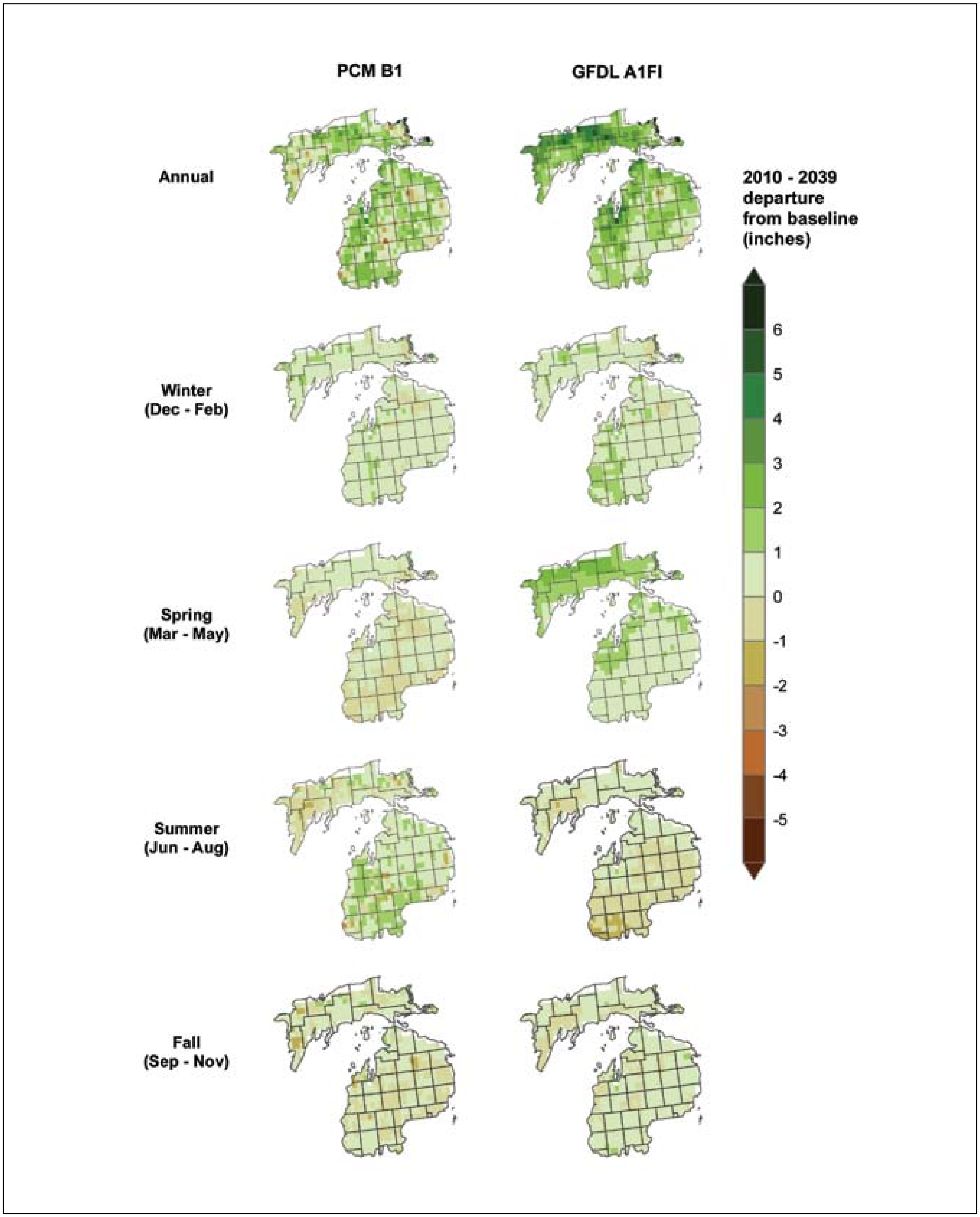

Figure 53.—Projected difference in precipitation (inches) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000), under two climate scenarios.

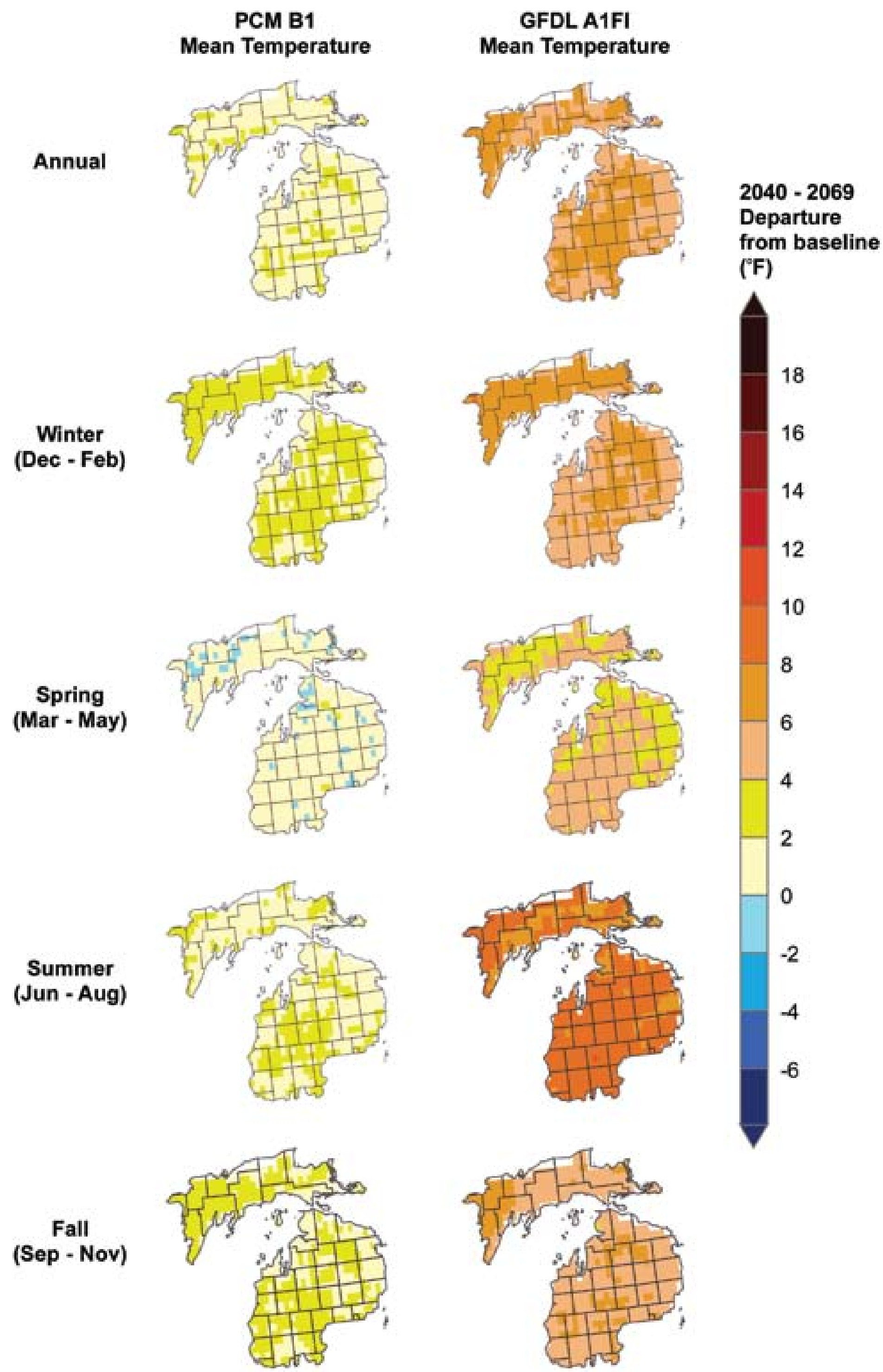

Figure 54.—Projected difference in mean daily temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000), under two climate scenarios.

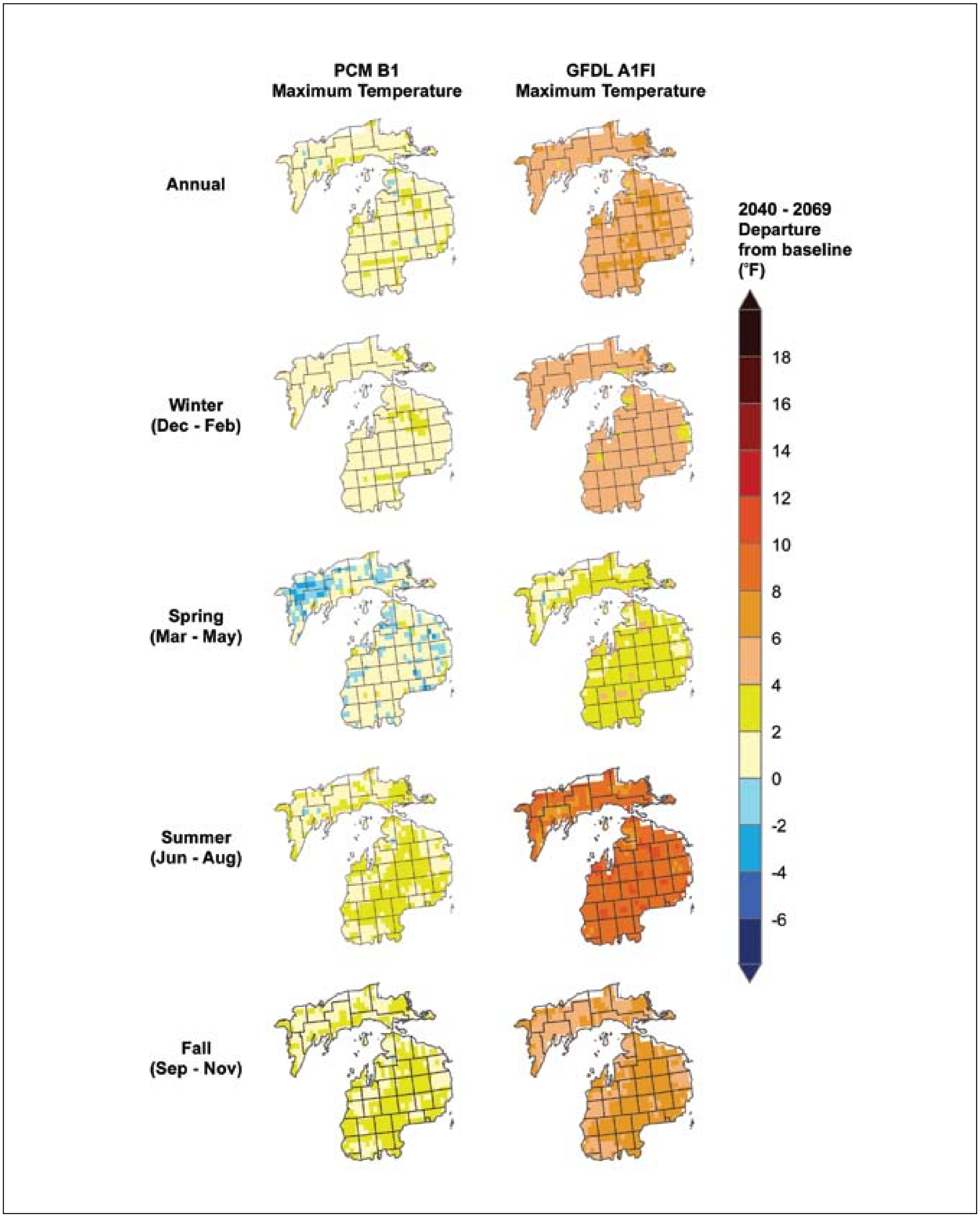

Figure 55.—Projected difference in mean maximum temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000), under two climate scenarios.

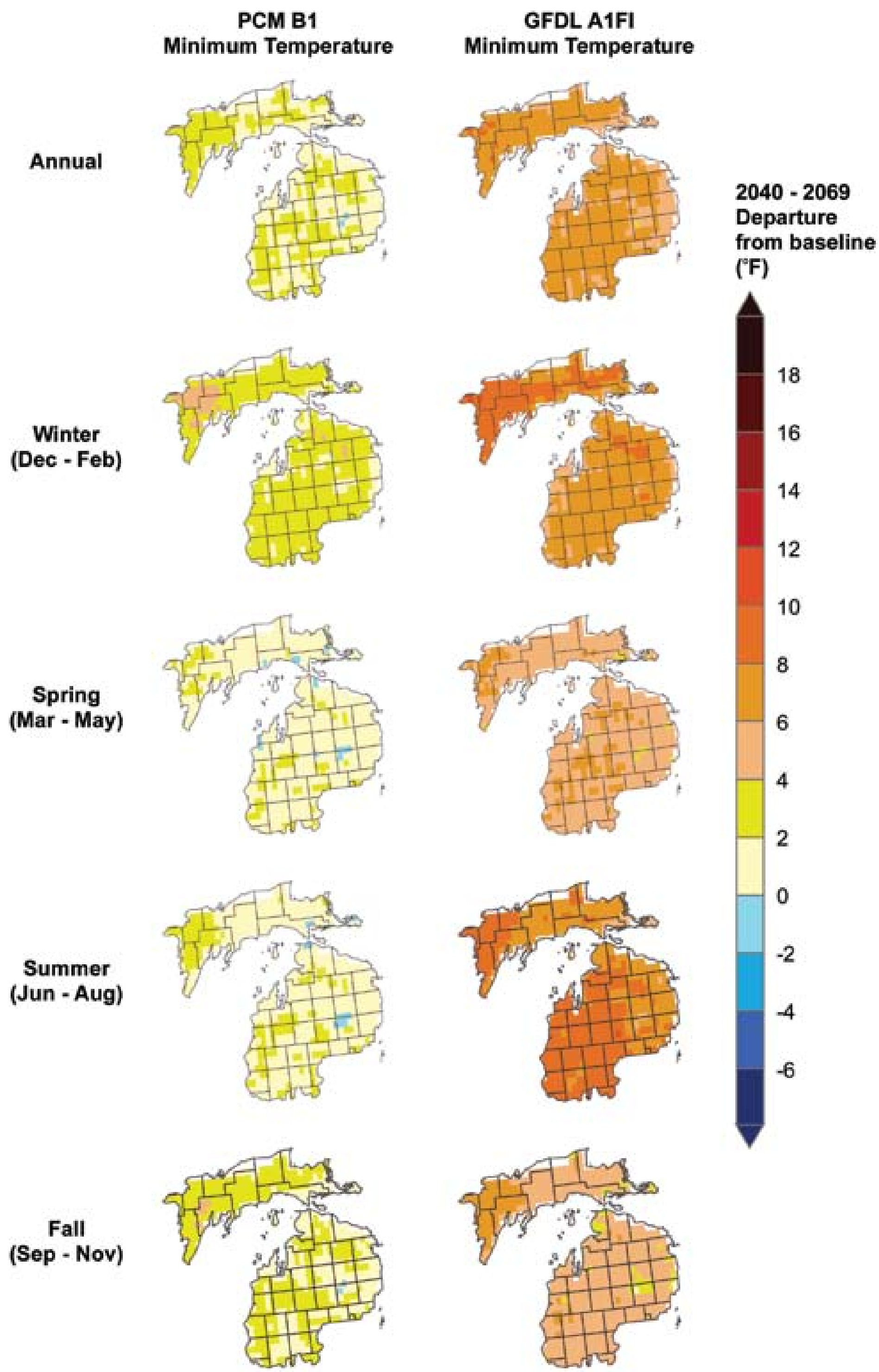

Figure 56.—Projected difference in mean minimum temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000), under two climate scenarios.

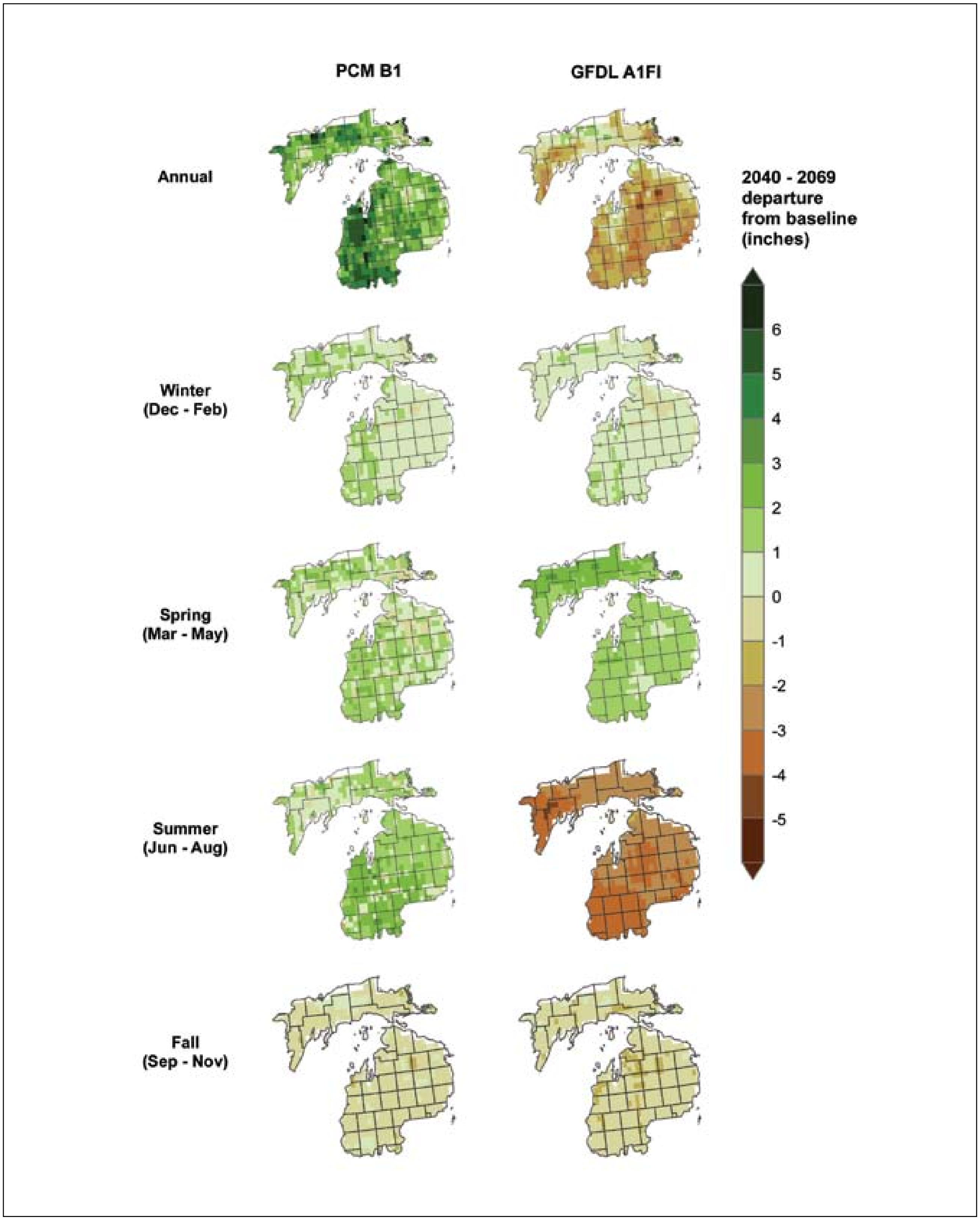

Figure 57.—Projected difference in precipitation (inches) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000), under two climate scenarios.

APPENDIX 4: SUPPLEMENTARY MODEL RESULTS

TREE ATLAS

This section provides additional model outputs for the 75 species considered for this assessment. Even more information is available online at the Climate Change Tree Atlas Web site (http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html), including detailed methods, importance value change maps, and additional statistics. Publications describing the Tree Atlas tools also include key definitions and methods descriptions (Iverson et al. 1999, 2008, 2011; Matthews et al. 2011).

Changes in Suitable Habitat

Measured area-weighted importance values (IVs) from the U.S. Forest Service, Forest Inventory and Analysis (FIA) as well as modeled current (1961 through 1990) and future IVs (2010 through 2039, 2040 through 2069, 2070 through 2099) from DISTRIB were calculated for each time period. Initially 134 tree species were modeled. If a species never had an area-weighted IV greater than 3 (FIA, current modeled, or future) across the region, it was deleted from the list because the species either has not had or is not projected to have habitat in the region or there were not enough data. Therefore, only a subset of all possible species is shown.

A set of rules was established to determine change classes for 2070 through 2099, which was used to create tables in Chapter 5. For most species, the classification rules are listed in Table 26, based on the ratio of future IVs to current modeled IVs.

A few exceptions applied to these general rules. When there was a zero in the numerator or denominator, a ratio could not be calculated. Instead, a species was classified as gaining new habitat if its FIA value was 0 and the future IV was greater than 3. A species' habitat was considered to be extirpated if the future IV was 0 and FIA values were greater than 3.

Special rules were created for rare species (Table 27). A species was considered rare if it had a

Table 26.—General classification rules used to determine change categories for suitable habitat for common tree species using the Tree Atlas DISTRIB model output (Current IV > 16)

Future:Current Modeled IV	Class
<0.5	large decrease
0.5 to 0.8	decrease
>0.8 to <1.2	no change
1.2 to 2.0	increase
>2	large increase

Table 27.—Special classification rules used to determine change categories for suitable habitat for rare tree species using the Tree Atlas DISTRIB model output (Current IV < 16)

Future:Current Modeled IV	Class
<0.2	large decrease
0.2 to <0.6	decrease
0.6 to <4	no change
4 to 8	increase
>8	large increase (not used when current modeled IV ≤3)

current modeled area-weighted IV that equaled less than 10 percent of the number of 12.5- by 12.5-mile pixels in the assessment area. This would mean that a species was present in only 10 percent or fewer of the pixels across the assessment area. The change classes are calculated differently for these species because their current infrequency tends to inflate the percentage change that is projected. There are 159 pixels in the Michigan assessment area, so the cutoff IV for determining a rare species is 16.

Special rules also applied to species that were known to be present (current FIA IV >0) but not modeled as present (current modeled = 0). In these cases, the FIA IV was used in place of the current modeled IV to calculate ratios. Then, change class rules were applied based on the FIA IV.

Complete DISTRIB results are displayed in Table 28.

Modifying Factors

Modifying factors are key life-history or environmental factors that may cause a species to occupy more or less suitable habitat than the model results suggest. Tables 29 and 30 describe the modifying factors and adaptability scores used in the Tree Atlas. These factors were developed by using a literature-based scoring system to capture the potential adaptability of species to changes in climate that cannot be adequately captured by DISTRIB (Matthews et al. 2011). This approach was used to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics like competition ability for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pests, and fire. This information distinguishes between species likely to be more tolerant (or sensitive) to environmental changes than the habitat models alone suggest.

For each biological and disturbance factor, a species was scored on a scale from -3 to +3. A score of -3 indicated a very negative response of that species to that factor. A score of +3 indicated a very positive response to that factor. To account for confidence in the literature about these factors, each of these scores was then multiplied by 0.5, 0.75, or 1, with 0.5 indicating low confidence and 1 indicating high confidence. Finally the score was further weighted by its relevance to future projected climate change by multiplying it by a relevance factor. A 4 indicated highly relevant and a 1 indicated not highly relevant to climate change. Means for individual biological scores and disturbance scores were then calculated to arrive at an overall biological and disturbance score for the species.

To arrive at an overall adaptability score for the species that could be compared across all modeled tree species, the mean, rescaled (0-6) values for biological and disturbance characteristics were plotted to form two sides of a right triangle; the hypotenuse was then a combination (disturbance and biological characteristics) metric, ranging from 0 to 8.5 (Fig. 58). For this assessment, adaptability scores below 3.2 are considered low, and scores above 5.3 are considered high.

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

Table 28.—Complete DISTRIB results for the 75 tree species in the assessment area

Common Name	Actual IV	Current IV	Model Reliability	DISTRIB results*: Modeled IV 2010-2039 PCM B1	Modeled IV 2010-2039 GFDL A1FI	Modeled IV 2040-2069 PCM B1	Modeled IV 2040-2069 GFDL A1FI	Modeled IV 2070-2099 PCM B1	Modeled IV 2070-2099 GFDL A1FI	Future : Current Suitable Habitat 2010-2039 PCM B1	Future : Current Suitable Habitat 2010-2039 GFDL A1FI	Future : Current Suitable Habitat 2040-2069 PCM B1	Future : Current Suitable Habitat 2040-2069 GFDL A1FI	Future : Current Suitable Habitat 2070-2099 PCM B1	Future : Current Suitable Habitat 2070-2099 GFDL A1FI	Change Class PCM B1	Change Class GFDL A1FI
American basswood	263	332	Medium	303	361	299	461	299	477	0.91	1.09	0.9	1.39	0.9	1.44	No Change	Increase
American beech	270	273	High	306	286	347	279	330	236	1.12	1.05	1.27	1.02	1.21	0.86	Increase	No Change
American elm	202	356	Medium	376	653	475	1187	494	1176	1.06	1.83	1.33	3.33	1.39	3.3	Increase	Large Increase
American hornbeam	74	83	Medium	111	137	147	221	146	204	1.34	1.65	1.77	2.66	1.76	2.46	Increase	Large Increase
Balsam fir	876	872	High	657	237	505	98	433	95	0.75	0.27	0.58	0.11	0.5	0.11	Decrease	Large Decrease
Balsam poplar	290	272	High	197	90	131	203	138	158	0.72	0.33	0.48	0.75	0.51	0.58	Decrease	Decrease
Bigtooth aspen	790	738	High	714	459	629	269	632	151	0.97	0.62	0.85	0.36	0.86	0.21	No Change	Large Decrease
Bitternut hickory	13	11	Low	19	86	31	162	34	195	1.73	7.82	2.82	14.73	3.09	17.73	No Change	Large Increase
Black ash	412	463	High	413	392	380	267	371	229	0.89	0.85	0.82	0.58	0.8	0.5	No Change	Decrease
Black cherry	408	522	High	641	809	825	646	799	503	1.23	1.55	1.58	1.24	1.53	0.96	Increase	No Change
Black hickory	0	0	High	0	0	0	79	0	138	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Black locust	1	17	Low	31	89	74	307	76	415	1.82	5.24	4.35	18.06	4.47	24.41	Large Increase	Large Increase
Black oak	182	243	High	287	596	432	700	434	832	1.18	2.45	1.78	2.88	1.79	3.42	Increase	Large Increase
Black spruce	419	402	High	288	38	173	5	128	4	0.72	0.1	0.43	0.01	0.32	0.01	Large Decrease	Large Decrease
Black walnut	5	4	Medium	23	137	43	338	62	438	5.75	34.25	10.75	84.5	15.5	109.5	Large Increase	Large Increase
Black willow	37	59	Low	65	125	76	244	85	279	1.1	2.12	1.29	4.14	1.44	4.73	Increase	Large Increase
Blackgum	3	4	High	5	11	21	82	20	90	1.25	2.75	5.25	20.5	5	22.5	Increase	Large Increase
Blackjack oak	0	0	Medium	0	0	0	82	0	169	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Boxelder	5	32	Medium	17	93	25	438	22	545	0.53	2.91	0.78	13.69	0.69	17.03	Decrease	Large Increase
Bur oak	22	55	Medium	20	129	49	419	29	476	0.36	2.35	0.89	7.62	0.53	8.66	Decrease	Large Increase
Chestnut oak	2	2	High	3	9	9	68	7	53	1.5	4.5	4.5	34	3.5	26.5	No Change	Increase
Chinquapin oak	0	0	Medium	0	4	1	107	0	171	NA	Mig.	Mig.	Mig.	NA	Mig.	NA	New Habitat
Chokecherry	71	67	Low	64	49	59	61	60	21	0.96	0.73	0.88	0.91	0.9	0.31	No Change	Large Decrease
Common persimmon	0	0	Medium	0	0	0	10	0	68	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Eastern cottonwood	21	80	Low	59	154	69	679	80	613	0.74	1.93	0.86	8.49	1	7.66	No Change	Large Increase
Eastern hemlock	209	275	High	262	222	293	117	277	89	0.95	0.81	1.07	0.43	1.01	0.32	No Change	Large Decrease
Eastern hophornbeam	168	229	Medium	211	228	212	322	215	328	0.92	1	0.93	1.41	0.94	1.43	No Change	Increase
Eastern redbud	0	0	Medium	0	6	0	196	0	342	NA	Mig.	NA	Mig.	NA	Mig.	NA	New Habitat
Eastern redcedar	168	2	Medium	5	209	12	1249	12	1405	2.5	104.5	6	624.5	6	702.5	Increase	Large Increase
Eastern white pine	460	514	High	498	526	535	347	522	210	0.97	1.02	1.04	0.68	1.02	0.41	No Change	Large Decrease
Flowering dogwood	4	8	High	23	69	61	233	62	253	2.88	8.63	7.63	29.13	7.75	31.63	Increase	Large Increase
Green ash	240	318	Medium	256	295	231	635	241	563	0.81	0.93	0.73	2	0.76	1.77	Decrease	Increase
Hackberry	0	2	Medium	4	107	20	440	19	529	2	53.5	10	220	9.5	264.5	New Habitat	New Habitat
Honeylocust	1	0	Low	1	35	6	210	6	279	1	35	6	210	6	279	Increase	Increase
Jack pine	903	844	High	708	463	578	280	540	268	0.84	0.55	0.69	0.33	0.64	0.32	Decrease	Large Decrease
Mockernut hickory	0	7	High	12	35	30	167	32	217	1.71	5	4.29	23.86	4.57	31	New Habitat	New Habitat
Mountain maple	38	25	High	12	0	6	0	6	0	0.48	0	0.24	0	0.24	0	Large Decrease	Large Decrease
Northern pin oak	59	57	Medium	48	73	60	72	52	173	0.84	1.28	1.05	1.26	0.91	3.04	No Change	Large Increase
Northern red oak	792	810	High	887	996	974	895	1008	716	1.1	1.23	1.2	1.11	1.24	0.88	Increase	No Change
Northern white-cedar	1246	1147	High	990	508	820	345	779	316	0.86	0.44	0.72	0.3	0.68	0.28	Decrease	Large Decrease
Ohio buckeye	1	0	Low	0	4	1	13	2	18	0	4	1	13	2	18	No Change	Increase
Osage-orange	0	0	Medium	2	12	12	95	6	133	Mig.	Mig.	Mig.	Mig.	Mig.	Mig.	New Habitat	New Habitat

(Table 28 continued on next page)

Table 28 (continued).

				DISTRIB results*													
				Modeled IV						Future : Current Suitable Habitat						Change Class	
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099			
Common Name	Actual IV	Current IV	Model Reliability	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI
Paper birch	462	512	High	422	337	390	91	366	43	0.82	0.66	0.76	0.18	0.72	0.08	Decrease	Large Decrease
Pawpaw	0	0	Low	0	0	0	3	0	22	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Peachleaf willow	9	0	Low	0	0	0	21	0	13	0	0	0	2.33	0	1.44	Large Decrease	No Change
Pignut hickory	0	10	High	19	70	56	200	58	245	1.9	7	5.6	20	5.8	24.5	New Habitat	New Habitat
Pin cherry	71	74	Medium	61	50	55	49	61	7	0.82	0.68	0.74	0.66	0.82	0.1	No Change	Large Decrease
Pin oak	7	6	Medium	7	51	17	198	18	264	1.17	8.5	2.83	33	3	44	No Change	Large Increase
Post oak	0	0	High	0	0	0	281	0	466	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Quaking aspen	1562	1563	High	1329	933	1058	356	1042	264	0.85	0.6	0.68	0.23	0.67	0.17	Decrease	Large Decrease
Red maple	1932	1907	High	1963	1673	1979	1402	1949	1198	1.03	0.88	1.04	0.74	1.02	0.63	No Change	Decrease
Red mulberry	0	1	Low	1	49	2	271	2	376	1	49	2	271	2	376	New Habitat	New Habitat
Red pine	975	865	Medium	889	509	786	261	747	193	1.03	0.59	0.91	0.3	0.86	0.22	No Change	Large Decrease
River birch	2	0	Low	0	2	1	6	0	35	0	1	0.5	3	0	17.5	Decrease	Increase
Rock elm	7	3	Low	2	2	1	19	1	26	0.67	0.67	0.33	6.33	0.33	8.67	Decrease	Increase
Sassafras	37	35	High	67	109	152	251	155	264	1.91	3.11	4.34	7.17	4.43	7.54	Large Increase	Large Increase
Scarlet oak	3	1	High	2	17	12	100	14	138	2	17	12	100	14	138	Increase	Increase
Shagbark hickory	3	31	Medium	39	186	74	330	84	384	1.26	6	2.39	10.65	2.71	12.39	Large Increase	Large Increase
Shellbark hickory	0	0	Low	0	0	0	16	0	23	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Shingle oak	0	0	Medium	0	0	0	81	0	112	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Silver maple	77	106	Medium	120	323	152	674	167	748	1.13	3.05	1.43	6.36	1.58	7.06	Increase	Large Increase
Slippery elm	19	13	Medium	30	162	62	380	81	422	2.31	12.46	4.77	29.23	6.23	32.46	Increase	Large Increase
Striped maple	20	15	High	8	4	12	6	9	3	0.53	0.27	0.8	0.4	0.6	0.2	No Change	Decrease
Sugar maple	1613	1680	High	1574	1043	1429	843	1385	698	0.94	0.62	0.85	0.5	0.82	0.42	No Change	Large Decrease
Sugarberry	0	0	Medium	0	0	0	1	0	36	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Swamp white oak	12	17	Low	15	28	17	106	19	115	0.88	1.65	1	6.24	1.12	6.77	No Change	Large Increase
Sweet birch	1	4	High	5	10	14	26	12	17	1.25	2.5	3.5	6.5	3	4.25	No Change	Increase
Sycamore	1	0	Medium	3	12	12	27	13	101	3	12	12	27	13	101	Increase	Increase
Tamarack (native)	204	240	High	181	131	151	97	148	90	0.75	0.55	0.63	0.4	0.62	0.38	Decrease	Large Decrease
White ash	255	391	High	418	459	473	724	484	629	1.07	1.17	1.21	1.85	1.24	1.61	Increase	Increase
White oak	389	369	High	518	744	604	943	628	937	1.4	2.02	1.64	2.56	1.7	2.54	Increase	Large Increase
White spruce	205	213	Medium	159	91	116	72	100	57	0.75	0.43	0.55	0.34	0.47	0.27	Large Decrease	Large Decrease
Wild plum	0	0	Low	0	0	0	14	0	114	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Yellow birch	176	227	High	195	134	208	43	184	38	0.86	0.59	0.92	0.19	0.81	0.17	No Change	Large Decrease
Yellow-poplar	0	3	High	11	24	33	76	30	98	3.67	8	11	25.33	10	32.67	New Habitat	New Habitat

*Current importance values (Current IV) are based on modeled results, and FIA IV values are calculated based on FIA inventory data. Early-century, mid-century, and late-century importance values are average values for the indicated years. Future:Current Suitable Habitat is a ratio of projected importance value to current importance value. Species are assigned to change classes based on the comparison between end-of-century (2070-2099) and current figures for area-weighted importance value (Tables 26-27).
NA = not applicable, no suitable habitat projected.
Mig. = new migrant, new suitable habitat projected.

Table 29.—Modifying factors for the 75 tree species in the assessment area

Common Name	DISTRIB Model Reliability	Modifying Factors* Positive Traits	Negative Traits	Adaptability Scores DistFact	BioFact	Adapt	Adapt Class
American basswood	Medium	COL	FTK	0.3	0.2	4.6	o
American beech	High	COL	INS FTK	-1.1	0	3.6	o
American elm	Medium	ESP	DISE INS	-0.8	0.3	4	o
American hornbeam	Medium	COL SES	FTK DRO	0.6	0.6	5.1	o
Balsam fir	High	COL	INS FTK DRO	-3	-0.4	2.7	—
Balsam poplar	High	FRG VRE	COL DRO	0.1	-0.6	4	o
Bigtooth aspen	High	FRG DISP	COL DRO FTK	1	0.2	5.1	o
Bitternut hickory	Low	DRO	COL	2.2	-0.8	5.6	+
Black ash	High		INS COL DISP DRO SES FTK ESP	-1.3	-3	1.7	—
Black cherry	High	DRO ESP	INS FTK COL	-1.6	-0.3	3	—
Black hickory	High		ESP COL	1	-2.3	4.1	o
Black locust	Low		COL INS	0	-0.6	3.8	o
Black oak	High	DRO ESP	INS DISE	0.5	0.4	4.9	o
Black spruce	High	COL ESP DISP	FTK INS DRO	-2.1	1.2	4.3	o
Black walnut	Medium	SES	COL DRO	0.4	-0.8	4	o
Black willow	Low		COL FTK DRO	-0.3	-2.1	2.8	—
Blackgum	High	COL FTK		1.5	0.8	5.9	+
Blackjack oak	Medium	DRO SES FRG VRE	COL FTK	1.6	0.2	5.6	+
Boxelder	Medium	SES DISP DRO COL SES	FTK	2.4	2.1	7.4	+
Bur oak	Medium	DRO FTK		2.8	-0.2	6.4	+
Chestnut oak	High	SES VRE ESP FTK	INS DISE	1.4	1.3	6.1	+
Chinquapin oak	Medium	SES		1.2	-0.7	4.8	o
Chokecherry	Low		COL	0.2	-0.9	3.8	o
Common persimmon	Medium	COL ESP		1.2	1	5.8	+
Eastern cottonwood	Low	SES	INS COL DISE FTK	0.2	-0.8	3.9	o
Eastern hemlock	High	COL	INS DRO	-1.3	-0.9	2.7	—
Eastern hophornbeam	Medium	COL ESP SES		1.7	1.3	6.4	+
Eastern redbud	Medium			0.9	0	4.9	o
Eastern redcedar	Medium	DRO	FTK COL INS	0.6	-1.5	3.9	o
Eastern white pine	High	DISP	DRO FTK INS	-2	0.1	3.3	o
Flowering dogwood	High	COL		0.1	1	5	o
Green ash	Medium		INS FTK COL	-0.1	-0.3	4	o
Hackberry	Medium	DRO	FTK	1.7	0.3	5.7	+
Honeylocust	Low		COL	1.9	-0.5	5.5	+
Jack pine	High	DRO	COL INS	1.9	-1.2	5.2	o
Mockernut hickory	High		FTK	1.7	-0.3	5.4	+
Mountain maple	High	COL VRE ESP	DRO FTK	0.8	1.5	5.9	+
Northern pin oak	Medium	DRO FTK	COL	2.5	-0.6	6	+
Northern red oak	High		INS	1.4	0.1	5.4	+
Northern white-cedar	High	COL	FTK	-0.7	0.5	4.2	o
Ohio buckeye	Low	COL	SES FTK	0.4	-1.9	3.5	o

(Table 29 continued on next page)

Table 29 (continued).

Common Name	DISTRIB Model Reliability	Modifying Factors* Positive Traits	Negative Traits	Adaptability Scores DistFact	BioFact	Adapt	Adapt Class
Osage-orange	Medium	ESP ESP		2.3	0.3	6.3	+
Paper birch	High	FRG DISP ESP	FTK COL INS DRO	-1.7	0.2	3.4	o
Pawpaw	Low	COL	DRO	-0.48	-0.32	3.7	
Peachleaf willow	Low		COL	0.1	-1.7	3.4	o
Pignut hickory	High	ESP	INS DRO	0.2	0.4	4.7	o
Pin cherry	Medium	SES FRG FTK	COL	0.5	-0.7	4.2	o
Pin oak	Medium		FTK COL INS DISE	-0.7	-1.4	2.8	—
Post oak	High	DRO SES FTK	COL INS DISE	2.2	-0.6	5.7	+
Quaking aspen	High	SES FRG ESP	COL DRO FTK	0.6	0	4.7	o
Red maple	High	SES ESP ESP COL DISP		3	3	8.5	+
Red mulberry	Low	COL DISP	FTK	0.1	0.6	4.7	o
Red pine	Medium		INS COL DISP	0.9	-2.4	3.9	o
River birch	Low	DISP	FTK COL DRO	-0.5	-0.3	3.7	o
Rock elm	Low		ESP ESP SES	-0.2	-2.6	2.8	—
Sassafras	High		COL FTK	0.5	-0.6	4.2	o
Scarlet oak	High	VRE ESP ESP	INS DISE FTK	-0.4	0.7	4.6	o
Shagbark hickory	Medium		INS FTK	-0.2	0.4	4.4	o
Shellbark hickory	Low	COL	FTK ESP	-0.5	-0.3	3.7	o
Shingle oak	Medium	ESP	COL	1.3	-0.7	4.9	o
Silver maple	Medium	DISP SES COL	DRO FTK	0.1	1.6	5.6	+
Slippery elm	Medium	COL	FTK DISE	0	0.7	4.8	o
Striped maple	High	COL SES	DRO	1	0.3	5.1	o
Sugar maple	High	COL ESP		0.9	1.3	5.8	+
Sugarberry	Medium	COL SES	FTK	-0.2	0.6	4.6	o
Swamp white oak	Low			1	-0.3	4.9	o
Sweet birch	High	DISP	FTK COL INS DISE	-1.3	-0.3	3.2	—
Sycamore	Medium			1.3	-0.9	4.8	o
Tamarack (native)	High		FTK COL INS	-0.5	-1.2	3.1	—
White ash	High		INS FTK COL	-2	-0.5	2.7	—
White oak	High	ESP ESP SES FTK	INS DISE	1.7	1	6.1	+
White spruce	Medium		INS	0.1	-0.6	3.9	o
Wild plum	Low		COL	0.5	-1.3	3.9	o
Yellow birch	High	DISP	FTK INS DISE	-1.4	0	3.4	o
Yellow-poplar	High	SES DISP ESP	INP	0.1	1.3	5.3	+

*Modifying factors are key life-history or environmental factors that may cause a species to occupy more or less suitable habitat than the model results suggest (Matthews et al. 2011). Explanations for the modifying factor codes are displayed in Table 30. Adaptation factor scores below 3.2 are considered low (-), and scores above 5.3 are considered high (+).

Table 30.—Description of Tree Atlas modifying factor codes

Code*	Description (if positive)	Description (if negative)
COL	Tolerant of shade or limited light conditions	Intolerant of shade or limited light conditions
DISE		Has a high number and/or severity of known pathogens that attack the species
DISP	High ability to effectively produce and distribute seeds	
DRO	Drought-tolerant	Susceptible to drought
ESP	Wide range of soil requirements	Narrow range of soil requirements
FRG	Regenerates well after fire	
FTK	Resistant to fire topkill	Susceptible to fire topkill
INS		Has a high number and/or severity of insects that may attack the species
INP		Strong negative effects of invasive plants on the species, either through competition for nutrients or as a pathogen
SES	High ability to regenerate with seeds to maintain future populations	Low ability to regenerate with seeds to maintain future populations
VRE	Capable of vegetative reproduction through stump sprouts or cloning	

*These codes are used to describe positive or negative modifying factors in Table 29. A species was given a code if information from the literature suggested that it had these characteristics. See Matthews et al. (2011) for a more thorough description of these factors and how they were assessed.

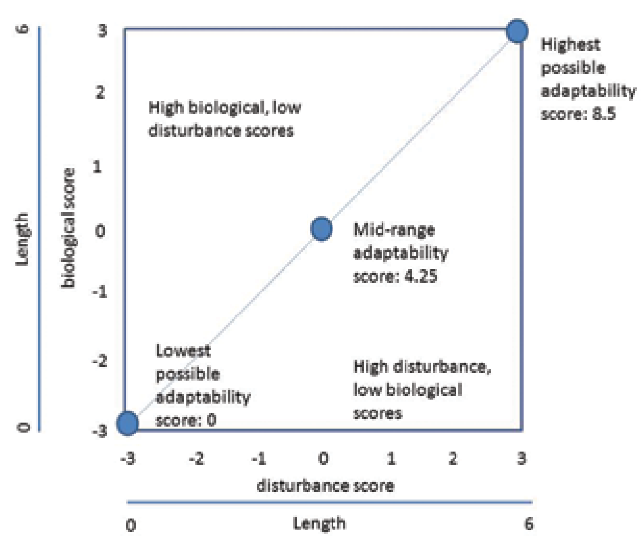

Figure 58.—Schematic showing how biological and disturbance modifying factors are translated into an overall adaptability score in the Tree Atlas model.

LANDIS-II

This section provides additional model outputs and methods for the model simulations developed for this assessment. More information is available online at the LANDIS-II Web site (http://www.landis-ii.org/), including detailed model descriptions and publications describing the LANDIS-II core model and extensions.

Biomass Projections

LANDIS-II outputs include biomass of individual species by age cohort (Table 31). For this assessment, we have combined values for separate age cohorts into a single biomass value by species.

Forest Type Classification

The forest-type maps presented in Chapter 5 (Fig. 40) rely on a simple classification scheme. To create these land cover maps, individual locations ("cells") in the LANDIS-II simulations were classified into six forest categories based on characteristic species composition. These classifications are based on the dominance of key indicator species (Table 32). The species assignment to groups is based on unique species within groups and a balance of high abundance species within groups. Certain species that do not contribute to the unique forest type dominance are subtracted from the dominance calculation. Species assignment adjustments were made based on matching the proportion of individual forest types found in regional FIA plots to the proportion of individual forest types found in LANDIS-II cells for the year 2000.

Management and Disturbance Scenarios

The simulations developed for this assessment were run with the Biomass Succession (v3.1), Base Fire (v3.0), and Base Wind (v2.0) extensions. Forest management was implemented using the Biomass Harvest extension (v2.1), and output was delivered through the Biomass Output extension (v.2.0) (www.landis-ii.org/exts). A business-as-usual forest management scenario was developed for a variety of forest types, ownerships, and harvest methods through conversations with local forest management experts (Table 33).

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Table 31.—Projected aboveground biomass for 26 species assessed with the LANDIS-II model

Species	Year 0 biomass (grams per square meter)	Year[a]	Current Climate: Biomass (grams per square meter)	Current Climate: Change from year 0[b] (%)	PCM B1 Climate: Biomass (grams per square meter)	PCM B1 Climate: Change relative to current climate biomass[c] (%)	GFDL A1FI Climate: Biomass (grams per square meter)	GFDL A1FI Climate: Change relative to current climate biomass[c] (%)
American basswood	122	40	791	648	1067	35	733	-7
		70	1352	1108	1733	28	925	-32
		100	1861	1525	2352	26	926	-50
American beech	211	40	490	232	621	27	488	0
		70	650	308	829	28	577	-11
		100	840	399	1133	35	806	-4
American elm	43	40	290	681	402	39	295	2
		70	459	1078	624	36	459	0
		100	533	1251	730	37	589	10
Balsam fir	242	40	858	354	580	-32	406	-53
		70	1573	649	1093	-31	275	-83
		100	1877	775	1096	-42	61	-97
Balsam poplar	100	40	204	204	185	-9	162	-21
		70	194	194	171	-12	120	-38
		100	153	153	129	-16	72	-53
Bigtooth aspen	568	40	632	111	652	3	570	-10
		70	462	81	494	7	364	-21
		100	295	52	334	13	183	-38
Black ash	67	40	102	153	76	-25	93	-9
		70	76	113	54	-28	41	-46
		100	60	89	36	-39	16	-73
Black cherry	261	40	897	343	1102	23	806	-10
		70	1183	452	1406	19	926	-22
		100	1252	479	1557	24	1043	-17
Black oak	248	40	361	145	408	13	321	-11
		70	327	132	381	17	246	-25
		100	250	101	326	30	199	-21
Black spruce	359	40	455	127	339	-26	329	-28
		70	403	112	237	-41	204	-50
		100	290	81	120	-59	97	-67
Eastern hemlock	89	40	138	155	137	-1	132	-5
		70	176	197	173	-2	156	-12
		100	216	242	212	-2	172	-21
Eastern white pine	683	40	2571	376	2898	13	2280	-11
		70	3,897	570	4,222	8	2,747	-30
		100	4,981	729	5,428	9	3,026	-39
Green ash	65	40	186	286	234	26	167	-10
		70	169	260	190	12	116	-31
		100	115	178	136	18	90	-22
Jack pine	233	40	281	121	253	-10	250	-11
		70	266	114	222	-17	171	-35
		100	227	97	188	-17	105	-54

(Table 31 continued on next page)

Table 31 (continued).

Species	Year 0 biomass (grams per square meter)	Year[a]	Current Climate: Biomass (grams per square meter)	Current Climate: Change from year 0[b] (%)	PCM B1 Climate: Biomass (grams per square meter)	PCM B1 Climate: Change relative to current climate biomass[c] (%)	GFDL A1FI Climate: Biomass (grams per square meter)	GFDL A1FI Climate: Change relative to current climate biomass[c] (%)
Northern pin oak	295	40	531	180	508	-4	442	-17
		70	572	194	517	-10	338	-41
		100	496	168	425	-14	227	-54
Northern red oak	997	40	1,573	158	1,627	3	1,350	-14
		70	1,564	157	1,596	2	1,105	-29
		100	1,303	131	1,381	6	853	-35
Northern white cedar	528	40	800	152	657	-18	694	-13
		70	914	173	702	-23	655	-28
		100	919	174	673	-27	579	-37
Paper birch	187	40	421	224	209	-50	260	-38
		70	425	227	134	-68	136	-68
		100	292	156	66	-77	22	-92
Quaking aspen	693	40	733	106	729	-1	632	-14
		70	532	77	536	1	367	-31
		100	265	38	266	0	96	-64
Red maple	787	40	1,226	156	1,445	18	1,170	-5
		70	1,166	148	1,423	22	1,114	-4
		100	1,173	149	1,504	28	1,151	-2
Red pine	599	40	1,192	199	991	-17	993	-17
		70	1,462	244	1,118	-24	904	-38
		100	1,391	232	991	-29	727	-48
Sugar maple	719	40	975	136	1,101	13	981	1
		70	925	129	1,126	22	1,015	10
		100	832	116	1,165	40	1,027	23
White ash	51	40	246	479	356	45	258	5
		70	354	689	474	34	336	-5
		100	427	829	581	36	462	8
White oak	412	40	845	205	962	14	755	-11
		70	1071	260	1,191	11	819	-24
		100	1,169	284	1,367	17	941	-19
White spruce	237	40	312	131	172	-45	171	-45
		70	305	129	77	-75	57	-81
		100	253	107	46	-82	16	-94
Yellow birch	76	40	405	531	368	-9	275	-32
		70	753	986	650	-14	258	-66
		100	1,080	1,415	855	-21	236	-78

[a] Year represents the number of years from the year 2000 (e.g., 40 = year 2040).
[b] Percentage change from Year 0 is calculated as the change in biomass from year 2000 (100% equals no net change).
[c] Change relative to current climate biomass is calculated as the proportional change compared to the biomass under the Current Climate scenario for the same year.

Table 32.—Classification rules for creating the maps based on LANDIS-II outputs (Fig. 40)

Forest Type	Indicator Species
Spruce/fir	Include black spruce, balsam fir, white spruce, and northern white-cedar Subtract sugar maple and jack pine
Oak association	Include northern red oak, white oak, black oak, and northern pin oak Subtract black spruce, balsam fir, and white spruce
Jack pine	Include jack pine and red pine
Aspen-birch	Include quaking aspen, bigtooth aspen, balsam poplar, and paper birch Subtract sugar maple and balsam fir
Red pine/white pine	Include red pine and white pine
Northern hardwoods	Include sugar maple, black cherry, northern red oak, and American basswood Subtract bigtooth aspen and quaking aspen

Table 33.—Business-as-usual (BAU) forest management scenario used in the LANDIS-II model for this assessment[a]

BAU Management Prescriptions	USFS	DNR	PIF	PNIF
Aspen-birch clearcut	1.7206	2.3902	3.4882	0.0641
Jack pine clearcut	0.8174	0.5291	0.0481	0.1198
Northern hardwood shelterwood	0.0808	0.0873	0.0635	0.1101
Northern hardwood patchcut	3.39	3.67	2.67	4.62
Oak clearcut	0.7933	0.5938	0.2915	0.1583
Oak patchcut	1.27	0.95	0.466	1.038
Oak shelterwood	0.508	0.38	0.186	0.415
Oak thinning	1.75	1.31	0.64	1.43
Birch shelterwood	0.0085	0.0129	0.0238	0.0138
Red pine clearcut	0.2313	0.1466	0.0202	0.0515
Red pine patchcut	0.3558	0.2255	0.0311	0.1611
Red pine shelterwood	0.089	0.0564	0.0078	0.0403
Red pine thinning	1.156	0.733	0.101	0.524
Upland spruce-fir clearcut	0.5361	0.9542	1.6218	0.1013
Swamp hardwoods clearcut	0.1126	0.1636	0.4962	0.0154
Swamp hardwoods patchcut	0.0576	0.0839	0.2545	0.1027
Swamp hardwoods shelterwood	0.0259	0.0378	0.1145	0.0462
Swamp hardwoods thinning	0.0115	0.0168	0.0509	0.0205
White pine clearcut	0.1467	0.1114	0.0623	0.0684
White pine patchcut	0.467	0.354	0.198	0.299
White pine shelterwood	0.1867	0.1417	0.0792	0.1198
White pine thinning	0.48	0.364	0.204	0.308

[a] For each harvest prescription, values represent the percentage of each management area treated per 5-year time step. Landowner categories are as follows: USFS = U.S. Forest Service, DNR = Michigan Department of Natural Resources, PIF = private industrial forestland, PNIF = private nonindustrial forestland.

APPENDIX 5: VULNERABILITY AND CONFIDENCE DETERMINATION

METHODS

To assess vulnerabilities to climate change for each forest type, we elicited input from a panel of 27 experts from a variety of land management and research organizations across the assessment area (Table 34). We sought to create a team of panelists who would be able to contribute a diversity of subject area expertise, management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology, management, and climate change impacts on forests in northern Michigan. This panel was assembled at an in-person workshop in Pellston, Michigan, in September 2012. Below, we describe the structured discussion process that the panel followed during the workshop and in subsequent conversations.

Forest Systems Assessed

The authors of this assessment used U.S. Forest Service, Forest Inventory and Analysis data and Michigan Natural Features Inventory abstracts (available at http://mnfi.anr.msu.edu/communities/

Table 34.—Participants in the September 2012 expert panel workshop

Name	Organization
Tim Baker	Hiawatha National Forest
Patricia Butler*	Michigan Technological University & Northern Institute of Applied Climate Science
Sophan Chhin	Michigan State University
Eric Clark	Sault Ste. Marie Tribe
Josh Cohen	Michigan Natural Features Inventory
Rich Corner	Huron-Manistee National Forests
Matthew Duveneck	Portland State University
Amy Clark Eagle	Michigan Department of Natural Resources
Dave Fehringer	The Forestland Group
Jon Fosgitt	Compass Land Consultants
Jim Gries	Hiawatha National Forest
Kim Hall	The Nature Conservancy
Tina Hall	The Nature Conservancy
Stephen Handler*	Forest Service Northern Research Station & Northern Institute of Applied Climate Science
Bob Heyd	Michigan Department of Natural Resources
Chris Hoving	Michigan Department of Natural Resources
Ines Ibáñez	University of Michigan
Louis Iverson	Forest Service, Northern Research Station
Don Kuhr	Michigan Department of Natural Resources
Jennifer Muladore	Huron Pines
Knute Nadelhoffer	University of Michigan
Dave Neumann	Michigan Department of Natural Resources
Matt Sands	Huron-Manistee National Forests
Rob Scheller	Portland State University
Randy Swaty	The Nature Conservancy
Leiloni Wonch	Sault Ste. Marie Tribe
Kirk Wythers	University of Minnesota & Boreal Forest and Community Resilience Project

*Workshop facilitators

index.cfm) to describe nine major forest types occurring in the assessment area (Chapter 1). These forest types were the focus of the expert panel workshop.

For each forest type, we extracted information related to the major system drivers, dominant species, and stressors that characterize that community from Michigan Natural Features Inventory abstracts and other sources. The panel was asked to comment on and suggest modifications to the community descriptions, and those suggestions were incorporated into the descriptions.

Potential Impacts

Potential impacts are the direct and indirect consequences of climate change on systems. Impacts are a function of a system's exposure to climate change and its sensitivity to any changes. Impacts could be beneficial or harmful to a particular forest or ecosystem type. To examine potential impacts, the panel was given several sources of background information on past and future climate change in the region (summarized in Chapters 3 and 4) and projected impacts on dominant tree species and forest productivity (summarized in Chapter 5). The panel was directed to focus on impacts to each community type from the present through the end of the century, but more weight was given to the end-of-century period. The panel assessed impacts by considering a range of climate futures bracketed by two scenarios: Hadley A1FI and PCM B1 (Box 9). Panelists were then led through a structured discussion process to consider this information for each forest community in the assessment.

Potential impacts on drivers and stressors were summarized into a spreadsheet based on climate model projections, the published literature, and insights from the panelists. Impacts on drivers were considered positive or negative if they would alter system drivers in a way that would be more or less favorable for that forest type. Impacts on stressors were considered negative if they increased the influence of that stressor or positive if they decreased the influence of that stressor on the forest type. Panelists were also asked to consider the potential for climate change to facilitate new stressors in the assessment area over the next century.

To assess potential impacts on dominant tree species, the panelists examined results from Tree Atlas, LANDIS-II, and PnET-CN, and were asked to consider those results in addition to their knowledge of life history traits and ecology of those species. The panel evaluated how much the models agreed with each other, between climate scenarios, and across space and time.

Box 9: A Note on Future Climate Scenarios Used in this Assessment

The Hadley A1FI model/emissions scenario combination was originally chosen as the "high-end" scenario instead of GFDL A1FI. We chose to replace the high-end scenario because the Hadley A1FI scenario produced extremely high results for northern Michigan that seemed to be an unnatural artifact of the downscaling process. The authors of the vulnerability assessment were uncomfortable publishing an assessment with unreliable data.

The Northern Institute of Applied Climate Science coordinated a discussion among all research teams conducting ecosystem modeling for the Climate Change Response Framework and all groups decided it would be best to use GFDL A1FI as a high-end scenario instead. All results summarized in Chapter 6 were vetted with the expert panelists to ensure their vulnerability rankings were still consistent with GFDL projections.

Finally, panelists were asked to consider the potential for interactions among anticipated climate trends, species impacts, and stressors. Input on these future ecosystem interactions relied primarily on the panelists' expertise and judgment because there are not many examples of published literature on complex interactions, nor are future interactions accurately represented by ecosystem models.

For each community type, panelists were each asked to identify which impacts they felt were most important to that system using an individual worksheet (see example at the end of this appendix). Panelists then determined an overall rating of potential impacts for each community type based on the summation of the impacts on drivers, stressors, and dominant species across a continuum from negative to positive.

Adaptive Capacity

Adaptive capacity is the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption. Panelists discussed the adaptive capacity of each forest system based on their ecological knowledge and management experience with the community types in the assessment area. Adaptive capacity factors for each community type were delineated in a spreadsheet. Panelists were told to focus on community characteristics that would increase or decrease the adaptive capacity of that system. Factors that the panel considered included characteristics of dominant species within each community (e.g., dispersal ability, genetic diversity, range limits) and comprehensive community characteristics (e.g., functional and species diversity, tolerance to a variety of disturbances, distribution across the landscape). Rankings were based on a continuous spectrum, so a mid-range score would indicate strength in some areas and a deficit in others. The panelists were directed to base their considerations on the current condition of the system given past and current management regimes, with no consideration of potential adaptation actions that could take place in the future.

Vulnerability

Vulnerability is the susceptibility of a system to the adverse effects of climate change. It is a function of the potential climate change impacts and the adaptive capacity of the system. Following extensive group discussion, panelists individually evaluated the potential impacts and adaptive capacity of each community type to arrive at a vulnerability rating. Participants were provided with individual worksheets and asked to list which impacts they felt were most important to that system in addition to the major factors that would contribute to the adaptive capacity of that system.

Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Fig. 59a). This vulnerability figure required the participants to evaluate the degree of potential impacts related to climate change as well as the adaptive capacity of the system to tolerate those impacts (Swanston and Janowiak 2012). Among the group, individual ratings were compared and discussed, with the goal of coming to a group determination through consensus. In many cases, the group determination was at or near the centroid of all individual determinations. Sometimes the group determination deviated from the centroid because further discussion convinced some group members to alter their original response. The group vulnerability determination was placed into one of five categories (low, low-moderate, moderate, moderate-high, and high) based on the discussion and consensus within the group, as well as the placement of the group determination on the figure. For example, if a vulnerability determination was on the border between low and moderate and the group agreed that it didn't completely fall into one or the other category, it would receive a low-moderate determination.

Confidence

Panelists were also directed to give a confidence rating to each of their individual vulnerability determinations (Fig. 59b). Panelists were asked to evaluate the amount of evidence they felt was available to support their vulnerability determination and the level of agreement among the available evidence (Mastrandrea et al. 2010). Panelists evaluated confidence individually and as a group, in a similar fashion to the vulnerability determination.

Forest Community Determinations

Determinations of vulnerability and confidence were made for nine forested systems in the assessment area. The vulnerability determinations described above, along with information and ideas put forward during the group discussions, were collected and interpreted in order to develop the vulnerability summary descriptions presented in Chapter 6.

Vulnerability Statements

Recurring themes and patterns that transcended individual forest systems were identified and developed into the vulnerability statements (in boldface) and supporting text in Chapter 6. The lead author developed the statements and supporting text based on workshop notes and literature pertinent to each statement. An initial confidence determination (evidence and agreement) was assigned based on the lead author's interpretation of the amount of information available to support each statement and the extent to which the information agreed. Each statement and its supporting literature discussion were sent to the expert panel for review.

VULNERABILITY AND CONFIDENCE FIGURES

For reference, figures of individual and group determinations for all nine forest types considered in this assessment are displayed below (Figs. 60 through 68). In each figure, individual panelist votes are indicated with a small circle and the group determination is indicated with a large square. We do not intend for direct comparison between these figures because the axes represent subjective, qualitative scales.

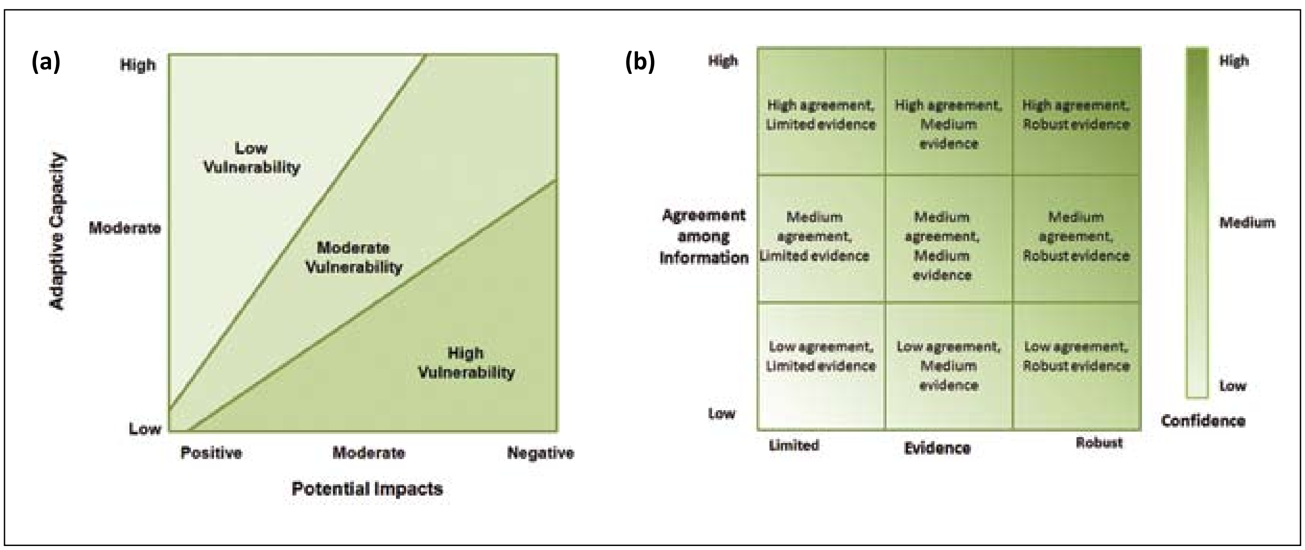

Figure 59.—Figure used for (a) vulnerability determination by expert panelists, based on Swanston and Janowiak (2012) and (b) confidence rating among expert panelists, adapted from Mastrandrea et al. (2010).

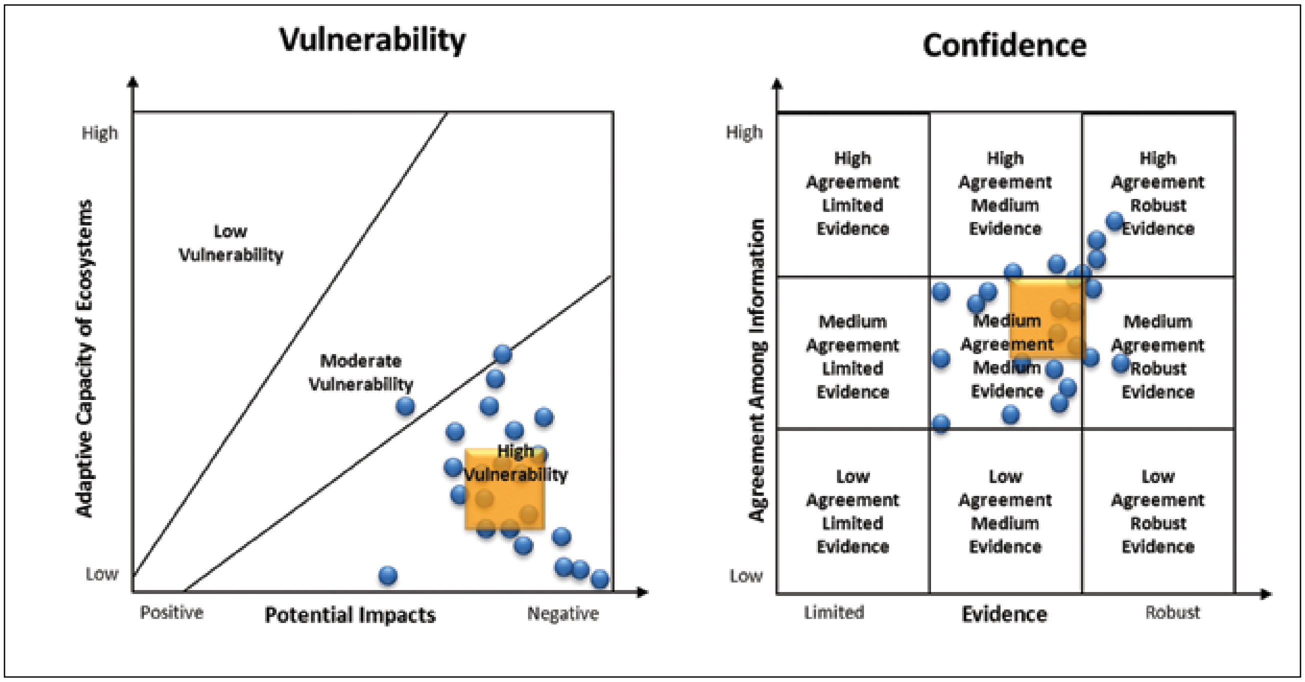

Figure 60.—Upland spruce-fir vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

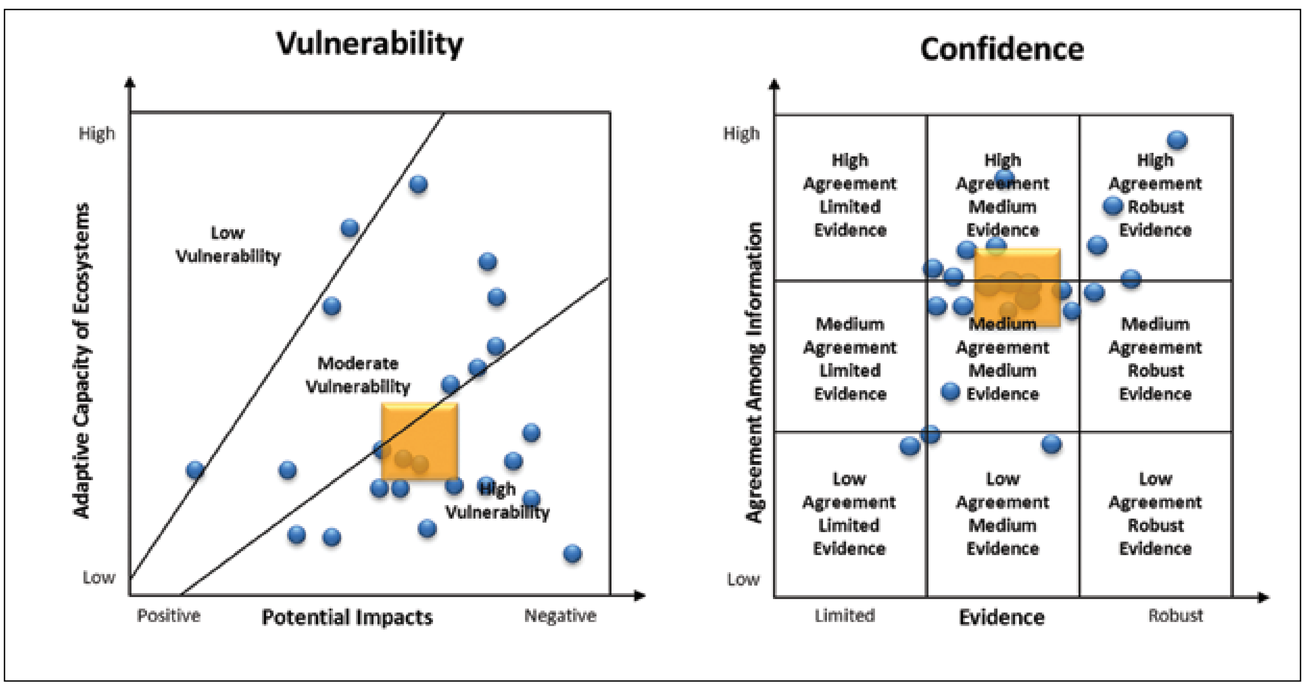

Figure 61.—Jack pine (including pine-oak) vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

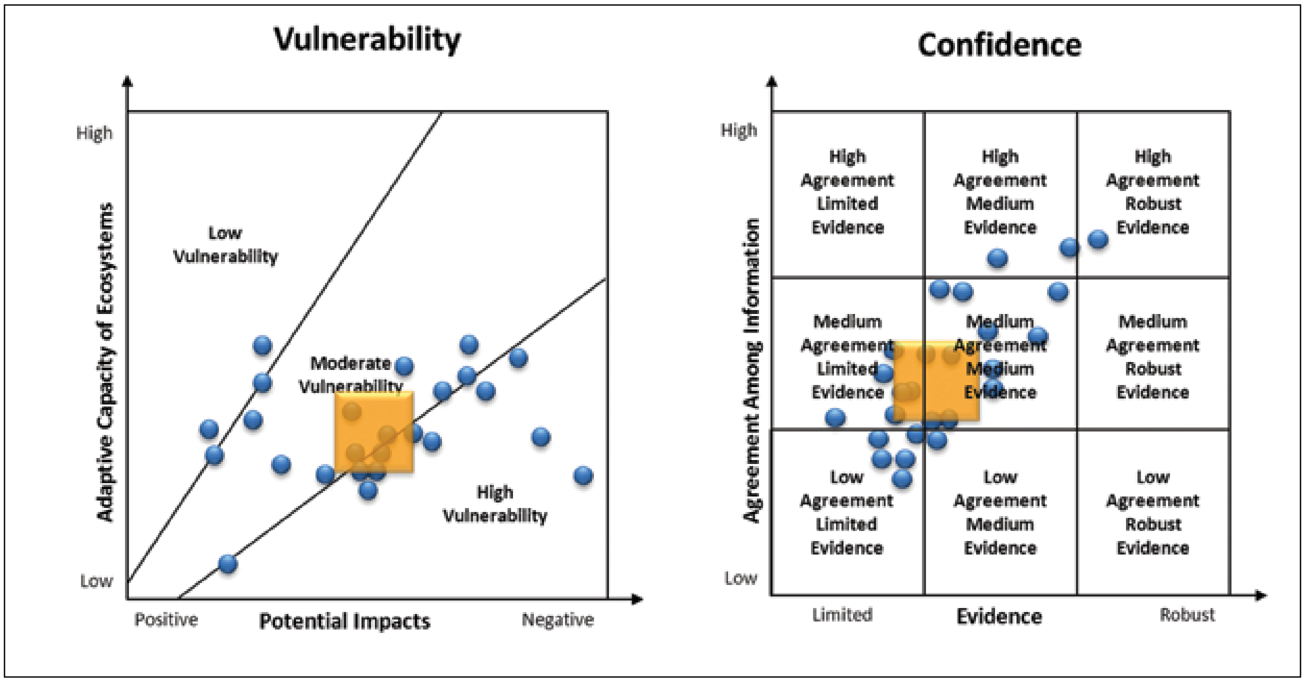

Figure 62.—Red pine-white pine vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

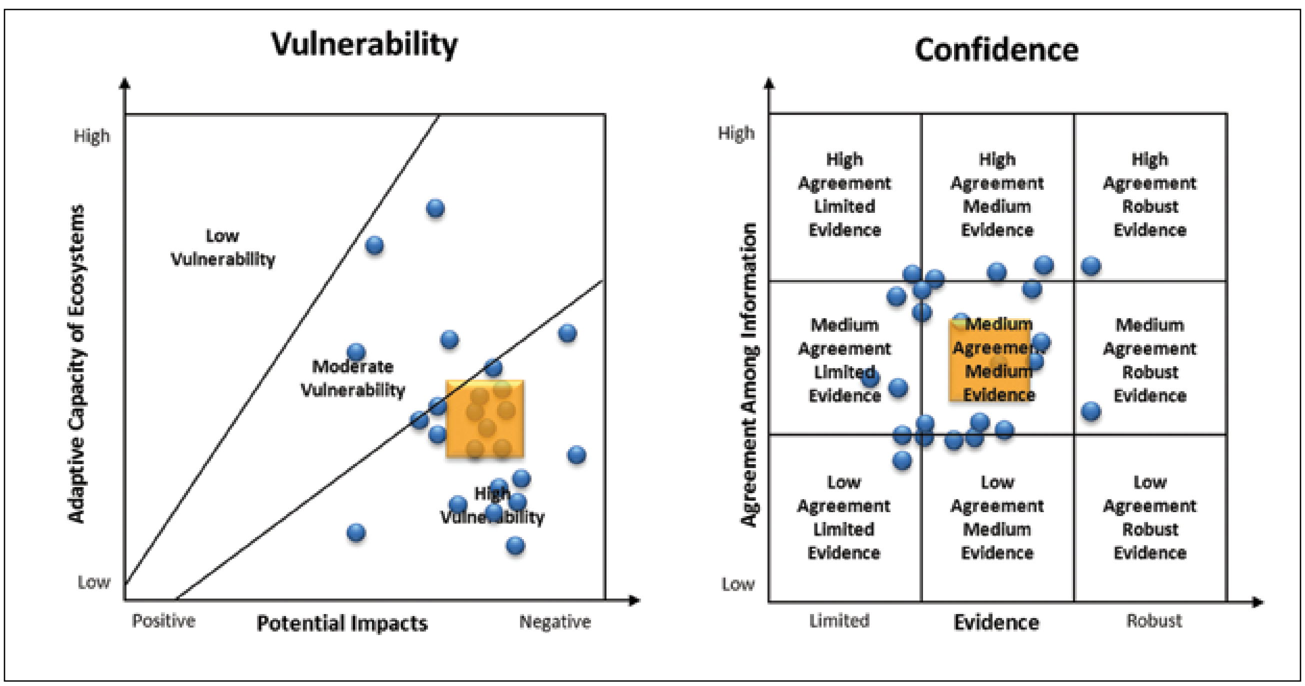

Figure 63.—Lowland conifers vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

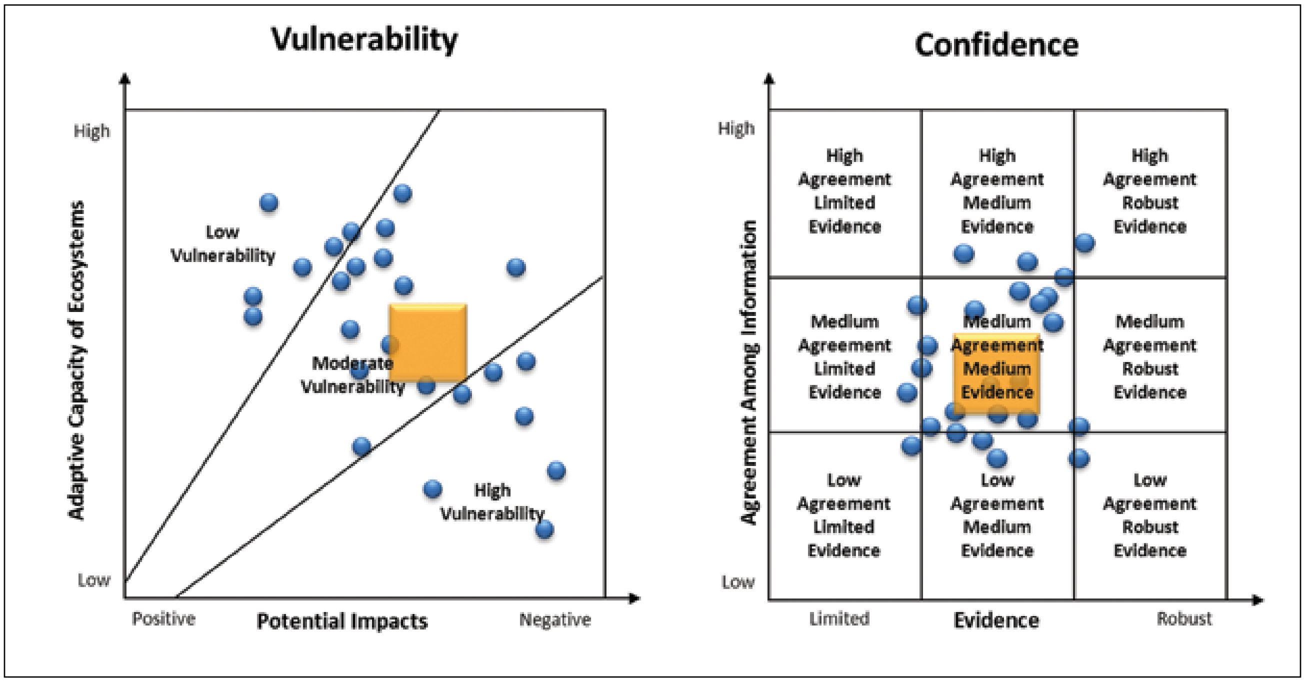

Figure 64.—Aspen-birch vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

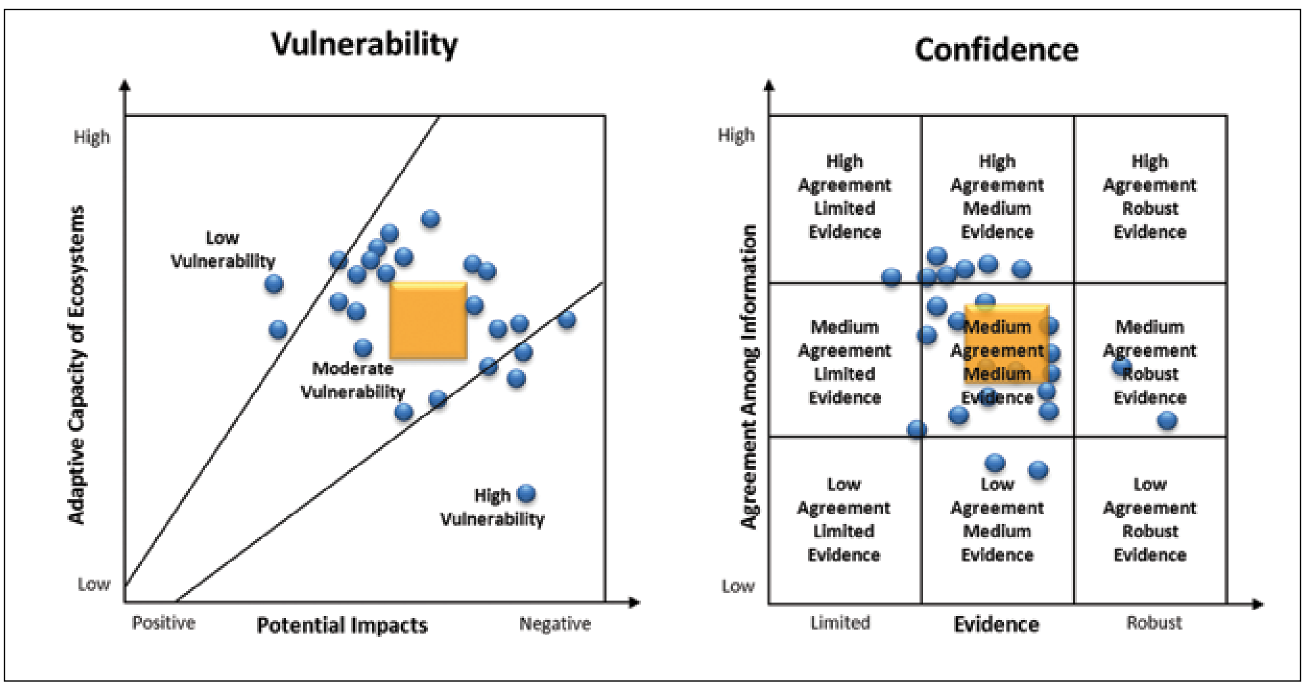

Figure 65.—Northern hardwoods vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

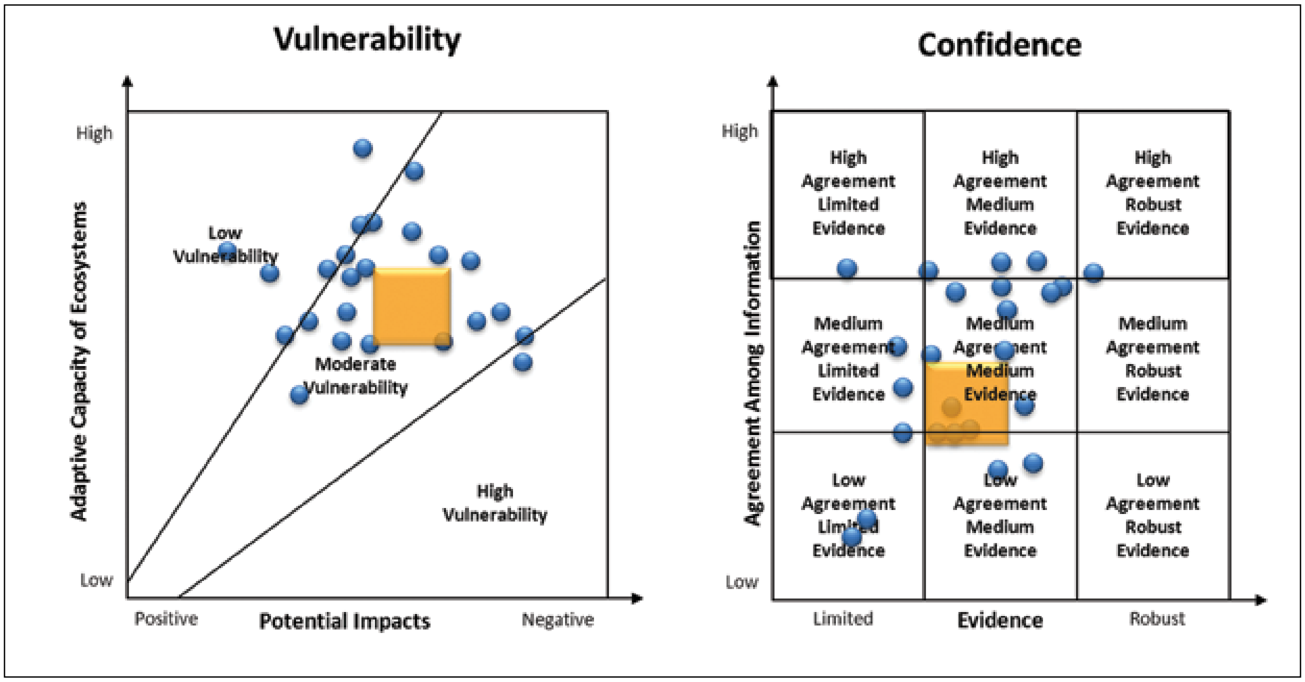

Figure 66.—Lowland and riparian hardwoods vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

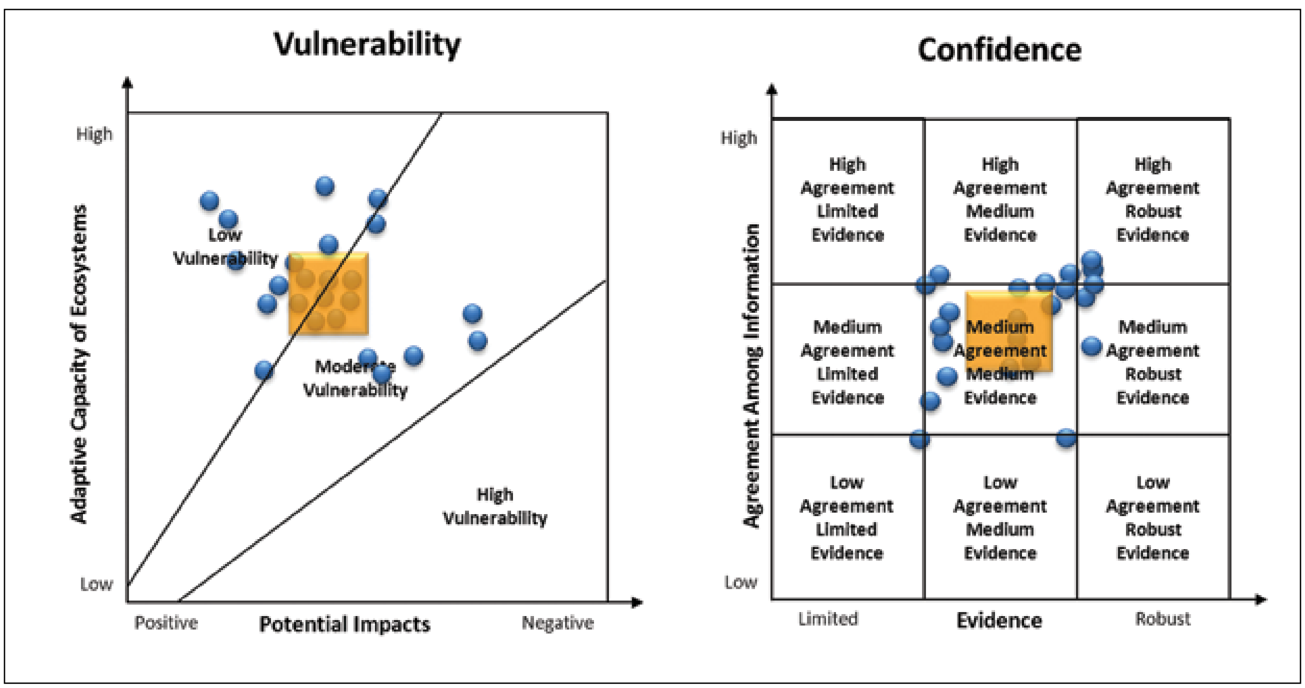

Figure 67.—Oak associations vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

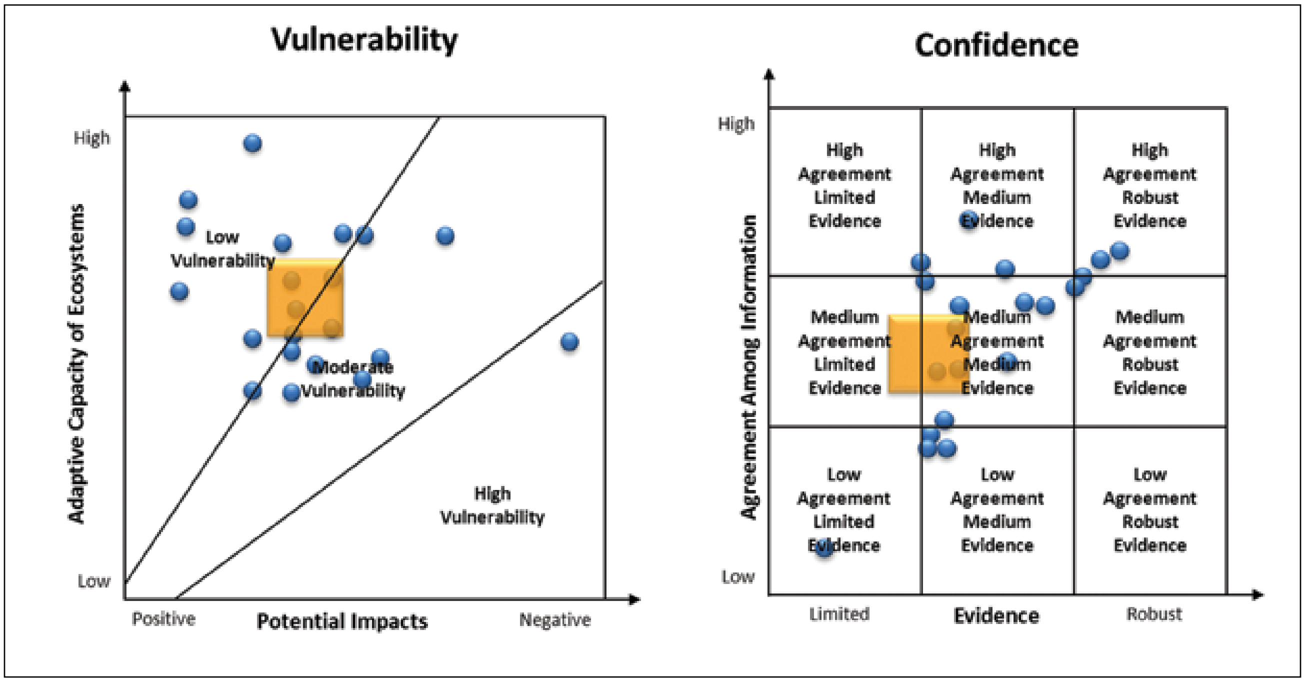

Figure 68.—Barrens vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

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Swanston, C.W.; Janowiak, M.K. 2012. **Forest adaptation resources: climate change tools and approaches for land managers.** Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 121 p. Available at http://www.nrs.fs.fed.us/pubs/40543. (Accessed November 5, 2013).

Example Vulnerability Determination Worksheet

Name: ______________________ **Ecosystem/Forest Type:** ______________________

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

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

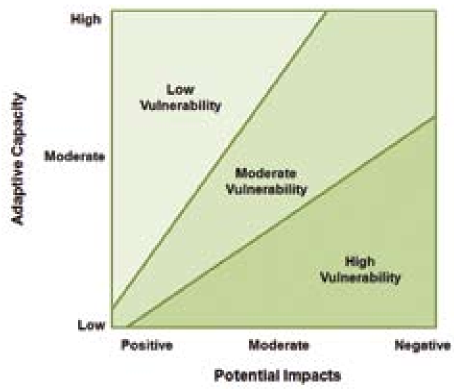
What do you think are the greatest potential impacts to the ecosystem?

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

(Continued on next page)

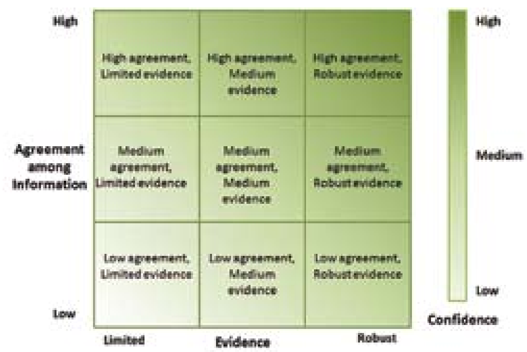
Vulnerability Determination

Use the handout for the vulnerability determination process and the notes that you have taken to plot your assessment of vulnerability on the figure below.



Confidence Rating

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



The ratings above are for the entire analysis area. Please note where you think potential impacts or adaptive capacity may vary substantially within the analysis area (e.g., forests in the eastern portion may be more prone to impact X).

APPENDIX 6: CONTRIBUTORS TO IMPLICATIONS CHAPTER

We relied on input from several subject-area experts from a variety of organizations to summarize the management implications of climate change in Chapter 7 (Table 35).

Table 35.—Contributors to Chapter 7

Name	Organization	Subject Area
Jad Daley	Trust for Public Land	Land acquisition
Mae Davenport	University of Minnesota	Forest-associated towns and cities
Marla Emery	U.S. Forest Service Northern Research Station	Nontimber forest products
David Fehringer	The Forestland Group, LLC	Forest management operations & infrastructure
Christopher Hoving	Michigan Department of Natural Resources	Wildlife
Lucinda Johnson	Natural Resources Research Institute	Water resources
Gary Johnson	University of Minnesota	Urban forests
David Neitzel	Minnesota Department of Health	Human health concerns
Adena Rissman	University of Wisconsin-Madison	Forest management operations
Chadwick Rittenhouse	University of Connecticut	Forest management operations
Robert Ziel	Lake States Fire Science Consortium	Fire and fuels

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Forests in northern Michigan will be affected directly and indirectly by a changing climate during the next 100 years. This assessment evaluates the vulnerability of forest ecosystems in Michigan's eastern Upper Peninsula and northern Lower Peninsula to a range of future climates. Information on current forest conditions, observed climate trends, projected climate changes, and impacts to forest ecosystems was considered in order to draw conclusions on climate change vulnerability. Upland spruce-fir forests were determined to be the most vulnerable, whereas oak associations and barrens were determined to be less vulnerable to projected changes in climate. Projected changes in climate and the associated ecosystem impacts and vulnerabilities will have important implications for economically valuable timber species, forest-dependent wildlife and plants, recreation, and long-range planning.

KEY WORDS: change, vulnerability, adaptive capacity, forests, Climate Change Tree Atlas, LANDIS-II, PnET-CN, expert elicitation, climate projections, impacts

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